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MATHEMATICAL METHOD FOR EXPEDITING SCRAP-OR-REWORK DECISION MAKING IN EPQ MODEL WITH FAILURE IN REPAIR

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Abstract- This study uses a mathematical method to develop an efficient rule for expediting scrap-or-rework decision making in economic production quantity (EPQ) model with failure-in-repair. The expected overall production-inventory costs and the optimal lot sizes for EPQ models with/without rework process are derived and compared. With straightforward numerical derivations, this paper develops an efficient rule including the exact critical value of unit repair cost for each reworked item and its approximation equations, to assist in determining whether it is beneficial to rework the repairable items. Numerical example with sensitivity analysis and discussion are provided to demonstrate their practical usages.

Keywords- Production; EPQ; Scrap-or-rework; Failure in repair Random defective rate.

1. INTRODUCTION

The Economic Order Quantity (EOQ) model was first introduced several decades ago to assist corporations in determining the optimal order quantity that minimizes overall inventory costs. Regardless of its simplicity, EOQ model is still applied industry-wide today [11,12,14,17]. In the manufacturing sector, when items are produced internally instead of being obtained from an outside supplier, the economic production quantity (EPQ) model is often used to determine the optimal production lot size. The classic EPQ model assumes that the manufacturing process will function perfectly at all times. But in reality, the production of defective items during a production run is inevitable. Sometimes, the imperfect quality items can be reworked and fixed with extra repairing cost [4,5,6,8,10,13,15]. For instances, printed circuit board assembly (PCBA) in the PCBA manufacturing, plastic goods in the plastic injection molding process, etc., sometimes employ rework as an acceptable process in terms of level of quality.

A considerable amount of research has been carried out to address the imperfect quality EPQ model [1,3,9,16]. Additional examples are surveyed as follows. Rosenblatt and Lee [11] proposed an EPQ model that deals with imperfect quality. They assumed that at some random point in time the process might shift from an in-control to an out-of-control state and a fixed percentage of defective items are produced.

Approximate solutions for obtaining an optimal lot size were developed in their paper. Cheng [2] formulated inventory as a geometric program and obtained closed-form optimal solutions for an EOQ model with demand-dependent unit production cost and imperfect production processes. Chung [7] investigated bounds for production lot sizing with machine breakdown conditions. This paper employs the optimal production lot-sizing results from the work of Chiu and Gong [4] and develops an efficient rule for expediting scrap-or-rework decision making (on whether it is beneficial or not to rework the repairable defective items) in EPQ model with assumptions of failure-in-repair and backlogging not permitted.

2. MATHEMATICAL MODELING AND ANALYSIS

This paper studies the decisions on whether to rework-or-scrap the defective items in an EPQ model with an imperfect rework process. We reconsider the model studied by [3,4] where the assumptions of the production rate 'P' is constant and is much larger than the demand rate 'λ', and 'x' percent of defective items are randomly generated by the regular production process; and the inspection cost per item is involved when all items are screened.

All defective items are assumed to be repairable and if the decision is to rework the defective items then they will be reworked right after the regular process ends, at a rate of 'P_1'. The rework process itself is assumed to be imperfect either, a portion 'θ_1' of defective items fail the reworking and become scrap items. The production rate 'd' of the defective items could be expressed as the production rate times the defective percentage, i.e. $d=Px$. Other notation used is displayed as follows.

Q_1 = production lot size per cycle for the EPQ model with the reworking of defective items,
Q_2 = production lot size per cycle for the EPQ model without the rework process,
C = production cost per item ($/item, inspection cost per item is included),
C_R = repair cost for each imperfect quality item reworked ($/item),
C_S = disposal cost for each scrap item produced ($/item),
H = the maximum level of on-hand inventory in units, when rework process ends,
K = setup cost for each production run;
h = holding cost per item per unit time ($/item/unit time),
h_1 = holding cost for each reworked items per unit time ($/item/unit time),
b = shortage cost per item per unit time (i.e. $/item/unit time),
$TCU(Q_1)$= the total production-inventory costs per unit time for the EPQ model with the reworking of defective items,
$TCU(Q_2)$= total production-inventory costs per unit time for the EPQ model without the rework process.

