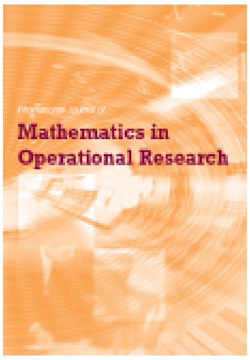

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Risk analysis on product quality improvement and supply chain performance for return contract with warranty

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Abstract: Products which require after sales services and associated with a warranty clause often pass through a series of quality checks and quality control measures. Improvement of quality of the product is an ongoing exercise and the manufacturer and the channel coordinator are expected to explore the impact of any initiative for quality improvement on the profitability and performance of the supply chain. It is important to carry out a risk benefit analysis before undertaking such quality improvement initiatives since it requires major financial investment. It is necessary to redesign the contract parameters after successful implementation of any quality improvement programme. The paper analyses the impact of the quality improvement initiative upon the profitability of the supply chain and describes how to redesign the contract parameters when return contracts are practised. It also does a risk analysis of the parties and the entire supply chain when return contract is practised along with warranty. It examines how change in order quantity and warranty length impacts supply chain risk as measured by variance of profit.

Keywords: warranty; quality; risk analysis; supply chain contract; return contracts; supply chain performance; redesign; supply chain risk.

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1 Introduction

In this competitive era of business, quality of a product is playing more significant role day by day in grabbing market share. To achieve this purpose a well designed and profitable quality development programme should be initiated. In order to achieve enhanced supply chain performance, one should focus on coordinating its quality decision, warranty policy and production level. The supply chain coordinator should also do a risk analysis of the channel performance and profitability and risks of the parties as a result of the quality development initiative.

A well coordinated supply chain with respect to the above three aspects delivers superior performances. These three aspects are closely interlinked and tend to affect each other. For example, if a quality improvement initiative is undertaken it will incur cost and at the same time it will enhance the quality of the product. If the quality of the product is measured by its failure rate, a quality improvement programme will result in a decrease in the failure rate. A decrease in failure rate implies that the event of failure of a product once it is sold becomes less probable. As an outcome, the manufacturer is now able to offer a higher warranty period to the customer with the same expected expenditure to fulfil the warranty obligations. Therefore, as a result of a quality development programme, there is a requirement for change in the warranty policies. Since, the current study assumes a warranty dependent demand, a shift in warranty policies is expected to bring a change in the demand. As a consequence, the supply chain needs to re-decide its production level to achieve coordination. Therefore, it is quite obvious that the quality development program of a product will create the necessity for re-coordination of the supply chain. After the completion of the quality improvement initiative, the coordinator of the supply chain should re-coordinate the supply chain's decision so that the quality level of the product, warranty strategies and the production level remain aligned to each other.

Enhancement of the quality of a product can be achieved in different ways. It can be achieved by undertaking a superior manufacturing process or a superior quality control process or in different other ways. Since, all of these involve cost, a thorough analysis of the impact of the quality improvement is to be done to decide the amount of investment to be undertaken.

Very few studies on channel contract considering both warranty and quality related issues are reported and the literature lacks attention in considering the return contracts along with quality and warranty factors. Especially return contracts are more closely associated with the quality and reliability of the product as well as warranty related issues such as warranty cost, warranty design and management etc. Therefore, the said issue needs to be addressed keeping in view the applicability of return contracts across various industries related to personal computer and its components, consumer electronics, apparel industry etc. It is also necessary to provide a guideline for enabling the channel managers to critically work out the benefit derived by the supply chain and its members through a quality improvement programme. This particular aspect is necessary and relevant in the context of oligopolistic competition with respect to various dimensions such as price, quality etc. The current study is restricted to the analysis of product quality, channel contract related to a single supply chain, but this analysis can be used further in future studies to understand the dynamics of competition in an oligopolistic market on various dimensions like price, quality and warranty. The competition issues may be analysed by assuming price and quality as two differentiable factors where warranty and after sales services are predictors of quality whereas price is not. It may also be analysed by assuming both price and warranty as signalling elements of quality. The assumptions need to be suitably justified keeping in view the nature and amount of information symmetry, information asymmetry existing among the consumers.

In this study related to quality issues, numerical analysis is performed to analyse the impact of quality development on supply chain performance by determining optimal order quantity, optimal warranty length and supply chain profit for various levels of improvement of the product. The study also examines with numerical examples how to recoordinate the supply chain after quality development of the product by re-designing the contract parameters both in case of buyback contract and quantity flexibility contract. The study then performs sensitivity analysis to determine how the optimal order quantity and optimal supply chain profit change with change in investment on quality of the product.

2 Literature review

Role of warranty as a signalling element and use of warranty as a tool for defensive and offensive marketing strategy was discussed by Menezes and Quelch (1990), Chu and Chintagunta (2009), Bouguerra et al. (2012). The rationale behind undertaking a quality improvement initiative is mainly to reduce warranty cost by improving reliability of the product. The reliability of the product can be improved either by ensuring suitable measures at the design stage or by implementing superior manufacturing process and quality control. Hussain (1997), Blischke and Murthy (2000), Bai and Pham (2006), Kumar et al. (2011) discussed on improving reliability during design by redundancy technique. Another proven method of achieving superior reliability is through research and development which was taken up by Fries and Sen (1996), Hussain and Murthy (1999), Murthy (2006), Wang et al. (2010). Weeding out non-conforming items through inspection was analysed by Balcer and Sahin (1986), Chen (1991), Murthy et al. (1993), Kwon (1996), Jun (2006). The method of Burn-in was explored by Mi (1997, 1999), Perlstein et al. (2001), Ulusoy et al. (2011), Ye et al. (2013) where as Environmental stress screening as a technique of reliability improvement was the focus of Coleman (1990), Kar and Nachlas (1997), Yan and English (1997), Pohl and Dietrich (1995, 1999), and Wu and Su (2002). Through Implementation of process improvement and thereby preventing occurrence of non-conforming items as a method of improving reliability of the product was discussed by Djamaludin et al. (1994, 1995), Chen et al. (1998), Yeh and Lo (1998), Yeh et al. (2000), Dai et al. (2012), Guajardo and Cohen (2012). The issue of optimal warranty management was discussed by Mitra and Patankar (1993, 2012), Lin et al. (2000), and Murthy and Kumar (2000). Hu (2008) discussed quality improvement and supply chain performance in the context of a revenue sharing contract. The current research work on supply chain risk models Nguyen (2022) described a frame work to develop and mitigate channel risk from the perspective of cost, performance and resources and Pató (2022) described a COVID-19 resilient supply chain risk framework to compute and analyse channel risk and adapt the model to reduce the amount of risk.

