An Approach to Evaluate the Profitability of Component Commonality

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Commonality or the use of same components (parts, assemblies, or subsystems) among multiple products can reduce component inventory and simplify processes and logistics while accommodating variations in product demand. Excessive commonality, however, causes some products to use high-performance components and increase product cost. This paper presents an approach for evaluating profitability of component commonality by integrating commonality and supply chain decisions. The proposed approach is demonstrated using commonality of electric-bicycle motors as an illustrative example. This paper presents a sensitivity analysis of the optimum commonality with respect to motor cost, demand variability, inventory-tracking cost, and inventory-ordering cost. [DOI: 10.1115/1.4036644]

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1 Introduction

Commonality is a product design approach in which the same components are shared across multiple products [1]. Commonality enables firms to offer product variety, pool risks, and reduce inventory by aggregating the demand for components [2]. While supply chain variables have been increasingly incorporated in product design [3], commonality and supply chain variables have not been fully optimized simultaneously. Some studies have developed various indices to evaluate the degree of commonality without incorporating supply chain variables. These indices have been developed to evaluate commonality within a product family [4], assess impacts of future design changes on component standardization and modularization [5], and balance commonality and diversity within a product family [6]. Optimization of a product family has also been proposed using a comprehensive commonality index [7]. Another group of studies used analytic or mathematical models to evaluate the benefits of commonality, even though optimization of commonality was not within the scope of the studies. These studies compared, for example, savings in inventory cost [8,9] and total supply chain cost (inventory cost and ordering cost) [10] between products with and without commonality (standardization). In another group of studies, supply chain variables were incorporated in product design; however, inventory decisions were not considered. For example, supplier selection [11] and supplier and facility selection [12] were optimized for modular product design; suppliers and product modules were simultaneously selected in applications of game theory in product-variant design [13,14]; module selection and supply chain decisions (locations of module production and product assembly) were integrated in an optimization of product-family design [15]. Optimization of component commonality incorporating inventory cost was proposed [16]; however, supplier lead time and product availability, which impact the amount of inventory, were not incorporated.

This paper demonstrates an approach to evaluate profitability of commonality by integrating commonality and supply chain decisions. Reduction of safety inventory and holding cost (a major benefit of commonality) changes with demand variability and supplier lead time (i.e., capability of a supplier to deliver an inventory-replenishment lot in a short period of time). At the same time, the profitability of commonality changes with target product availability (i.e., how many customer orders can be satisfied from the product inventory) and additional cost incurred by using more expensive components to achieve commonality. This paper illustrates an approach for finding a commonality that maximizes the profitability by optimizing supply chain variables (supplier lead time, product availability, and safety inventory).

The rest of this paper is organized as follows: Section 2 describes the overall framework used to find optimum commonality by optimizing supply chain variables. Section 3 illustrates the proposed approach using commonality of electric-bicycle motors as an illustrative example. Section 4 illustrates the sensitivity of optimum commonality with respect to motor cost, demand variability, inventory-tracking cost, and inventory-ordering cost. Section 5 concludes this paper with a discussion of future work.

2 Approach

2.1 Variables and Parameters. Commonality-related decisions, parameters, uncertainties, and causal or associative relationships among them may be identified by constructing an influence diagram [17]. In an influence diagram (Fig. 1), decision variables and parameters are shown as rectangular nodes, uncertainties are shown as oval nodes, the objective of the decisions is shown as the hexagonal value node, and causal or associative relationships between the nodes are shown by arrows [18]. A node at the end of an arrow is the output of a function or a formula that takes the node at the beginning of the arrow as input.

