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Reverse logistics decision making for modular products: the impact of supply chain strategies

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Abstract. The importance of product modularity in mitigating negative product-related environmental effects has been widely recognized in practice and in research. This study analyzes how a company's supply chain strategy is linked with a product's optimal level of modularity and how this affects efficient reverse logistics decision making. We address this problem by formulating two optimization problems; one for a company adopting a push and one for a company adopting a pull supply chain strategy.

Keywords: supply chain management; reverse logistics; strategic planning

Introduction

For many companies, modular product design has proven to be a successful design paradigm in developing new products. While the concept of modular product architecture is not new, research only hesitantly began to analyze the impacts of modularity on a product's life-cycle costs as well as its effects on efficient reverse logistics operations. Mazahir *et al*. (2011) highlight the importance of the supply chain strategy for product design and reverse logistics. As modular designs improve a product's 3R abilities (reduce, reuse, recycle), Huang *et al*. (2012) note that modularity can be seen as a strategy in mitigating a product's negative environmental impact and additionally it can reduce recycling or remanufacturing costs. The aim of our article is three-fold: we investigate the impact of supply chain strategy decisions on product modularity as well as the impact of product modularity on consumer behavior and reverse logistics decision making.

While the benefits and drawbacks of modular designs concerning producers are well discussed in the literature, the possible effects for consumers tend to be neglected. Modular products allow for the efficient design of products and allow specialized manufacturers to produce the modules more effectively. Modular products enable an increased feasibility for postponement that helps in reacting to changes in product requirements or demand (Swaminathan and Lee 2003). Furthermore, simple assembly operations facilitate the usage of low-skilled labor (see for instance Sako 2005). Service operations for modular products tend to be easier than for their integral counterparts, as modules may simply be replaced. These benefits of modular product designs are accompanied by certain drawbacks: The interfaces between modules represent a possible weakness of products that are designed highly modular, because of "potential interface losses and suboptimal use of space, mass and energy during operations" (Hölttä-Otto and de Weck, 2007). The suboptimal use of space typically makes the products bulkier. However, in situations where products are designed highly modular, the usage of standardized modules enable an increased inter-connectivity and hence an increased usability for consumers.

Focusing on reverse logistics implications, modularity can become environmentally beneficial by expanding the useful life of products, since only components become obsolete and are discarded, instead of the entire product. Research on the impact of modularity on repair operations and the disassembly of end-of-life products can be found for instance in Tseng *et al*. (2008) and Huang *et al*. (2012). However, potential positive effects of modular products on the environment may be damped by an accelerated obsolescence of modules (see Ülkü *et al*., 2012).

Hypothesis Development

Companies following a pull strategy initiate production in response to a customer order. Push strategies on the contrary, are characterized by companies' anticipatory behavior of future customer orders. In a push strategy, companies will make forecasts that can help them in making effective capacity planning decisions. Based on the characteristics of push and pull strategies, we can conclude that the pull strategy focuses more on responsiveness by taking advantages of effects of mass customization. Since product modularity is a crucial factor in increasing a company's abilities for mass customization, we formulate hypothesis 1 as follows:

Hypothesis 1: When a company adopts a pull strategy, the optimal level of modularity will be higher.

According to Nowak and Hofer (2014), product returns have a tendency to show chaotic behavior and are thus difficult to forecast. We expect that a company in a pull strategy can deal with this situation more effectively than a company in a push strategy that bases its capacity planning on long-time forecasts. This directly leads us to hypothesis 2 and 3:

Hypothesis 2: Optimal remanufacturing quantities are higher for a company adopting a pull strategy.

Hypothesis 3: Increasing the return rate is more beneficial for a company under a pull strategy.

As optimal remanufacturing quantities might increase when there is shift of customers' preferences towards remanufactured products, a company under a pull strategy may be able to deal with this situation more effectively, in order to be in line with hypothesis 2. Therefore, we expect that profits of a company under a pull strategy experience a higher increase than the profits of a company following a push strategy. This believe is expressed by our last hypothesis:

Hypothesis 4: A shift of customers' preferences towards remanufactured products is more beneficial for a company under a pull strategy.