The EPQ model with the reworking of defective items has the optimal production lot-size and the optimal expected annual costs [4] as shown in Equations (1) and (2).

$$Q_1^* = \sqrt{\frac{2K\lambda}{h\left(1-\frac{\lambda}{P}\right)+\frac{\lambda}{P_1}[h_1-h(1-\theta_1)]E[x^2]-2h\theta_1\left(1-\frac{\lambda}{P}\right)E[x]+h\theta_1^2E[x^2]}} \tag{1}$$

$$E[TCU(Q_1)] = \lambda\left[\frac{C}{1-\theta_1 E[x]} + \frac{C_R E[x]}{1-\theta_1 E[x]} + \frac{C_S \theta_1 E[x]}{1-\theta_1 E[x]}\right] + \frac{K\lambda}{Q_1}\frac{1}{1-\theta_1 E[x]} + \frac{hQ_1}{2}\left(1-\frac{\lambda}{P}\right)\frac{1}{1-\theta_1 E[x]}$$
$$+\frac{\lambda Q_1}{2P_1}[h_1 - h(1-\theta_1)]\frac{E[x^2]}{1-\theta_1 E[x]} - hQ_1\theta_1\left(1-\frac{\lambda}{P}\right)\frac{E[x]}{1-\theta_1 E[x]} + \frac{hQ_1\theta_1^2}{2}\frac{E[x^2]}{1-\theta_1 E[x]} \quad (2)$$

When the rework process is not considered, the optimal production lot-size and the optimal expected annual costs [3] are as shown in Equations (3) and (4).

$$Q_2^* = \sqrt{\frac{2K\lambda}{h\left(1-\frac{\lambda}{P}\right) - 2h\left(1-\frac{\lambda}{P}\right)E[x] + hE[x^2]}} \quad (3)$$

$$E\left[TCU\left(Q_2\right)\right] = \lambda\left[\frac{C}{1-E[x]} + \frac{C_S E[x]}{1-E[x]}\right] + \frac{K\lambda}{Q_2}\frac{1}{1-E[x]} + \frac{hQ_2}{2}\left(1-\frac{\lambda}{P}\right)\frac{1}{1-E[x]}$$
$$-hQ_2\left(1-\frac{\lambda}{P}\right)\frac{E[x]}{1-E[x]} + \frac{hQ_2}{2}\frac{E[x^2]}{1-E[x]} \quad (4)$$

The decision on whether to rework or to scrap defective items in such an imperfect quality EPQ model, can be determined by selecting the smaller values between Equations (2) and (4). Let C_γ represents the breakeven value of unit repair cost that makes the optimal expected annual costs *E[TCU(Q*$_1$*)=E[TCU(Q*$_2$*)]*. Hence from Equations (2) and (4), we obtain C_γ as:

$$C_\gamma = \frac{C(1-\theta_1)}{1-E[x]} + \frac{C_S(1-\theta_1)}{1-E[x]} + \frac{K}{Q_1 E[x]}\left(\frac{1-\theta_1 E[x]}{W(1-E[x])} - 1\right) + \frac{hQ_1}{2\lambda E[x]}\left(1-\frac{\lambda}{P}\right)\left(W\frac{1-\theta_1 E[x]}{1-E[x]} - 1\right)$$
$$-\frac{Q_1 E[x^2]}{2P_1 E[x]}\left[h_1 - h(1-\theta_1)\right] - \frac{hQ_1}{\lambda}\left(1-\frac{\lambda}{P}\right)\left(W\frac{1-\theta_1 E[x]}{1-E[x]} - \theta_1\right) + \frac{hQ_1 E[x^2]}{2\lambda E[x]}\left(W\frac{1-\theta_1 E[x]}{1-E[x]} - \theta_1^2\right) \quad (5)$$