2.2 Formulae. In this paper, inventory is continuously monitored (continuous review) and a predetermined lot size, Q, is ordered when the inventory falls to the reorder point (ROP) [19]. In this study, we used an economic order quantity (EOQ) in Eq. (1) as an inventory-replenishment lot size Q [19], p. 275. In Eq. (1), D_Y is an average annual demand, S is a fixed inventory-ordering cost, and H is an inventory-holding cost per unit per year. Demand is described by both an average weekly demand (D) and a standard deviation of the weekly demand (σ_D). The average annual demand (D_Y) is calculated by multiplying the weekly demand by 52 (number of weeks per year), i.e., $D_Y = 52D$

$$Q = \mathrm{EOQ} = \sqrt{\frac{2D_Y S}{H}} \quad (1)$$

Once a replenishment lot is ordered, the lot arrives after supplier lead time (i.e., inventory-replenishment lead time), which is described by an average lead time (L) and a standard deviation of lead time (s_L). The standard deviation of demand during a lead time (σ_L) is calculated from the standard deviation of weekly demand (σ_D) and the standard deviation of lead time (s_L) as shown in Eq. (2). The standard deviation of demand during lead time (σ_L) in Eq. (2) [19], p. 327 assumes that weekly demands are independent of one another

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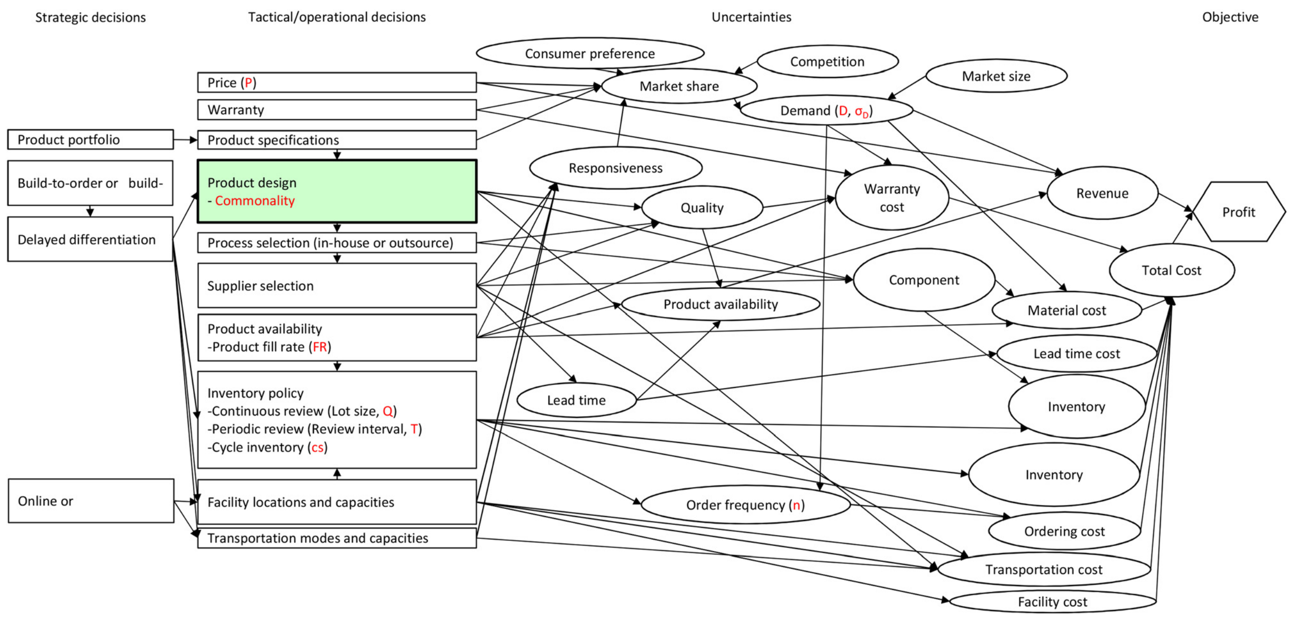

Fig. 1 Commonality-related decisions, parameters, and uncertainties

$$\sigma_L = \sqrt{L(\sigma_D)^2 + (D \times s_L)^2} \tag{2}$$

We assume that a different lead time corresponds to a different supplier and a supplier who can deliver a lot in a shorter time charges a higher cost for transportation per unit (l). Therefore, an additional unit cost due to a shorter lead time (l) is modeled as a reciprocal function of the lead time (e.g., $l = 10/L$ in this study). The standard deviation of lead time (s_L) is assumed to increase if a shorter lead time is targeted; therefore, the standard deviation of lead time s_L is modeled as a reciprocal function of the lead time (e.g., $s_L = 2/L$ in this study).