Model formulation

In our models, we assume a two-period profit maximization problem, where sales from the first period generate product returns in the second period. This two-period set-up allows us to determine remanufacturing quantities in the second period endogenously within the model. Additionally, we assume that sales prices are solely dependent on the level of modularity. In our model for a company following a push strategy, we assume a newsvendor-like setup, where consumers take the price as given and then decide if they are willing to accept the price or not. Based on the producers' effects of modularity as described briefly in section 1, we model production costs of new products by a quadratic convex function. Unit remanufacturing costs are assumed to be linearly decreasing with the level of modularity. This assumption is also in line with the findings of Fernández and Kekäle (2005). Chen and Chie (2007) find a positive impact of product modularity on consumers' satisfaction. Due to their result, we assume the sales price to be a positive increasing function with the level of modularity. In our models, we operationalize the degree of modularity by an index on the unit interval. Such indices are calculated for various products for instance by Hölttä-Otto and de Weck (2007). The following table summarizes the decision variables, the parameters and the functions used in the following optimization problems:

Table 1. Parameters and functions used in the formulation of the optimization problems

Parameters	*Range*	*Base case*	*Description*
a	$a > 0$	5	fixed production costs for new products
b	$b > 0$	70	shape parameter in the cost function for new products
c	$0 \leq c \leq 1$	0.8	parameter that determines the minimum cost for producing a new product
d	$d > 0$	40	cost to remanufacture a completely integral product

Parameters	*Range*	*Base case*	*Description*
e	$e \geq 0$	35	slope in the remanufacturing cost function
f	$f \geq 0$	60	sales price for a completely integral new product
g	$g \geq 0$	5	slope in the price function for a new product
α	$\alpha \geq 1$	1.4	increase in unit production costs when following a pull strategy
β	$0 \leq \beta \leq 1$	0.9	discount factor for profits from period 2
γ	$0 \leq \gamma \leq 1$	simulation	product return rate
δ	$0 < \delta < 1$	simulation	consumption share parameter
θ	$0 \leq \theta \leq 1$	0.9	factor that lowers the sales price for a remanufactured product
ϵ	$0 \leq \epsilon \leq 1$	0.1	factor that determines the maximum feasible level of modularity $1-\epsilon$
M	$M > 0$	100	maximum demand
Decision variables		*Description*	
$q_{1,v}$		production quantity of new products in period 1 under strategy v, where $v = 1$ for a pull strategy and $v = 2$ for a push strategy	
$q_{2,v}$		production quantity of new products in period 2 under strategy v	
$q_{2,v}^r$		production quantity of remanufactured products in period 2 under strategy v	
m_v		level of modularity under strategy v, where $0 \leq m_v \leq 1-\epsilon$	
Function		*Description*	
$c^p(m_v) = a + b\left(\frac{m_v}{1-\epsilon} - c\right)^2$		unit production cost for a new product	
$c^r(m_v) = d - e\frac{m_v}{1-\epsilon}$		unit remanufacturing cost	
$p(m_v) = f + g\frac{m_v}{1-\epsilon}$		sales price for a new product	

Pull model

As common in the literature, we assume that production in the pull case is initiated in response to a customer order. Consequently, the company faces no demand uncertainty. However, unit production costs will be higher than in the push case by a factor $\alpha \geq 1$, since a small planning horizon will impede prescient capacity planning.

$$\max_{q_{1,1},\, q_{2,1},\, q^r_{2,1},\, m_1} \Pi_1 = q_{1,1}\big(p(m_1) - \alpha c^p(m_1)\big)$$
$$+ \beta\big[q_{2,1}\big(p(m_1) - \alpha c^p(m_1)\big) + q^r_{2,1}\big(\theta p(m_1) - c^r(m_1)\big)\big]$$
$$q_{1,1} \le M$$
$$q_{2,1} \le \delta M$$
$$q^r_{2,1} \le \min\big(\gamma q_{1,1}, (1-\delta)M\big)$$
$$m_1 \le 1 - \epsilon$$
$$q_{1,1}, q_{2,1}, q^r_{2,1} \ge 0$$