where

$$W = \sqrt{\frac{h\left(1-\frac{\lambda}{P}\right) + \frac{\lambda}{P_1}\left[h_1 - h(1-\theta_1)\right]E[x^2] - 2h\theta_1\left(1-\frac{\lambda}{P}\right)E[x] + h\theta_1^2 E[x^2]}{h\left(1-\frac{\lambda}{P}\right) - 2h\left(1-\frac{\lambda}{P}\right)E[x] + hE[x^2]}}$$

If we let $$\omega = \frac{1}{Q}\frac{1}{E[x]}\frac{\left(1-\theta_1 E[x]\right) - W\left(1-E[x]\right)}{W} \quad (6)$$

and

$$\varepsilon = \frac{hQ_1}{\lambda}\frac{1}{1-E[x]}\left\{\begin{aligned} &+\frac{1}{2}\frac{1}{E[x]}\left(1-\frac{\lambda}{P}\right)\left[W\left(1-\theta_1 E[x]\right) - \left(1-E[x]\right)\right] \\ &-\left(1-\frac{\lambda}{P}\right)\left[W\left(1-\theta_1 E[x]\right) - \theta_1\left(1-E[x]\right)\right] \\ &+\frac{1}{2}\frac{E\left[x^2\right]}{E[x]}\left[W\left(1-\theta_1 E[x]\right) - \theta_1^2\left(1-E[x]\right)\right] \end{aligned}\right\} - \frac{Q_1}{2P_1}\frac{E\left[x^2\right]}{E[x]}\left[h_1 - h(1-\theta_1)\right] \quad (7)$$

Substituting ω and ε in Equation (5), one obtains:

$$C_\gamma = \left(C + C_S + \frac{K\omega}{1-\theta_1}\right)\frac{1-\theta_1}{1-E[x]} + \varepsilon \quad (8)$$

The decisions on either to rework or to scrap the defective items in an imperfect quality EPQ model can be made by comparing C_R and C_γ. That is, for instance, if $C_R < C_\gamma$ then it will be better off to rework the repairable defective items.

In Equation (8), suppose we would like to find an approximation to Cr without involving the complex computation of ε, then let χ_1 satisfies the following:

$$C_\gamma = \chi_1 \left[\left(C + C_S + \frac{K\omega}{1-\theta_1}\right)\frac{1-\theta_1}{1-E[x]}\right] \tag{9}$$

Let $$\Upsilon_1 = \left(C + C_S + \frac{K\omega}{1-\theta_1}\right)\frac{1-\theta_1}{1-E[x]},$$

$$\therefore\ \chi_1 = 1 + \left(\frac{\varepsilon}{\Upsilon_1}\right). \tag{10}$$

Hence, if an approximation to (ε/Υ_1) is obtainable, then the computation of Cr can be simplified as was shown in Equation (9). Furthermore, let

$$\Upsilon_2 = (C + C_S)\frac{1-\theta_1}{1-E[x]} \quad \text{and} \quad \varepsilon_x = \frac{K\omega}{1-E[x]};$$

if we would like to find an approximation to Cr without involving the complicated computations of ε_x and ε; then let χ_2 satisfies the following:

$$C_\gamma = \chi_2 \left[(C + C_S)\frac{1-\theta_1}{1-E[x]}\right] \tag{11}$$

$$\therefore\ \chi_2 = 1 + \left(\frac{\varepsilon_x + \varepsilon}{\Upsilon_2}\right). \tag{12}$$

Hence, if an approximation of $(\varepsilon_x+\varepsilon)/\Upsilon_2$ is obtainable, then computation of Cr can be simplified as was shown in Equation (11).