Various supply chain optimisation models have been discussed in literature viz: supply chain optimisation under freight discount for steel products (Tharani and Uthayakumar, 2021), an order quantity supply chain optimisation model under continuous review policy (Dewi et al., 2022), a revenue sharing price optimisation model under warranty and green sensitive demand (Samanta et al., 2022) recently. The literature dealing with channel contracts with warranty and risk analysis on various supply chain decisions on quality improvement for products offering warranty lacks attention.

3 Model

The current study assumes a two stage supply chain consisting of one manufacturer and one retailer. The manufacturer acts as a global coordinator and decides on the contract parameters (buyback rate b or amount of flexibility α, wholesale price w and warranty length k). The retailer decides on the order quantity q. The manufacturer offers a free replacement warranty to the customer if product fails before the stipulated warranty period. Demand can be expressed as $x(k, d) = y(k) + d$ where $y(k)$ is an increasing function and concave in warranty length k. $y(k) = \gamma - \delta k^{-\phi}$, where γ, δ and φ are positive constants. d follows a statistical distribution. It is also assumed that Y, the time for the first failure of the product follows an exponential (β) distribution. The following values of the exogenous variables are assumed to perform the numerical analysis. $\gamma = 300$, $\delta = 260$, $\varphi = 1.3$, $p = 100$, $c_m = 40$, $c_r = 10$, $g_m = 4$, $g_r = 7$, $v = 20$, $r = 50$. Where p denote the retail price, c_m and c_r denote the manufacturer's production cost and retailer's procuring cost per unit respectively. g_m and g_r denote manufacturer's cost of lost sales and retailer's cost of lost sales respectively. v denotes the salvage value of the product and r denotes the cost of warranty per unit. Demand for different product show different patterns and may be approximated assuming different distributions. The current study performs numerical analysis assuming uniform or a normal demand distribution. The expected profit functions of the retailer and the manufacturer in case of buy back contract are given by the following two equations (Nandi, 2014),

$$\pi_r(q,k) = (p - b + g_r)S(q,k) + (b - w - c_r)q - g_r\mu(k) \tag{1}$$

$$\pi_m(q,k) = [g_m + b - v - r\Pr(Y \le k)]S(q,k) + (w + v - b - c_m)q - g_m\mu(k) \tag{2}$$

Similarly, the expected profit functions of the retailer and the manufacturer in case of quantity flexibility contract are given by the following two equations (Nandi, 2014),

$$\begin{aligned}\pi_r(q,k) = {} & (p - w + g_r)S(q,k) - \{w(1-\alpha) - v(1-\alpha) + c_r\}q - g_r\mu(k) \\ & + (w - v)S\{q(1-\alpha), k\}\end{aligned} \tag{3}$$

$$\begin{aligned}\pi_m(q,k) = {} & [w - v + g_m - r\Pr(Y \le k)]S(q,k) - (w - v)S\{q(1-\alpha), k\} \\ & + [v + (w - v)(1-\alpha) - c_m]q - g_m\mu(k)\end{aligned} \tag{4}$$

where $S(q, k)$ denotes expected sales and $\mu(k)$ denotes the expected total demand.

3.1 Numerical analysis assuming uniform demand distribution

In case of uniform distribution, it is assumed that $d \sim U(500, 800)$ i.e., d follows a uniform distribution with lower limit 500 and upper limit 800.

Table 1 Impact of quality development on supply chain profit, optimal order quantity and optimal warranty length

Failure rate (β)	*Optimal order quantity*	*Optimal warranty length*	*Supply chain's profit*	*Increase in supply chain's profit (%)*
0.020	954	4	38,918	10.22
0.022	953	4	38,591	9.30
0.024	935	3	38,342	8.59
0.026	935	3	38,100	7.91
0.028	934	3	37,860	7.23
0.030	934	3	37,620	6.55
0.032	934	3	37,383	5.88
0.034	933	3	37,146	5.21
0.036	933	3	36,912	4.54
0.038	933	3	36,678	3.88
0.040	932	3	36,446	3.22
0.042	932	3	36,216	2.57
0.044	932	3	35,987	1.92
0.046	931	3	35,759	1.28
0.048	931	3	35,533	0.64
0.050	931	3	35,308	0.00

Table 1 shows the impact of quality development of the product on optimal order quantity, optimal warranty length and supply chain profit. It also shows how improvement of quality of a product impacts the supply chain performance by enhancing its profit. For example, it is observed from this table that when the failure rate of the product is decreased from 0.05 to 0.04 due to a quality development initiative, the renewed optimal order quantity becomes 932 units. The optimal warranty length remains unchanged at 3. The corresponding supply chain profit is increased by 3.22% to become 36,446. Again, when the failure rate is further improved to 0.022, the optimal order quantity, optimal warranty length and corresponding supply chain profit become 953 units, 4 and 38,591 respectively. In this case there is an increase of 9.30% for the supply chain profit and there is also an increase in the optimal warranty length. When there is an improvement in the quality of the product, the failure rate gets changed and it disturbs the coordination of the supply chain. Therefore, there is a change in the optimal order quantity and optimal warranty length to achieve the channel coordination again. Therefore, there is an increase in the supply chain profit.