Since the objective function is concave and all constraints are convex, solving the system of Karush-Kuhn-Tucker (KKT) conditions is necessary and sufficient for a maximum. It is easy to verify, that the following set of values satisfies the system of KKTs:

$$q^*_{1,1} = M$$
$$\mathrm{q}^*_{2,1} = \delta\mathrm{M}$$
$$\mathrm{q}^{r*}_{2,1} = q^*_{1,1}\min\big(\gamma, (1-\delta)\big)$$
$$m^*_1 = \begin{cases} (1-\epsilon) & \text{for } c > 1 - \Omega_1 \\ (1-\epsilon)(c + \Omega_1) & \text{for } c \le 1 - \Omega_1 \end{cases}$$

where $\Omega_1 = \frac{q^*_{1,1} i + \beta(\mathrm{q}^*_{2,1} i + \mathrm{q}^{r*}_{2,1}(\theta i + e))}{2b\alpha(q^*_{1,1} + \beta \mathrm{q}^*_{2,1})}$

Push model

Our model describing the production and product design problem for a company under a push strategy reflects the fact that at the time when the production decision is made, no information on future demand is available. Note that such a two period formulation of a newsvendor problem in the context of closed-loop supply chains was previously used by Reimann and Lechner (2012). In the formulation of the optimization problem,

$$S_D\big(q_{2,2}\big) = E\left[\begin{cases} q_{2,2} & \text{for } q_{2,2} \le \delta u \\ \delta u & \text{for } q_{2,2} > \delta u \end{cases}\right]$$

and

$$S_D\big(q^r_{2,2}\big) = E\left[\begin{cases} q^r_{2,2} & \text{for } q^r_{2,2} \le (1-\delta)u \\ (1-\delta)u & \text{for } q^r_{2,2} > (1-\delta)u \end{cases}\right]$$

determine the expected sales for a given production level $q_{2,2}$ ($q^r_{2,2}$) depending on random demand u. The parameter δ reflects the fact that customers can distinguish between new and remanufactured products. When $\delta = 0$, customers' preferences are such that only remanufactured products are consumed and when $\delta = 1$, consumption is only for new products. Assuming a continuous uniform distribution on the interval $[0, M]$, we can find for instance a closed-form expression for expected sales of new products in period 2,

$S_D(q_{2,2}) = q_{2,2} - \frac{(q_{2,2})^2}{2\delta M}$.

$$\max_{q_{1,2},\, q_{2,2},\, q_{2,2}^{r},\, m_2} \Pi_2 = S_D\big(q_{1,2}\big)p(m_2) - q_{1,2}c^p(m_2) + \beta[S_D\big(q_{2,2}\big)p(m_2) - q_2c^p(m_2) + S_D\big(q_{2,2}^r\big)\theta p(m_2) - q_{2,2}^r c^r(m_2)]$$
$$q_{2,2}^r \le \gamma S_D(q_{1,2})$$
$$m_2 \le 1-\epsilon$$
$$q_{1,2}, q_{2,2}, q_{2,2}^r, m_2 \ge 0$$

With the derivatives of the expected sales, i.e. $S_D'\big(q_{2,2}\big) = F_D^{-1}\left(\frac{1}{\delta}q_{2,2}\right)$ and $S_D'\big(q_{2,2}^r\big) = F_D^{-1}\left(\frac{1}{1-\delta}q_{2,2}^r\right)$, where $F_D^{-1}(\xi) = \xi M$ for $\xi \in [0,1]$ denotes the inverse cumulative density function of the uniform continuous distribution on $[0, M]$, it is easy to verify that the following values for the decision variables satisfy the system KKT conditions,