Product cost consists of the cost of a component (C) that is considered for commonality and the cost of product-specific components that are unique to each product. Inventory-holding cost per unit per year (H) is calculated by multiplying the percentage inventory-holding cost (h) and the cost of the component (C); thus, $H = hC$.

Cost of reviewing inventory is the cost of tracking inventory (r) per week. When a replenishment order is placed, a fixed inventory-ordering cost (S) is incurred at each inventory-ordering instance. Inventory replenishment frequency n is calculated by dividing annual demand D_Y by lot size Q, i.e., $n = D_Y/Q$. Transportation cost of the inventory replenishment is the transportation cost per unit (t) multiplied by the lot size Q.

Product availability (α) is measured by product fill rate (FR), i.e., $\alpha = \text{FR}$. Product fill rate FR is defined as the proportion of demand that is satisfied from the inventory. A cycle inventory (cs) is defined as an average inventory due to lot size Q; it is half of a lot size, i.e., $\text{cs} = Q/2$. Safety inventory is calculated assuming demand and lead time are normally distributed [19], p. 317, and by using a standard normal cumulative distribution function, $F_s()$, and standard normal density function, $f_s()$. There is no closed formula for calculating a safety inventory when the product fill rate FR is used as a target product availability in continuous review. Safety inventory (ss) needs to be iteratively searched for a given FR using the following equation [19], p. 322:

$$(1 - \text{FR})Q = -\text{ss}\left[1 - F_S\left(\frac{\text{ss}}{\sigma_L}\right)\right] + \sigma_L f_S\left(\frac{\text{ss}}{\sigma_L}\right) \tag{3}$$

When commonality is not considered for product i, expected annual revenue (ER_i) is calculated using Eq. (4), expected annual total cost (EC_i) is calculated using Eq. (5), and expected annual profit (EP_i) is calculated using Eq. (6). We assume that all components except components considered for commonality are always available. Therefore, the availability of the products is equal to the availability of the components considered for commonality. In Eq. (4), P is price. In Eq. (5), C_{Oi} is the sum of all the costs irrelevant to commonality, which includes the cost of product-specific components and their holding costs. Subscript i represents different products

$$\text{ER} = \text{Price} \times \text{Sales} = \text{Price} \times \text{Product availability} \times \text{Demand}$$
$$\text{ER}_i = P_i \alpha_i D_{Yi} \tag{4}$$

$$\begin{aligned}\text{EC} = {} & \text{Material cost} + \text{Lead time cost} + \text{Inventory holding cost} \\ & + \text{Inventory tracking cost} + \text{Ordering cost} + \text{Transportation cost} \\ & + \text{Other cost irrelevant to commonality}\end{aligned}$$

$$\begin{aligned}\text{EC}_i &= C_i D_{Yi} + l n_i Q_i + (\text{cs}_i + \text{ss}_i)H_i + fr + n_i S + t n_i Q_i + C_{Oi} \\ &= C_i D_{Yi} + \frac{10}{L} n_i Q_i + (\text{cs}_i + \text{ss}_i)H_i + 52r + n_i S + t n_i Q_i + C_{Oi}\end{aligned} \tag{5}$$

$$\begin{aligned}\text{EP}_i &= \text{ER}_i - \text{EC}_i \\ &= (\alpha_i P_i - C_i)D_{Yi} - \left(\frac{10}{L} + t\right) n_i Q_i - (\text{cs}_i + \text{ss}_i)H_i \\ &\quad - 52r - n_i S - C_{Oi}\end{aligned} \tag{6}$$