3.2 Recoordination of supply chain for buyback contract by redesigning contract parameters

Table 2 represents how the supply chain is re-coordinated by redesigning its contract parameters after the quality development of the product. For different levels of improvement of the product, the table also shows the increase in profit for the retailer as well as for the manufacturer. For example, when the failure rate of the product is 0.05, in order to coordinate the channel (i.e., maximise the supply chain profit), the wholesale price should be 69.35 corresponding to the buyback rate 64. In this case the retailer has a profit of 16,850 and the manufacturer has a profit of 18,458. When the failure rate of the product becomes 0.04 as a result of the quality development of the product, the wholesale price has to be reset to 69.11 corresponding to the same buyback rate 64. Therefore, with decrease in the failure rate a decrease in the wholesale price is observed when the buyback rate remains unchanged. The retailer's profit is increased to 17,073 and the manufacturer's profit is increased to 19,373. Therefore, the retailer's profit is increased by 1.32% and the manufacturer's profit is increased by 4.96%. When the failure rate is further decreased to 0.022, the wholesale price is reset to 68.86 in order to achieve channel coordination. The retailer's profit is further increased to 17,718 (increase of 5.15%) and the manufacturer's profit is increased to 20,873 (increase of 13.08%). It is interesting to note that within the same optimal warranty length there is a continuous increase in the profit of both the parties in the supply chain with decrease in the failure rate of the product. Another observation which can be made from the same table that with decrease in the failure rate the increase in profit takes place at a faster rate in case of the manufacturer compared to that of the retailer. It may also be noted that in case the wholesale price is kept unchanged, the coordinator of the supply chain has to re-adjust the buyback rate, after the quality development initiative, in order to achieve channel coordination.

Table 2 Recoordination of the supply chain after quality development and its impact on profit share of each member in case of buyback contract when buyback rate is 64

Failure rate (β)	*Wholesale price*	*Retailer's profit*	*Increase in retailer's profit (%)*	*Manufacturer's profit*	*Increase in manufacturer's profit (%)*	*Supply chain's profit*
0.020	68.80	17,775	5.49	21,143	14.55	38,918
0.022	68.86	17,718	5.15	20,873	13.08	38,591
0.024	68.74	17,419	3.38	20,923	13.35	38,342
0.026	68.79	17,372	3.10	20,728	12.30	38,100
0.028	68.83	17,335	2.88	20,525	11.20	37,860
0.030	68.88	17,288	2.60	20,332	10.15	37,620
0.032	68.93	17,241	2.32	20,142	9.12	37,383
0.034	68.97	17,204	2.10	19,942	8.04	37,146
0.036	69.02	17,157	1.82	19,755	7.03	36,912
0.038	69.07	17,111	1.55	19,567	6.01	36,678
0.040	69.11	17,073	1.32	19,373	4.96	36,446
0.042	69.16	17,027	1.05	19,189	3.96	36,216
0.044	69.21	16,980	0.77	19,007	2.97	35,987
0.046	69.26	16,934	0.50	18,825	1.99	35,759
0.048	69.30	16,896	0.27	18,637	0.97	35,533
0.050	69.35	16,850	0.00	18,458	0.00	35,308

3.3 Recoordination of supply chain for quantity flexibility contract by redesigning contract parameters

Table 3 shows that in case of a quantity flexibility contract, how a quality development initiative results in redesigning of the contract parameters. It also shows the amount of increase in profit both for the manufacturer and the retailer at different levels of improvement in quality of the product. For example, when the failure rate of the product is 0.05, the wholesale price of the product is 69.27, assuming that $\alpha = 0.18$. The profits of the retailer and the manufacturer are 17,198 and 18,110 respectively. As a result of quality development, when the failure rate is decreased to 0.03, the wholesale price is decreased and readjusted at 67.51 while the value of α is kept unchanged at 0.18. There is an increase in profit both for the retailer (8.91%) and the manufacturer (4.31%). The increased profits for the retailer and the manufacturer are 18,730 and 18,890 respectively. When the failure rate of the product is further decreased to 0.024, wholesale price is decreased to 66.95. The retailer's and the manufacturer's profits are further increased to 19,218 and 19,124 respectively. In this case the increase in profits for the retailer and the manufacturer are 11.75% and 5.60% respectively. It is interesting to observe that in case of quantity flexibility contract, within the same warranty length the rate of increase in profit for the retailer with improvement in quality is much faster compared to that of the manufacturer.

Table 3 Recoordination of the supply chain after quality development and its impact on profit share of each member in case of quantity flexibility contract when $\alpha = 0.18$

Failure rate (β)	*Wholesale price*	*Retailer's profit*	*Increase in retailer's profit (%)*	*Manufacturer's profit*	*Increase in manufacturer's profit (%)*	*Supply chain's profit*
0.020	68.30	18,479	7.45	20,439	12.86	38,918
0.022	68.70	18,123	5.38	20,468	13.02	38,591
0.024	66.95	19,218	11.75	19,124	5.60	38,342
0.026	67.06	19,122	11.19	18,978	4.79	38,100
0.028	67.41	18,817	9.41	19,043	5.15	37,860
0.030	67.51	18,730	8.91	18,890	4.31	37,620
0.032	67.61	18,643	8.40	18,740	3.48	37,383
0.034	67.97	18,329	6.58	18,817	3.90	37,146
0.036	68.07	18,242	6.07	18,670	3.09	36,912
0.038	68.17	18,155	5.56	18,523	2.28	36,678
0.040	68.52	17,851	3.80	18,595	2.68	36,446
0.042	68.62	17,764	3.29	18,452	1.89	36,216
0.046	69.08	17,363	0.96	18,396	1.58	35,759
0.048	69.18	17,276	0.45	18,257	0.81	35,533
0.050	69.27	17,198	0.00	18,110	0.00	35,308

3.4 Cost associated with quality improvement of a product

The initiative taken by a supply chain or any member of the supply chain to improve the quality of the product involves cost. Cost is incurred by undertaking a superior manufacturing process or a superior quality control process or in different other ways. Since, the quality of a product is measured by its failure rate or hazard rate, the expression for the cost incurred in quality development of a product involves the failure rates of the product both before and after the quality development of the product. If β_0 denotes the initial failure rate of the product and β denotes the failure rate of the product after the quality development, the cost incurred is of the form $C_0 + C_1\ln(\beta/\beta_0)$ (Sahin and Polatoglu, 1998) or $C\ln(\beta/\beta_0)$ (Porteus, 1986; Zhu et al., 2007), where C_0, C_1 and C are positive constants. In the current study, the first expression is used to calculate the cost assuming that there is a fixed portion involved in every quality improvement initiative irrespective of the level of improvement of quality of the product.