$$q_{1,2}^* = M\begin{cases} 1-\dfrac{c^p(m_2^*)}{p(m_2)+\gamma\lambda}, & q_2^r = M\left(1-\dfrac{c^r(m_2^*)}{\theta p(m_2^*)}\right)(1-\delta) \\ 1-\dfrac{c^p(m_2^*)}{p(m_2^*)}, & else \end{cases}$$
$$q_{2,2}^* = M\left(1-\frac{c^p(m_2^*)}{p(m_2^*)}\right)\delta$$
$$q_{2,2}^{r*} = \min\left(\gamma S_D\big(q_{1,2}^*\big), M\left(1-\frac{c^r(m_2^*)}{\theta p(m_2^*)}\right)(1-\delta)\right)$$
$$m_2^* = \begin{cases}(1-\epsilon) & \text{for } c > 1-\Omega_2 \\ (1-\epsilon)(c+\Omega_2) & \text{for } c \le 1-\Omega_2\end{cases}$$
with $\lambda = \beta\left(\theta p(m_2^*) - c^r(m_2^*) - \frac{\theta p(m_2^*)q_{2,2}^r}{M(1-\delta)}\right)$ and $\Omega_2 = \frac{S_D(q_{1,2}^*)i+\beta(S_D(q_{2,2}^*)i+S_D(q_{2,2}^{r*})\theta i+q_{2,2}^{r*}e)}{2b(q_{1,2}^*+\beta q_{2,2}^*)}$.

Results

The solutions of the optimization problems are calculated in MATLAB using the functions and parameters from table 1. The numerical simulations show that hypothesis 1 is not always true: Figure 1 shows parameter ranges of the customer share parameter δ and the return rate γ, where the level of modularity in a push strategy is higher than in a pull strategy.

Figure 1 illustrates, in which situations hypothesis 1 is true and when it is false: Especially in situations when the return rate is high, we can find situations where the optimal level of modularity will be higher in the push case than in the pull case. In these situations, hypothesis 1 will not be true. From the solutions of the optimization problems, it can be seen that according to our models, hypothesis 2 will always be true: First, it can be shown easily that $S_D\big(q_{1,2}\big) \le q_{1,1}\ \forall q_{1,1}$ and second
$M\left(1-\frac{c^r(m_2)}{\theta p(m_2)}\right)(1-\delta) \le M(1-\delta)$ holds, since $\frac{c^r(m_2)}{\theta p(m_2)} \ge 0\ \forall m_2$.

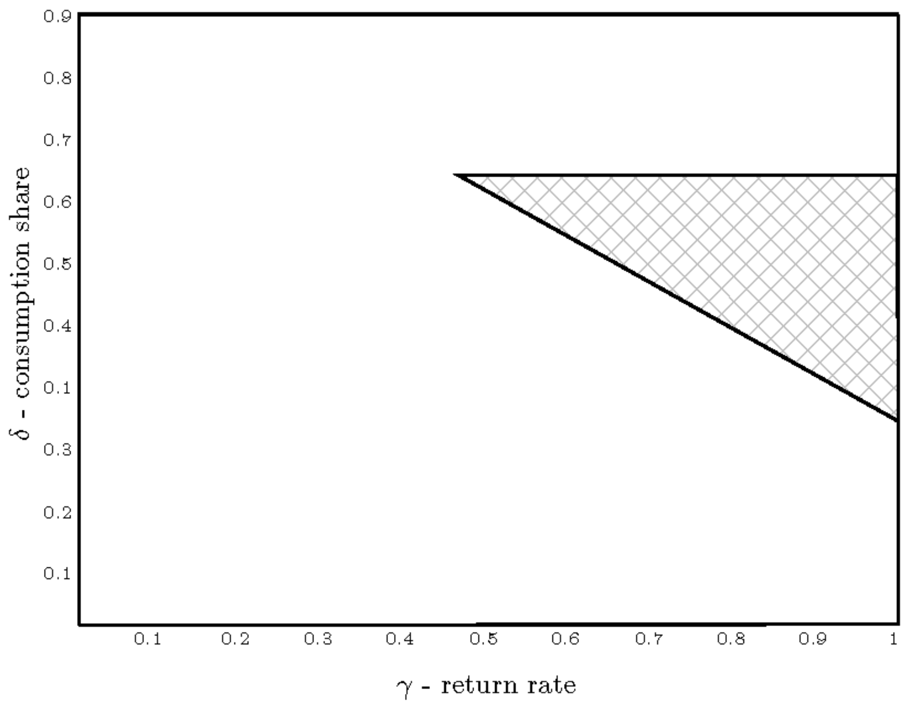

Fig. 1. The level of modularity is higher in a push strategy than in a pull strategy when $\boldsymbol{\delta}$ and $\boldsymbol{\gamma}$ satisfy the parameter constellation given in the grey shaded areas (i.e. where $\boldsymbol{m_1^*} / \boldsymbol{m_2^*} < 1$).