When commonality is considered between component i of product i and component j of product j ($i < j$), we assume that the performance of component j is higher than the performance of component i. We then assume that the higher-performance component j can replace the lower-performance component i for commonality. We further assume that all components except components i and j are always available. Therefore, the availability of the two products, i and j, are equal to the availability, α_{ij}, of the common component, j. Expected annual revenue of the two products, i and j, (ER_{ij}) is calculated using Eq. (7). Expected annual total cost of the two products, i and j, (EC_{ij}) is calculated using Eq. (8). Subscript ij is used to indicate that the product availability, order frequency, lot size, cycle inventory, and safety inventory of component j are for the aggregated demand of product i and product j. In Eq. (8), the first term is the cost of the common component, j, (C_j) multiplied by the total demand of both products, i.e., $D_{Yi}+D_{Yj}$. Remaining terms are the lead time cost, inventory-holding cost, inventory-tracking cost, ordering cost, and transportation cost of the common component, j, and the costs that are irrelevant to commonality (C_{Oi} and C_{Oj}). Expected annual profit of the two products, i and j, (EP_{ij}) is calculated using Eq. (9). Expected revenue, expected cost, and expected profit of commonality in more than two products are calculated similarly to the commonality in the two products

$$\mathrm{ER}_{ij} = \mathrm{ER}_i + \mathrm{ER}_j = P_i \alpha_{ij} D_{Yi} + P_j \alpha_{ij} D_{Yj} = \alpha_{ij}(P_i D_{Yi} + P_j D_{Yj}) \quad (7)$$

$$\mathrm{EC}_{ij} = C_j(D_{Yi} + D_{Yj}) + \frac{10}{L} n_{ij} Q_{ij} + (\mathrm{cs}_{ij} + \mathrm{ss}_{ij}) H_j + 52r + n_{ij} S + t n_{ij} Q_{ij} + C_{Oi} + C_{Oj} \quad (8)$$

$$\mathrm{EP}_{ij} = \mathrm{ER}_{ij} - \mathrm{EC}_{ij} \quad (9)$$

2.3 Commonality Decision Model. For each candidate commonality, we maximize the expected profit EP in Eq. (10) and choose the commonality with the highest expected profit

Suppose F is a set of feasible commonality, where $f = 1, \ldots, F$. For example, $f = 3$ may represent a commonality among products 1, 2, and 3, and no commonality among the remaining products.

Objective

For a commonality in set F, choose the commonality that maximizes the expected profit (EP)

$$\mathrm{EP} = \mathrm{EP}_{\text{Products without commonality}} + \mathrm{EP}_{\text{Products with commonality}}$$

where $\mathrm{EP}_{\text{Products without commonality}}$ is calculated similar to Eq. (4)–(6) and $\mathrm{EP}_{\text{Products with commonality}}$ is calculated similar to Eq. (7)–(9).

Decision variables for the products

Product availability $\alpha = \mathrm{FR}$ (fill rate)

Supplier (inventory–replenishment) lead time (week) L

Safety inventory ss

Constraints for the products with common component

Supplier (inventory–replenishment) lead time $L : L \geq 1$

FR and ss: $(1 - \mathrm{FR})Q = -\mathrm{ss}\left[1 - F_S\left(\frac{\mathrm{ss}}{\sigma_L}\right)\right] + \sigma_L f_S\left(\frac{\mathrm{ss}}{\sigma_L}\right)$

(10)

3 Illustrative Example

Commonality and supply chain decisions are illustrated using electric bicycles (e-bikes) as products and motors as the components to be considered for commonality.

3.1 Electric Bicycles and Motors. Motor sizes are benchmarked among e-bikes manufactured by Accell Group. Accell Group is a global bicycle and parts manufacturer in The Netherlands[2]. Accell Group owns various e-bike brands including IZIP, eFlow, and Haibike sold in the U.S. through Currie Technologies, Simi Valley, CA[3]. IZIP, eFlow, and Haibike e-bikes are categorized into three classes: pedal-assist (pedalec) (class 1), throttle-on-demand (class 2), or speed-pedalec (class 3)[4]. IZIP e-bikes are offered in all three classes; eFlow is offered as speed pedalec (class 3), and Haibike is offered as both pedalec and speed-pedalec (class 1 and 3)[5]. Among the 33 e-bikes, the majority of motors are either 250, 350, or 500 W motors. Only one e-bike uses a 400 W motor and one e-bike uses a 750 W motor.