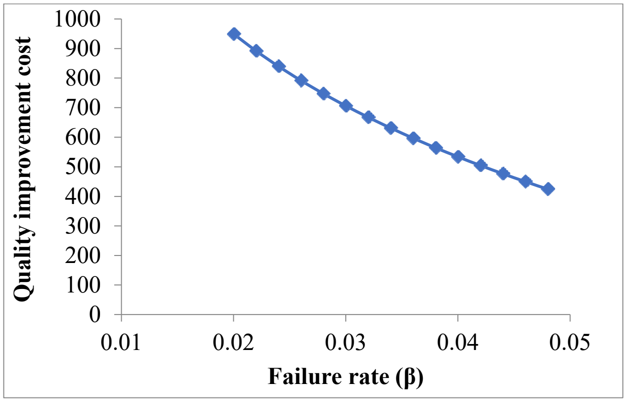
3.5 Sensitivity analysis

Assuming $C_0 = 400$ and $C_1 = 600$, sensitivity analysis is performed to investigate the change in investment with different failure rates, change in supply chain profit with different investments on quality and change in optimal warranty length with different investments on quality. If the manufacturer incurs cost in the quality development of the product, he can decide the desired level of improvement of quality of the product by taking into consideration the cost incurred by him in the process and the amount of increase in his profit (can be obtained from the tables for the appropriate type of contract).

Table 4 Different failure rates and corresponding investments for quality improvement

Failure rate (β)	*Investment*
0.020	949.77
0.022	892.59
0.024	840.38
0.026	792.36
0.028	747.89
0.030	706.50
0.032	667.77
0.034	631.40
0.036	597.10
0.038	564.66
0.040	533.89
0.042	504.61
0.044	476.70
0.046	450.03
0.048	424.49

Figure 1 Quality improvement cost versus failure rate (see online version for colours)



Given are the descriptions for different numerical analyses performed assuming a uniform distribution of *d*. Table 4 and Figure 1 represent change in investment with different failure rates. Different investments on quality and corresponding supply chain profits are given in Table 5 and Figure 2. Table 6 and Figure 3 show how optimal warranty length is changed with different investment on quality.

Table 5 Different investments on quality and corresponding supply chain profits

Investment	*Supply chain's profit*
949.77	38,918
892.59	38,591
840.38	38,342
792.36	38,100
747.89	37,860
706.50	37,620
667.77	37,383
631.40	37,146
597.10	36,912
564.66	36,678
533.89	36,446
504.61	36,216
476.70	35,987
450.03	35,759
424.49	35,533

Figure 2 Supply chain profits versus investments on quality (see online version for colours)

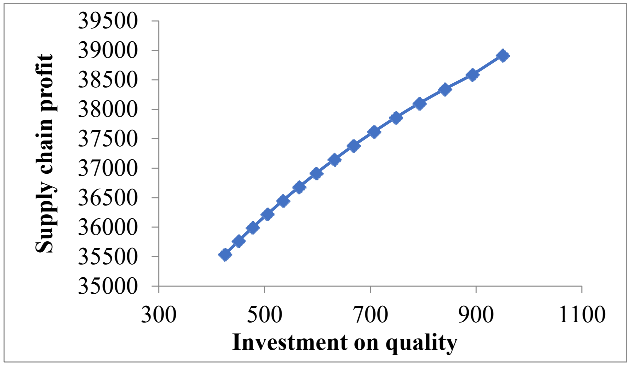


Figure 3 Optimal warranty length versus investments on quality (see online version for colours)

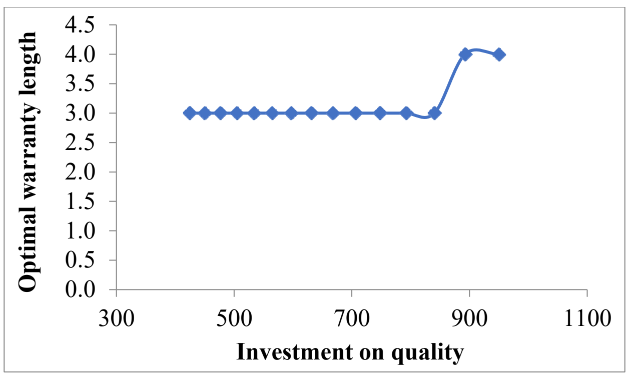


Table 6 Different investments on quality and corresponding optimal warranty lengths

Investment	*Optimal warranty length*
949.77	4
892.59	4
840.38	3
792.36	3
747.89	3
706.50	3
667.77	3
631.40	3
597.10	3
564.66	3
533.89	3
504.61	3
476.70	3
450.03	3
424.49	3

3.6 Numerical analysis assuming normal demand distribution

Numerical analysis is carried out with respect to the normal distribution under the assumption that $d \sim N(\mu, \sigma^2)$, where $\mu = 650$ and $\sigma = 100$ i.e., $\in$ follows a normal distribution with mean 650 and standard distribution 100.