A numerical example is provided in the following section to demonstrate the above equations' practical usages. Sensitivity analysis of C_γ in regard to various cost-related parameters and the estimated ranges for χ_1 and χ_2 are presented in Section 3.

3. A NUMERICAL EXAMPLE AND DISCUSSION

An item can be produced at a rate P=10,000 units per year and this item has experienced a relatively flat demand of 4,000 units per year. The percentage of defective items produced x is assumed to follow the uniform distribution over the interval [0, 0.1]. Right after the regular production process ends, all of the imperfect quality items can be reworked, at a rate of P_1=600 units per year. The rework process is considered to be imperfect, when it finishes a portion θ_1=0.1 of the reworked items fail the repairing and become scrap items. Other parameters are given below:

K = \$450 for each production run,
C = \$2 per item,

C_R = \$0.5 repaired cost for each item reworked,
C_S = \$0.3 disposal cost for each scrap item,
h = \$0.6 per item per unit time,
h_1 = \$0.8 per item reworked per unit time.

For the decision on either to rework or to scrap the repairable defective items, one can use Equation (8) and find the critical value of repair cost C_γ = \$2.18. In this example, since C_R=\$0.5 < C_γ , so "to rework" is a better choice. □

To verify the above decision, for the case of reworking the repairable defective items, one can use Equations (1) and (2) and obtain Q_1* = 3,153 and the optimal annual expected costs $E[TCU(Q_1^*)]$= \$9,294. On the other hand, suppose all defective items (whether they are repairable or not) are treated as scrap items and are discarded, then using Equations (3) and (4), one obtains Q_2* = 3,323 and $E[TCU(Q_2^*)]$ = \$9,625. Obviously, $E[TCU(Q_1^*)] < E[TCU(Q_2^*)]$, the above result is confirmed.

3.1 Sensitivity Analysis

From the above example and Equation (8), the critical value of C_γ, is determined by a set of parameters S={x, θ_1, C, C_S, K, h, h_1}. For θ_1 falls within the range [0.1, 0.3]; for C_S/C limits within [0.1, 0.5] and h_1/h falls within the interval of [1, 1.5]; and for K/h ranges from 400 to 1000; the impact of these variations on the components ε and ε_x of C_γ are analyzed and the results are presented in Table 1 (in Appendix). From analysis and Equations (2) and (4), the behavior of the optimal expected annual cost with respect to defective rate x can also be obtained as follows: As x increases, $E[TCU(Q_1)]$ and $E[TCU(Q_2)]$ both increase, and the difference between the costs increases too.

The behavior of Cr and its simplified forms with respect to the defective rate x is depicted as in Figure 1. One notices that ε and $K\omega/[1\text{-}E[x]]$ are both negative and they are relatively small in comparison with the value of $(C+Cs)(1-\theta_1)/[1-E[x]]$.

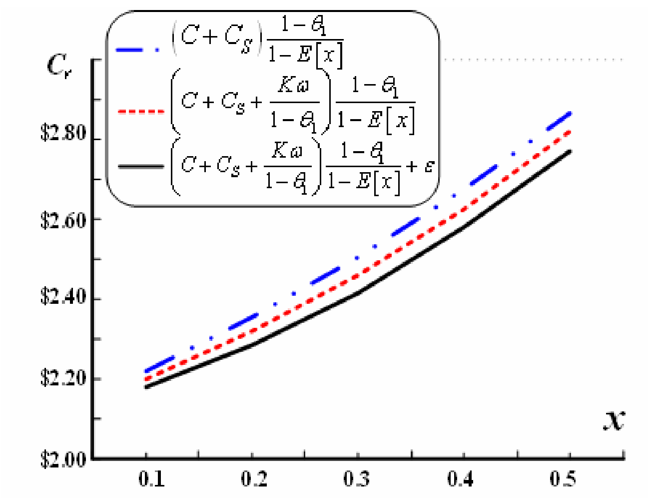

Figure 1: The behavior of Cr and its simplified forms with respect to the defective rate x

The behavior of the optimal expected annual cost with respect to the scrap rate θ_1 value is illustrated as in Figure 2. One notices that as θ_1 increases, $E[TCU(Q_1)]$ increases, and the difference between the costs reduces. When θ_1 approaches to 1, $E[TCU(Q_1)] = E[TCU(Q_2)]$ as one would expect.