In order to shed light on the validity of hypothesis 3 and 4, we calculate the ratio between profits for a pull supply chain strategy and profits for a push strategy, i.e.

$$\Pi_1(q_{1,1}^*, q_{2,1}^*, q_{2,1}^{*r})/\Pi_2(q_{1,2}^*, q_{2,2}^*, q_{2,2}^{*r}):$$

When analyzing the impact of increases in the return rate or the consumption share, we have to distinguish between situations when the consumption share for remanufactured products is smaller than the return rate (above the diagonal from the top-left to the bottom-right corner in figure 2, i.e. $(1-\delta) < \gamma$) or when the share parameter for remanufactured products is greater than the return rate (i.e. $(1-\delta) > \gamma$). In cases when $(1-\delta) > \gamma$ holds, an increase of the return rate, will raise the profit ratio and will hence make the pull strategy more beneficial compared to the push strategy. The contrary will be true for situation where $(1-\delta) < \gamma$. Thus, hypothesis 3 will only be true for situations where $(1-\delta) > \gamma$. In cases when $(1-\delta) < \gamma$ holds, an increase in the consumption share for remanufactured products (i.e. a decrease in δ) will lower the profit ratio and will hence make the push strategy more beneficial compared to the pull strategy. We can therefore conclude that hypothesis 3 is true for situations where $(1-\delta) > \gamma$ and hypothesis 4 is true for situations where $(1-\delta) < \gamma$ holds, meaning situations where the consumption share for remanufactured products is lower than the return rate.

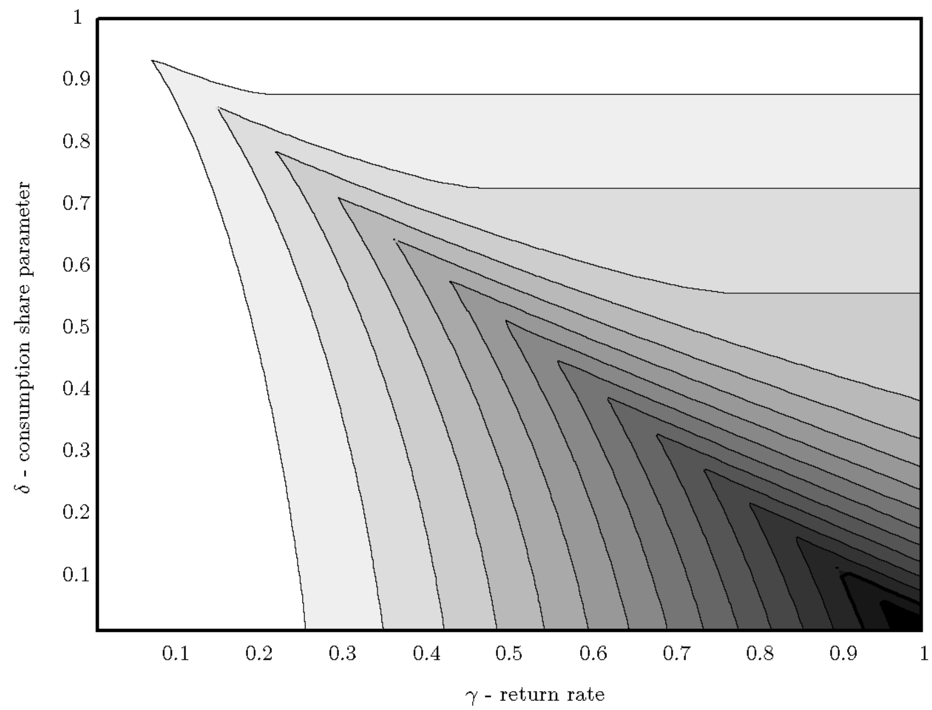

Fig. 2. Ratio between profits in the pull and in the push case for various values of the return rate $\boldsymbol{\gamma}$ and the consumption share parameter $\boldsymbol{\delta}$. Darker shadings denote higher profit ratios.