Table 7 Impact of quality development on supply chain profit, optimal order quantity and optimal warranty length

Failure rate (β)	*Optimal order quantity*	*Optimal warranty length*	*Supply chain's profit*	*Increase in supply chain's profit (%)*
0.020	947	4	38,660	10.25
0.022	947	4	38,335	9.32
0.024	928	3	38,083	8.60
0.026	928	3	37,843	7.92
0.028	928	3	37,603	7.23
0.030	927	3	37,366	6.56
0.032	927	3	37,129	5.88
0.034	927	3	36,894	5.21
0.036	926	3	36,661	4.55
0.038	926	3	36,429	3.89
0.040	926	3	36,198	3.23
0.042	925	3	35,969	2.58
0.044	925	3	35,741	1.92
0.046	925	3	35,515	1.28
0.048	925	3	35,290	0.64
0.050	924	3	35,066	0.00

Table 7 represents the impact of improvement of quality of the product upon the optimal order quantity, optimal warranty length and supply chain profit. In case of normal distribution also, it is observed that with improvement of the quality of the product i.e., with decrease in the failure rate there is an increase in the supply chain profit. In case of optimal order quantity and optimal warranty length, they either remain unaltered or increase with decrease in the failure rate of the product. For example, when the failure rate of the decreases from 0.05 to 0.04 due to quality development of the product, the optimal order quantity increases from 924 units to 926 units. The optimal warranty length is 3 in both the cases. The supply chain profit increases from 35,066 to 36,198. Therefore, as a result of this quality development initiative the supply chain profit is enhanced by 3.23%. When the failure rate is further decreased to 0.022, the optimal order quantity becomes 947 units, the optimal warranty length is increased to 4 and there is an increase of the supply chain profit of 9.32%. The enhanced supply chain profit is 38,335. It is also observed from Table 7 that with decrease in the failure rate of the product, there is a continuous increase in the supply chain profit.

3.7 Recoordination of supply chain for buyback contract by redesigning contract parameters

Table 8 shows how to redesign the contract parameters i.e., how to re-coordinate the supply chain after a quality improvement initiative is undertaken in case of a buyback contract. It also shows the amount of increase in the overall supply chain profit as well as the amount of increase in the profit of both the parties in the supply chain as a result of the improvement of the quality of the product. In case of normal distribution also, it is observed that with decrease in the failure rate of the product there is a decrease in wholesale price in order to achieve channel coordination. For example, when the failure rate of the product decreases from 0.05 to 0.03, the retailer's profit is increased from 16,726 to 17,161. The manufacturer's profit increases from 18,340 to 20,205. Therefore, due to quality improvement, the profits of the retailer and the manufacturer are enhanced by 2.60% and 10.17% respectively. When the failure rate of the product is further decreased to 0.02, the profits of the retailer and the manufacturer are increased to 17,648 and 21,012 respectively. The increase in profits for the retailer and the manufacturer are 5.51% and 14.57% respectively. In this case also (as observed in buyback contract for uniform demand distribution), there is a continuous increase in profits for both the parties in the supply chain within the same warranty length with decrease in the failure rate of the product.

Table 8 Recoordination of the supply chain after quality development and its impact on profit share of each member in case of buyback contract when buyback rate is 64

Failure rate (β)	*Wholesale price*	*Retailer's profit*	*Increase in retailer's profit (%)*	*Manufacturer's profit*	*Increase in manufacturer's profit (%)*	*Supply chain's profit*
0.020	68.80	17,648	5.51	21,012	14.57	38,660
0.022	68.86	17,591	5.17	20,744	13.11	38,335
0.024	68.74	17,291	3.38	20,792	13.37	38,083
0.026	68.79	17,245	3.10	20,598	12.31	37,843
0.028	68.83	17,208	2.88	20,395	11.21	37,603
0.030	68.88	17,161	2.60	20,205	10.17	37,366
0.032	68.93	17,115	2.33	20,014	9.13	37,129
0.034	68.97	17,078	2.10	19,816	8.05	36,894
0.036	69.02	17,032	1.83	19,629	7.03	36,661
0.038	69.07	16,985	1.55	19,444	6.02	36,429
0.040	69.11	16,948	1.33	19,250	4.96	36,198
0.042	69.16	16,902	1.05	19,067	3.96	35,969
0.044	69.21	16,856	0.78	18,885	2.97	35,741
0.046	69.26	16,810	0.50	18,705	1.99	35,515
0.048	69.30	16,773	0.28	18,517	0.97	35,290
0.050	69.35	16,726	0.00	18,340	0.00	35,066

3.8 Recoordination of supply chain for quantity flexibility contract by redesigning contract parameters

Redesigning of the contract parameters due to a quality development initiative in case of quantity flexibility contract is represented in Table 9. This analysis is carried out when the stochastic part of the demand (d) follows a normal distribution. The same table also shows the amount of increase in profit both for the manufacturer and the retailer at different levels of improvement in quality of the product. For example, when the failure rate of the product is 0.05, the wholesale price of the product is 71.11, assuming that α =0.20. The profits of the retailer and the manufacturer are 15,376 and 19,690 respectively. As a result of quality development, when the failure rate is decreased to 0.03, the wholesale price is decreased and readjusted at 69.80 while the value of α is kept unchanged at 0.20. There is an increase in profit both for the retailer (7.39%) and the manufacturer (5.91%). The increased profits for the retailer and the manufacturer are 16,512 and 20,854 respectively. When the failure rate of the product is further decreased to 0.024, wholesale price is decreased to 69.39. The retailer's and the manufacturer's profits are further increased to 16,868 and 21,215 respectively. In this case the increase in profits for the retailer and the manufacturer are 9.70% and 7.75% respectively.