3.2 Design and Supply Chain Decisions. In this study, we simulated commonality decisions on motors in three e-bikes and supply chain decisions on product availability ($\mathrm{FR} = \alpha$), supplier lead time (L), and safety inventory (ss). Three e-bikes are labeled "luxury," which uses a 500 W motor, "popular," which uses a 350 W motor, and "affordable," which uses a 250 W motor. Based on the assumption that only a motor with greater power can replace the current motor, we compared five commonality decisions in Table 1. In case 1 (labeled as none), no commonality is considered. In case 2 (labeled as low-end), 350 W motors are used for both popular and affordable e-bikes. In case 3 (labeled as high-end), 500 W motors are used for both luxury and popular e-bikes. In case 4 (labeled as high-low), 500 W motors are used for both luxury and affordable e-bikes. In case 5 (labeled as all), 500 W motors are used for all e-bikes.

3.3 Model Parameters. Table 2 summarizes the parameters used in this illustrative example, which include average demand (D), demand variability (σ_D), price (P), cost of motor (C), inventory-holding cost as percentage of component cost (h), inventory-tracking cost per week (r), fixed inventory-ordering cost (S), transportation cost per unit (t), and sum of costs that are irrelevant to commonality (C_O).

Table 1 Commonality decisions

Case	Commonality	E-bike		
		Luxury	Popular	Affordable
1	None	500 W	350 W	250 W
2	Low-end	500 W	350 W	350 W
3	High-end	500 W	500 W	250 W
4	High-low	500 W	350 W	500 W
5	All	500 W	500 W	500 W

[2]http://www.accell-group.com/en
[3]http://www.accell-group.com/files/0/5/0/1/AnualReport2014.pdf
[4]http://electricbikereview.com/
[5]http://electricbikereview.com/top-10-electric-bikes/

Table 2 Model parameters

		E-bike		
		Luxury	Popular	Affordable
D	Units per week	5	10	5
σ_D	Units per week	3	6	3
P	$per unit	2000	1000	500
C	$per unit	170	150	130
h	Percentage	40	40	40
r	$per week	50	50	50
S	$per order	1000	1000	1000
t	$per unit	10	10	10
C_O	$per unit	1500	692	288

3.4 Results. Figure 2 summarizes the results of optimization: profit, material cost, inventory-holding cost, the sum of inventory tracking and ordering costs, and optimum parameters (product availability, inventories, lead time, and order frequency). Under the conditions studied in this paper, low-end commonality (using 350 W motors for both popular and affordable e-bikes) maximizes the profit.

The material cost, inventory-holding cost, and the sum of inventory tracking and ordering cost change with commonality. The material cost increases as the degree of commonality increases because of using more expensive motors in low-end products (i.e., popular and/or affordable e-bikes). The inventory-holding cost decreases as the degree of commonality increases due to inventory reduction achieved through aggregation of motor demands by commonality. The sum of inventory tracking and inventory-ordering cost also decreases as the degree of commonality increases. This cost reduces because order frequency, which is the annual demand divided by lot size, decreases as the lot size increases when motor demands are aggregated through commonality.

4 Sensitivity Analysis

In this section, we performed a sensitivity analysis of the optimum commonality with respect to (1) cost differences, ΔC, between 500 W, 350 W, and 250 W motors that impact material cost and inventory holding cost; (2) demand variability, σ_D, that impacts safety inventory, product availability, and inventory holding cost; (3) inventory-tracking cost per week, r; and (4) inventory-ordering cost, S. These conditions are summarized below.