The behavior of Cr and its simplified forms with respect to λ/P is illustrated in Figure 3. One notices that as λ/P increases, the value of Cr decreases slightly.

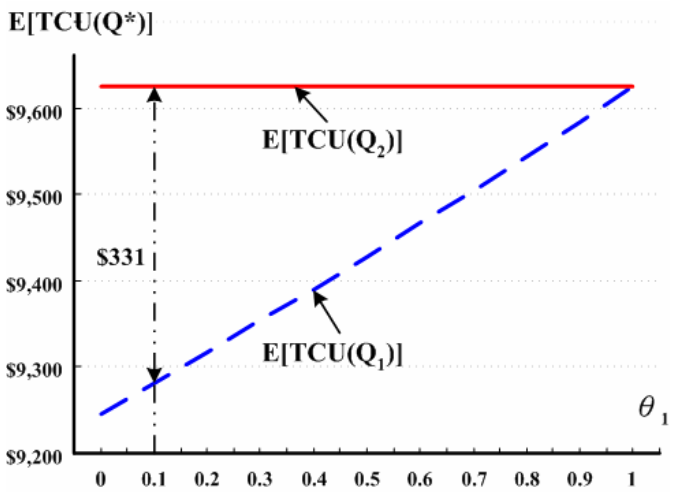

Figure 2: The behavior of the optimal expected annual costs with respect to the scrap rate θ_1

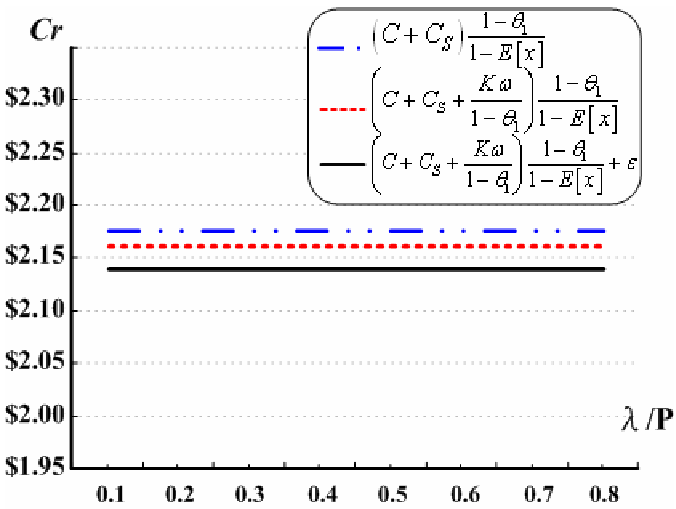

Figure 3: The behavior of *Cr* and its simplified forms with respect to λ/P

3.2 Comments on Sensitivity Analysis

From the analytical results of Table 1, one realizes that $(\varepsilon/Y_1) \in [-8.57\%, -0.02\%]$, hence from Equation (10), we obtain $\chi_1 \in [0.9143,\ 0.9998]$. One notices that as *K/h* ratio increases, the range of χ_1 becomes narrower; and as *Cs/C* decreases, the range of χ_1 is thinner too. Since the approximation to (ε/Y_1) is obtainable, one can use the following procedures to determine whether or not "to rework" the defective items.