Summary

In this article we have shown the influence of supply chain strategies on a product's optimal degree of modularity by explicitly considering reverse logistics operations and the impact of customers' preferences for new and remanufactured products. Based on the analysis of two optimization problems – one for a company under a pull and one for a company under a push strategy – we found cases where the optimal level of modularity is higher under a push than under a pull strategy. These cases can mainly be found when the return rate from period 1 sales is high. Additionally, we determined that an increase in the return rate is more desirable in terms of profits under a pull strategy when the consumption share for remanufactured products is higher than the return rate. However, when the consumption share for remanufactured products is higher than the return rate, the push strategy becomes more beneficial when customers increasingly prefer remanufactured products. These results are subject to several limitations concerning the formulation of the optimization problems. In our models for instance, we assume that the company can decide freely on the optimal level of modularity and that the company is not restricted by other supply chain members' product design decisions. These interdependencies could effectively be analyzed by a variational inequality formulation of the optimization problems of all supply chain members, similar to the work of Wakolbinger *et al*. (2014). The analysis of these effects, however, is subject to future research. The general formulation of the optimization problems as done in this article is an abstraction of reality as it does not assume a specific position in the supply chain of the company under consideration. Additionally, by considering just a pure pull and a push strategy, we do not analyze hybrid strategies that gain increasing relevance in practice.

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References

Chen SH and Chie BT (2007). Modularity, product innovation, and consumer satisfaction: an agent-based approach. In: Yao X, Yin H, Tino P, Corchado E and Byrne W (eds). Intelligent Data Engineering and Automated Learning – IDEAL 2007, Lecture Notes in Computer Science Vol. 4881, Springer Berlin Heidelberg pp 1053-1062

Fernández I and Kekäle T (2005). The influence of modularity and industry clockspeed on reverse logistics strategy: Implications for the purchasing function. Journal of Purchasing and Supply Management 11 (4): 193-205

Hölttä-Otto K and de Weck O (2007). Degree of modularity in engineering systems and products with technical and business constraints. Concurrent Engineering: Research and Applications 15 (2): 113-126

Huang CC, Liang WY and Chang ZY (2012). A novel approach to product modularity and product disassembly with consideration of 3R-abilities. Computers & Industrial Engineering 62(1): 97-107

Mazahir S, Lassagne M and Kerbache L (2011). Reverse logistics and push-pull manufacturing systems: the case of electronic products. Supply Chain Forum. An International Journal 12 (2): 92-103

Newcomb P, Bras B, Rosen D (1996). Implications of modularity on product design for the life cycle. In: Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers Engineering Conference

Nowak T, Hofer V (2014). On stabilizing volatile product returns. European Journal of Operational Research 234: 701-708

Reimann M and Lechner G (2012). Production and remanufacturing strategies in a closed-loop supply chain: a two-period newsvendor problem. In: Choi TM (ed). Handbook of Newsvendor Problems. Models, Extensions and Applications. International Series in Operations Research & Management Science Volume 176. Springer Science+Business Media New York, pp 219-247

Sako M (2005). Modularity and outsourcing: the nature of co-evolution of product architecture and organization architecture in the global automotive industry. In: Prencipe A, Davies A and Hobday M (eds). The business of systems integration. Oxford University Press pp 229-253

Swaminathan JM and Lee H (2003). Design for postponement. In: Graves SC and Kok AG (eds). Handbooks in operations research & management science, volume 11, supply chain management: design, coordination and operation. Elsevier B.V., Amsterdam pp 199-226

Tseng HE, Chang CC and Cheng CJ (2010). Disassembly-oriented assessment methodology for product modularity. International Journal of Production Research 48 (14): 4297-4320

Wakolbinger T, Toyasaki F, Nowak T and Nagurney A (2014). When and for whom would e-waste be a treasure trove? Insights from a network equilibrium model of e-waste flows. International Journal of Production Economics 154: 263-273.