Table 9 Recoordination of the supply chain after quality development and its impact on profit share of each member in case of quantity flexibility contract when α=0.20

Failure rate (β)	*Wholesale price*	*Retailer's profit*	*Increase in retailer's profit (%)*	*Manufacturer's profit*	*Increase in manufacturer's profit (%)*	*Supply chain's profit*
0.020	70.10	16,653	8.31	22,007	11.77	38,660
0.022	70.23	16,537	7.55	21,798	10.71	38,335
0.024	69.39	16,868	9.70	21,215	7.75	38,083
0.026	69.49	16,781	9.14	21,062	6.97	37,843
0.028	69.59	16,694	8.57	20,909	6.19	37,603
0.030	69.80	16,512	7.39	20,854	5.91	37,366
0.032	69.91	16,417	6.77	20,712	5.19	37,129
0.034	70.01	16,330	6.20	20,564	4.44	36,894
0.036	70.21	16,157	5.08	20,504	4.13	36,661
0.038	70.31	16,070	4.51	20,359	3.40	36,429
0.040	70.41	15,983	3.95	20,215	2.67	36,198
0.042	70.61	15,810	2.82	20,159	2.38	35,969
0.044	70.71	15,723	2.26	20,018	1.67	35,741
0.046	70.81	15,636	1.69	19,879	0.96	35,515
0.048	70.91	15,550	1.13	19,740	0.25	35,290
0.050	71.11	15,376	0.00	19,690	0.00	35,066

3.9 Sensitivity analysis

Given below are the descriptions for different numerical analyses performed assuming a normal distribution of d. Different investments on quality and corresponding supply chain profits are given in Table 10 and Figure 4. Table 11 and Figure 5 show how optimal warranty length is changed with different investments on quality.

Table 10 Different investments on quality and corresponding supply chain profit

Investment	*Supply chain's profit*
949.77	38,660
892.59	38,335
840.38	38,083
792.36	37,843
747.89	37,603
706.50	37,366
667.77	37,129
631.40	36,894
597.10	36,661
564.66	36,429
533.89	36,198
504.61	35,969
476.70	35,741
450.03	35,515
424.49	35,290

Table 11 Different investments on quality and corresponding optimal warranty lengths

Investment	*Optimal warranty length*
949.77	4
892.59	4
840.38	3
792.36	3
747.89	3
706.50	3
667.77	3
631.40	3
597.10	3
564.66	3
533.89	3
504.61	3
476.70	3
450.03	3
424.49	3

Figure 4 Supply chain profits versus investments on quality (see online version for colours)

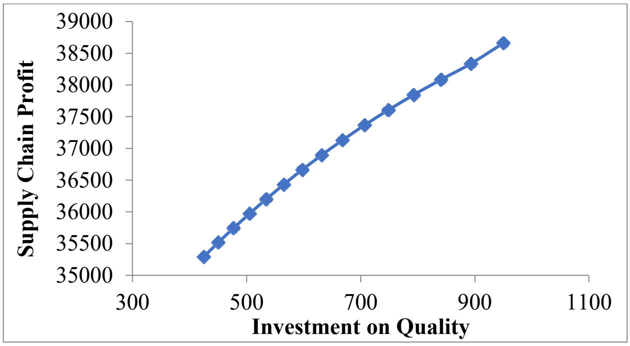
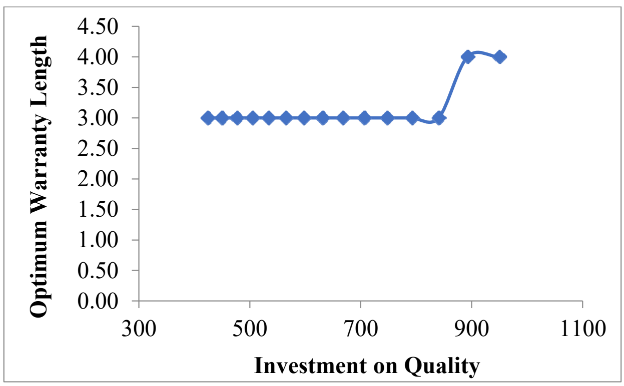


Figure 5 Optimal warranty length versus investments on quality (see online version for colours)



4 Expressions of risk

The risk expressions are measured both for the buyback contract with free replacement warranty and quantity flexibility contract with free replacement warranty. The risk is measured by calculating the variance in profit without taking into account the cost of lost sales. This is because cost of lost sales does not affect the real or absolute profit earned. Table 12 shows the expressions for risk.

It is evident from the given risk expression in Table 12 for the total supply chain that the global coordinator of the supply chain can manipulate or adjust the risk faced by the supply chain by changing the order quantity or the warranty period offered. Therefore, it is important to analyse how the risk faced by the supply chain is affected by the change of the aforesaid decision variables when the values of other parameters are kept unchanged.

First, the impact of change in order quantity and the impact of change in the warranty length upon risks borne by the retailer, manufacturer and the total supply chain are examined. For numerical analysis regarding risk it is assumed that $d \sim U(500, 800)$ i.e., d follows a uniform distribution with lower limit 500 and upper limit 800.

Table 12 Expressions of risk borne by the manufacturer, retailer and total supply chain for buyback contract and quantity flexibility contract with FRW policy

Type of contract	*Risk borne by manufacturer*	*Risk borne by retailer*	*Risk borne by total supply chain*
Buyback contract with FRW policy	$(b - v - r\Pr(Y \le k))^2\xi(q)$	$(p - b)^2\xi(q)$	$(p - v - r\Pr(Y \le k))^2\xi(q)$
Quantity flexibility contract with FRW policy	$(w - v - r\Pr(Y \le k))^2\xi(q) + (w - v)^2\xi\{q(1 - \alpha)\} - 3(w - v - r\Pr(Y \le k))\xi(w - v)\ \mathrm{Cov}((q - x)^+, (q(1 - \alpha) - x)^+)$	$(p - w)^2\xi(q) + (w + v)^2\xi\{q(1 - \alpha)\} + 2(p - w)(w - v)\ \mathrm{Cov}((q - x)^+, (q(1 - \alpha) - x)^+)$	$(p - v - r\Pr(Y \le k))^2\xi(q)$

Note: where $\xi(q) = Var(q - x)^+ = 2q\int_0^q F(x|k)dx - 2\int_0^q xF(x|k)dx - \left(\int_0^q F(x|k)dx\right)^2$ as given by Choi et al. (2008).

4.1 Impact of change in order quantity on risk

Table 13 and Figure 6 represent the impact of change in order quantity on the risks borne by the retailer, manufacturer and the total supply chain when the warranty length is optimal i.e., 3 and the buyback rate is 61. From Table 13 it is evident that with increase in the order quantity there is an increase in the risks borne by the retailer, manufacturer and the total supply chain.