$$\begin{aligned}
&\text{If } C_R < \left\{\text{the lower bound of}\left(\chi_1\left[\frac{(C+C_S)(1-\theta_1)+K\omega}{1-E[x]}\right]\right)\right\} \text{ then "rework",}\\
&\quad\text{else if } C_R > \left\{\text{the upper bound of}\left(\chi_1\left[\frac{(C+C_S)(1-\theta_1)+K\omega}{1-E[x]}\right]\right)\right\} \text{ then "scrap",}\\
&\qquad\text{else if } C_R < C_\gamma \text{ then "rework", otherwise "scrap".}
\end{aligned} \tag{13}$$

Also, from the example and analytical results of Table 1, one realizes that the range of $(\varepsilon_x+\varepsilon)/Y_2 \in [-15.78\%, -0.03\%]$. Hence, from Eq. (12), we obtain $\chi_2 \in [0.8422,\ 0.9997]$. One notices that as *Cs/C* decreases, the range of χ_2 becomes narrower; and as *K/h* ratio increases, the range of χ_2 is thinner too. For example, if *K/h* ≧ 600 then $\chi_2 \in [0.8714,\ 0.9997]$. Once χ_2 is available, one can use the following procedures for the rework-or-scrap decision making.

$$\begin{aligned}
&\text{If } C_R < \left\{\text{the lower bound of}\left(\chi_2\left[\frac{(C+C_S)(1-\theta_1)}{1-E[x]}\right]\right)\right\} \text{ then "rework",}\\
&\quad\text{else if } C_R > \left\{\text{the upper bound of}\left(\chi_2\left[\frac{(C+C_S)(1-\theta_1)}{1-E[x]}\right]\right)\right\} \text{ then "scrap",}\\
&\qquad\text{else, use Equation (13) for decision making.}
\end{aligned} \tag{14}$$

For instance, if we take advantage of Equation (14) to resolve the example stated earlier, since all parameters fall within the anticipated ranges and *K/h* ≧ 600:

$$\because C_R = \$0.5 < \left\{\text{the lower bound of}\left([0.8714, 0.9997]\frac{(\$2+\$0.3)(1-0.1)}{1-0.05}\right)\right\} = \$1.90,$$

$\therefore$ decision is to "rework".

4. CONCLUSION

This paper uses a mathematical method to develop an efficient rule for practitioners in production-inventory management to expedite scrap-or-rework decision making in EPQ model with failure in repair. With straightforward derivations, this study proposes a set of mathematical equations, including the exact critical point of repair cost and its approximated forms, to assist in determining whether it is beneficial to rework the defective items. A numerical example with sensitivity analysis and discussion is provided to demonstrate practical usages of these decision procedures. For future research, one interesting topic among others will be to consider a similar model with backlogging permitted.

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APPENDIX

Table 1: Variations of parameters in S effects on the components of C_γ, when x =0.1