Figure 6 Change in retailer's, manufacturer's and supply chain's risk with change in order quantity (see online version for colours)

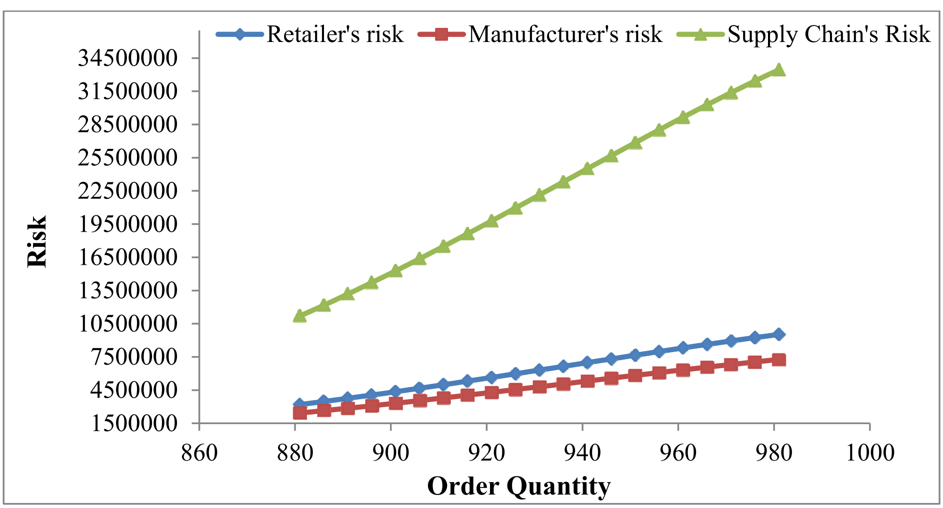


Table 13 Impact of change in order quantity on risks borne by manufacturer, retailer and total supply chain when warranty length is 3 and buyback rate is 61

Order quantity	*Retailer's risk*	*Manufacturer's risk*	*Supply chain's risk*
881	0.3193×10^7	0.2432×10^7	1.1199×10^7
886	0.3470×10^7	0.2643×10^7	1.2170×10^7
891	0.3757×10^7	0.2861×10^7	1.3176×10^7
896	0.4053×10^7	0.3087×10^7	1.4213×10^7
901	0.4357×10^7	0.3318×10^7	1.5280×10^7
906	0.4669×10^7	0.3556×10^7	1.6373×10^7
911	0.4987×10^7	0.3798×10^7	1.7490×10^7
916	0.5312×10^7	0.4045×10^7	1.8628×10^7
921	0.5641×10^7	0.4296×10^7	1.9782×10^7
926	0.5974×10^7	0.4550×10^7	2.0951×10^7
931	0.6310×10^7	0.4806×10^7	2.2128×10^7
936	0.6647×10^7	0.5063×10^7	2.3312×10^7
941	0.6985×10^7	0.5320×10^7	2.4497×10^7
946	0.7322×10^7	0.5577×10^7	2.5679×10^7
951	0.7657×10^7	0.5832×10^7	2.6854×10^7
956	0.7988×10^7	0.6084×10^7	2.8015×10^7
961	0.8315×10^7	0.6333×10^7	2.9159×10^7
966	0.8634×10^7	0.6576×10^7	3.0280×10^7
971	0.8946×10^7	0.6813×10^7	3.1372×10^7
976	0.9247×10^7	0.7043×10^7	3.2429×10^7
981	0.9537×10^7	0.7263×10^7	3.3446×10^7

From Table 13 it is observed that when the order quantity is 881 units, warranty length is optimal i.e., 3 and buyback rate is 61, the risks borne by the retailer, manufacturer and the total supply chain are 0.3193×10^7, 0.2432×10^7 and 1.1199×10^7 respectively. When the order quantity increases to 981 units with the same warranty length and buyback rate as before, the risks borne by the retailer, manufacturer and the total supply chain become 0.9537×10^7, 0.7263×10^7 and 3.3446×10^7 respectively. The risk is calculated in case of the buyback contract where manufacturer solely bears the warranty cost. Therefore, in this case, when the warranty period is kept optimal and buyback rate is 61, the retailer always bears more risk compared to manufacturer for all order quantities. This is because with these set of parameters the profit share of the retailer is more compared to that of the manufacturer for all the order quantities. Hence, the risk borne is also higher in case of the retailer. Figure 6 shows that with increase in order quantity with the same warranty period (in this example the warranty period is set as 3 which is optimal) the risks borne by the retailer, manufacturer and the total supply chain increase linearly. It can be also be noted from the same figure that with increase in order quantity the rate of increase in the risk borne by the total supply chain is higher compared to the rate of increase of the risk borne by the individual parties in the supply chain.

4.2 *Impact of change in warranty length on risk*

Table 14 and Figure 7 represent the effect of change in warranty length on the risks borne by the retailer, the manufacturer and the total supply chain when the order quantity is kept optimal (911 units in this case) and the buyback rate is 61. In this analysis it is assumed that warranty lengths can assume fractional values also (values starting from 1 to 5 with a step size of 0.2). With this set of possible values for the warranty length, it can be observed from Table 15 that the optimal order quantity is 911. Table 14 shows that with increase in the warranty length, initially the risks borne by the retailer, manufacturer and the total supply chain increase and then the risks borne by the same parties gradually decrease. For example, when the warranty length increases from 1 to 1.2 the risks borne by the retailer, manufacturer and the total supply chain increase from 0.6257×10^7 to 1.1195×10^7, 0.6117×10^7 to 1.0678×10^7 and 2.4746×10^7 to 4.3739×10^7 respectively. Again, when the warranty length increases from 1.2 to 5 the risks borne by the retailer, manufacturer and total supply chain decrease to 0.3180×10^7, 0.1874×10^7 and 0.9936×10^7 respectively. Figure 7 shows the nature of risk versus warranty length curves for the retailer, manufacturer and the total supply chain.