x	θ	C_S/C	h_1/h	K/h	ε	$\left[\frac{\varepsilon}{Y_1}\right]\%$	ε_x	$\left[\frac{\varepsilon_x+\varepsilon}{Y_2}\right]\%$	x	θ	C_S/C	h_1/h	K/h	ε	$\left[\frac{\varepsilon}{Y_1}\right]\%$	ε_x	$\left[\frac{\varepsilon_x+\varepsilon}{Y_2}\right]\%$
0.1	0.1	0.1	1	400	-0.001	-0.02%	-0.001	-0.05%	0.1	0.3	0.1	1	400	-0.016	-0.66%	-0.016	-1.32%
				600	-0.001	-0.02%	-0.001	-0.04%					600	-0.013	-0.54%	-0.013	-1.07%
				800	-0.001	-0.02%	-0.001	-0.03%					800	-0.011	-0.47%	-0.011	-0.93%
				1000	0.000	-0.02%	0.000	-0.03%					1000	-0.010	-0.42%	-0.010	-0.83%
			1.25	400	-0.019	-0.61%	-0.019	-1.21%				1.25	400	-0.034	-1.43%	-0.034	-2.81%
				600	-0.015	-0.49%	-0.015	-0.98%					600	-0.028	-1.16%	-0.028	-2.29%
				800	-0.013	-0.43%	-0.013	-0.85%					800	-0.024	-1.00%	-0.024	-1.98%
				1000	-0.012	-0.38%	-0.012	-0.76%					1000	-0.022	-0.90%	-0.022	-1.78%
			1.5	400	-0.037	-1.19%	-0.037	-2.36%				1.5	400	-0.052	-2.20%	-0.052	-4.30%
				600	-0.030	-0.97%	-0.030	-1.92%					600	-0.043	-1.78%	-0.043	-3.51%
				800	-0.026	-0.84%	-0.026	-1.66%					800	-0.037	-1.54%	-0.037	-3.03%
				1000	-0.023	-0.75%	-0.023	-1.49%					1000	-0.033	-1.38%	-0.033	-2.72%
		0.3	1	400	-0.001	-0.06%	-0.001	-0.12%			0.3	1	400	-0.016	-1.70%	-0.016	-3.34%
				600	-0.001	-0.05%	-0.001	-0.10%					600	-0.013	-1.38%	-0.013	-2.72%
				800	-0.001	-0.04%	-0.001	-0.09%					800	-0.011	-1.19%	-0.011	-2.35%
				1000	0.000	-0.04%	0.000	-0.08%					1000	-0.010	-1.07%	-0.010	-2.11%
			1.25	400	-0.019	-1.55%	-0.019	-3.06%				1.25	400	-0.034	-3.70%	-0.034	-7.14%
				600	-0.015	-1.26%	-0.015	-2.49%					600	-0.028	-3.00%	-0.028	-5.82%
				800	-0.013	-1.09%	-0.013	-2.15%					800	-0.024	-2.58%	-0.024	-5.03%
				1000	-0.012	-0.98%	-0.012	-1.93%					1000	-0.022	-2.31%	-0.022	-4.51%
			1.5	400	-0.037	-3.09%	-0.037	-5.99%				1.5	400	-0.052	-5.78%	-0.052	-10.93%
				600	-0.030	-2.50%	-0.030	-4.88%					600	-0.043	-4.66%	-0.043	-8.90%
				800	-0.026	-2.15%	-0.026	-4.21%					800	-0.037	-4.00%	-0.037	-7.69%
				1000	-0.023	-1.93%	-0.023	-3.78%					1000	-0.033	-3.57%	-0.033	-6.90%
		0.5	1	400	-0.001	-0.09%	-0.001	-0.18%			0.5	1	400	-0.016	-2.47%	-0.016	-4.83%
				600	-0.001	-0.07%	-0.001	-0.14%					600	-0.013	-2.01%	-0.013	-3.93%
				800	-0.001	-0.06%	-0.001	-0.12%					800	-0.011	-1.73%	-0.011	-3.40%
				1000	0.000	-0.06%	0.000	-0.11%					1000	-0.010	-1.55%	-0.010	-3.05%
			1.25	400	-0.019	-2.26%	-0.019	-4.42%				1.25	400	-0.034	-5.44%	-0.034	-10.32%
				600	-0.015	-1.83%	-0.015	-3.60%					600	-0.028	-4.39%	-0.028	-8.41%
				800	-0.013	-1.58%	-0.013	-3.11%					800	-0.024	-3.77%	-0.024	-7.26%
				1000	-0.012	-1.41%	-0.012	-2.79%					1000	-0.022	-3.36%	-0.022	-6.51%
			1.5	400	-0.037	-4.52%	-0.037	-8.65%				1.5	400	-0.052	-8.57%	-0.052	-15.78%
				600	-0.030	-3.65%	-0.030	-7.04%					600	-0.043	-6.87%	-0.043	-12.86%
				800	-0.026	-3.14%	-0.026	-6.09%					800	-0.037	-5.88%	-0.037	-11.11%
				1000	-0.023	-2.80%	-0.023	-5.46%					1000	-0.033	-5.24%	-0.033	-9.96%