Table 14 Impact of change in warranty length on risks borne by manufacturer, retailer and total supply chain when order quantity is 911 units and buyback rate is 61

Warranty length	*Retailer's risk*	*Manufacturer's risk*	*Supply chain's risk*
1.0	0.6257×10^7	0.6117×10^7	2.4746×10^7
1.2	1.1195×10^7	1.0678×10^7	4.3739×10^7
1.4	1.1099×10^7	1.0328×10^7	4.2840×10^7
1.6	1.0013×10^7	0.9089×10^7	3.8182×10^7
1.8	0.8869×10^7	0.7852×10^7	3.3412×10^7
2.0	0.7874×10^7	0.6799×10^7	2.9307×10^7
2.2	0.7050×10^7	0.5938×10^7	2.5927×10^7
2.4	0.6376×10^7	0.5237×10^7	2.3169×10^7
2.6	0.5823×10^7	0.4665×10^7	2.0911×10^7
2.8	0.5367×10^7	0.4192×10^7	1.9046×10^7
3.0	0.4987×10^7	0.3798×10^7	1.7490×10^7
3.2	0.4668×10^7	0.3466×10^7	1.6178×10^7
3.4	0.4397×10^7	0.3183×10^7	1.5061×10^7
3.6	0.4164×10^7	0.2939×10^7	1.4100×10^7
3.8	0.3964×10^7	0.2727×10^7	1.3266×10^7
4.0	0.3789×10^7	0.2541×10^7	1.2536×10^7
4.2	0.3636×10^7	0.2377×10^7	1.1893×10^7
4.4	0.3502×10^7	0.2230×10^7	1.1321×10^7
4.6	0.3382×10^7	0.2099×10^7	1.0810×10^7
4.8	0.3275×10^7	0.1981×10^7	1.0351×10^7
5.0	0.3180×10^7	0.1874×10^7	0.9936×10^7

Figure 7 Change in retailer's, manufacturer's and supply chain's risk with change in warranty length (see online version for colours)

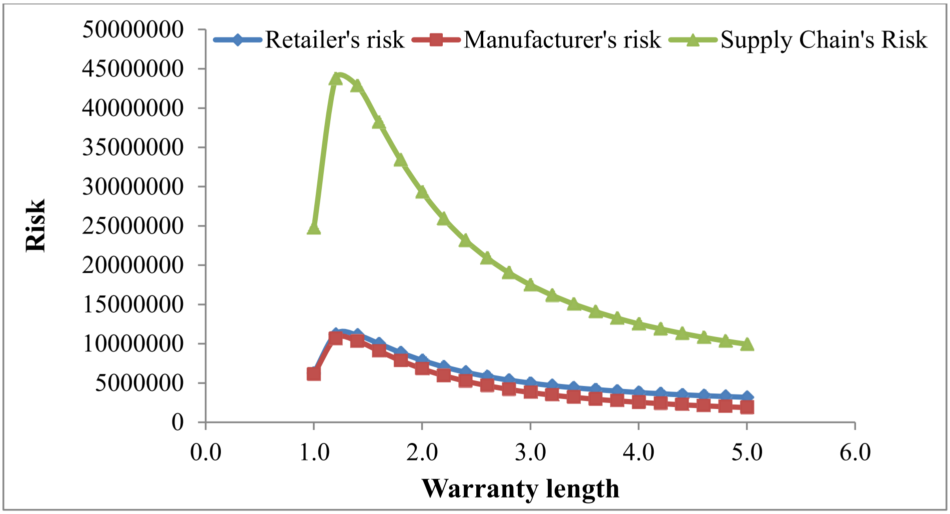


Table 15 Values of different warranty length (values from 1 to 5 with a step size of 0.2) corresponding optimal order quantity, supply chain profit and supply chain risk

Warranty length	*Optimal order quantity*	*Supply chain profit*	*Supply chain risk*
1.0	738	29,842	2.6202×10^7
1.2	793	32,107	2.5919×10^7
1.4	829	33,503	2.5278×10^7
1.6	856	34,383	2.5037×10^7
1.8	875	34,935	2.4472×10^7
2.0	890	35,268	2.4053×10^7
2.2	902	35,447	2.3690×10^7
2.4	911	35,516	2.3169×10^7
2.6	919	35,503	2.2839×10^7
2.8	925	35,429	2.2355×10^7
3.0	931	35,308	2.2128×10^7
3.2	935	35,149	2.1633×10^7
3.4	939	34,962	2.1301×10^7
3.6	942	34,753	2.0874×10^7
3.8	945	34,525	2.0557×10^7
4.0	947	34,282	2.0108×10^7
4.2	949	34,027	1.9738×10^7
4.4	951	33,763	1.9435×10^7
4.6	953	33,492	1.9187×10^7
4.8	954	33,215	1.8774×10^7
5.0	955	32,932	1.8406×10^7

From Table 14 and Figure 7 with increase in the warranty length the following two things act simultaneously. Firstly, there is an increase in the warranty cost which acts towards decreasing the profit as well as risk. Secondly, increase in warranty length results in increase in the expected demand which acts towards increasing the profit as well as increasing the risk. When there is an increase of the warranty length from 1 to 1.2 the second factor dominates the first one as there is a relatively larger impact on expected demand. Again, when the warranty length starts increasing gradually from 1.2 and onwards, the first factor dominates the second one. This explains why the risk increases initially and then the risk starts decreasing with increase in the warranty length.

5 Conclusions and future scope

The study helps to understand the impact of the quality development on the overall profitability of the supply chain and the profit share of each member. The novelty of the current study lies in the fact that it guides the channel coordinator to determine the contract parameters and decision variables in the newly coordinated chain, after the quality development of the product when return contracts are practised. The present study assumes that the failure rate follows an exponential distribution. Future studies can be done assuming that the failure rate of the product follows other distributions such as Weibull, normal, lognormal distribution. The study can be more complex by measuring the reliability of the product considering multiple components. Future study may be done with respect to a relatively complex supply chain structure such as single manufacturer multiple retailer environment and vice versa.

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