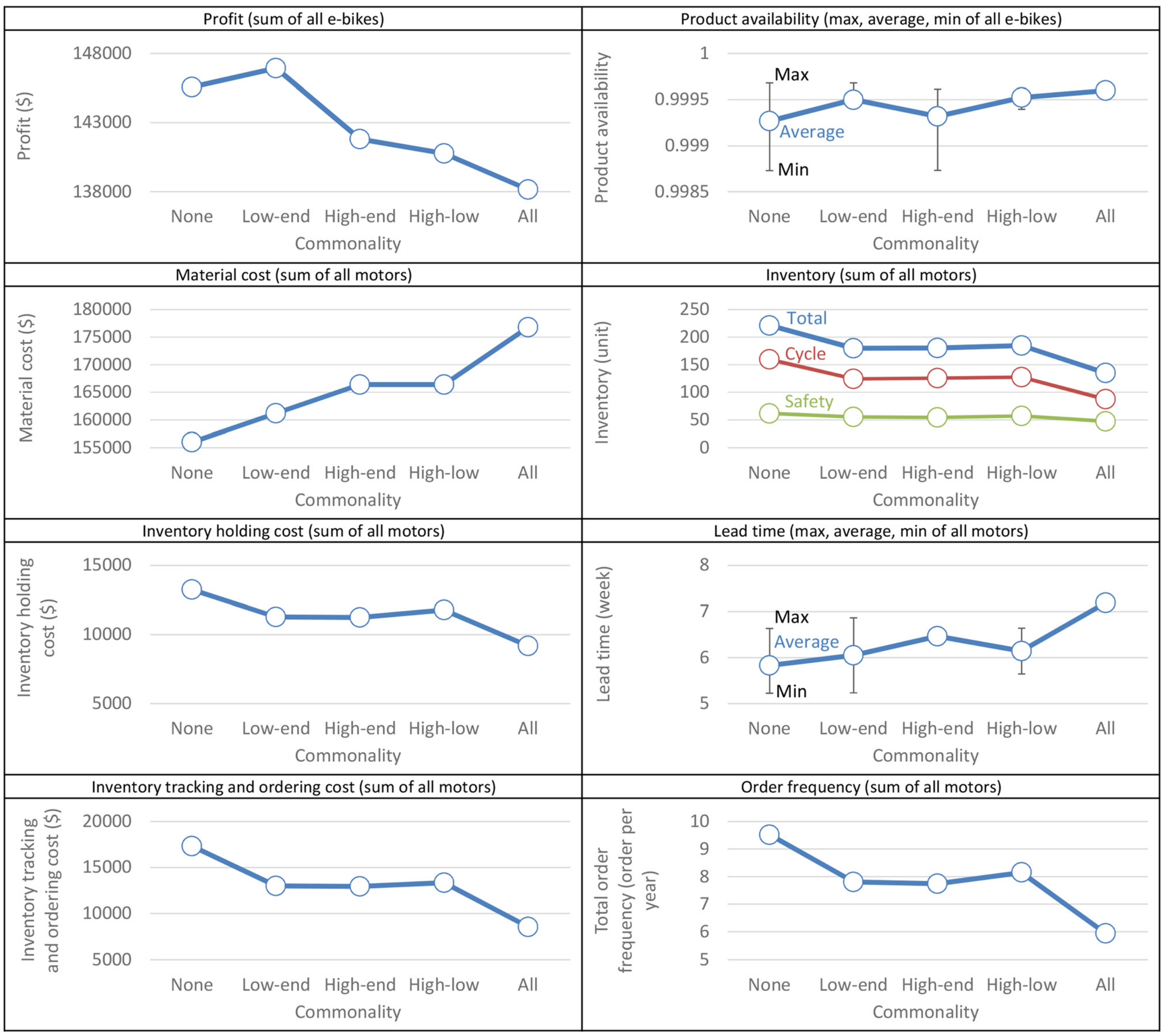

Fig. 2 Optimization results

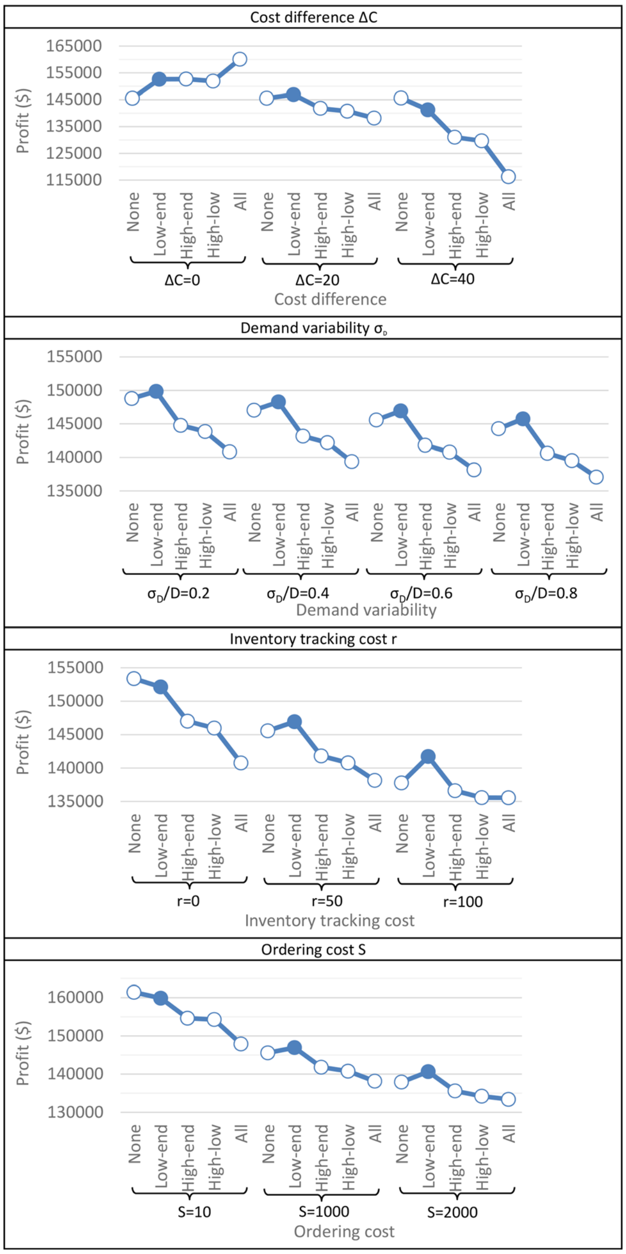

Fig. 3 Sensitivity analysis

- The impact of motor cost differences ΔC on profit is compared in three cases: (1) cost differences among motors are negligible $\Delta C = 0$ (all motors are $C = 150$), (2) cost differences are medium $\Delta C = 20$ as in the base case, and (3) the cost differences are large $\Delta C = 40$ ($C = 110$ for 250 W motor, $C = 150$ for 350 W motor, and $C = 190$ for 500 W motor).
- The impact of demand variability on profit is compared in four cases: small ($\sigma_D/D = 20\%$), medium ($\sigma_D/D = 40\%$), large ($\sigma_D/D = 60\%$), and very large ($\sigma_D/D = 80\%$) variability of demand.
- The impact of inventory-tracking cost r on profit is compared in three cases: negligible ($r = 0$), medium ($r = 50$), and high ($r = 100$) inventory-tracking cost per week.
- The impact of inventory-ordering cost S on profit is compared in three cases: low ($S = 10$), medium ($S = 1000$), and high ($S = 2000$) ordering cost.

Figure 3 shows the results of sensitivity analysis with filled circles indicating low-end commonality that was optimum in Sec. 3. When motor costs are the same ($\Delta C = 0$), the optimum commonality is to use 500 W motors in all e-bikes (all). In contrast, when the motor costs differ significantly ($\Delta C = 40$), the optimum commonality is no commonality (None). For demand variability, optimum commonality is low-end commonality for all demand variabilities. When inventory-tracking cost is negligible ($r = 0$) or when inventory-ordering cost is low ($S = 10$), the optimum commonality changes to no commonality (none).

5 Conclusions

This paper illustrated an approach to assess profitability of commonality by integrating commonality decisions and supply chain decisions. Supply chain decisions included inventory-replenishment lead time (which assumed that a different lead time corresponds to a different supplier), product availability, and safety inventory. The proposed approach was illustrated by motor commonality for three electric bicycles (e-bikes). Sensitivity of profit was analyzed with respect to the degree of commonality and motor cost difference, demand variability, inventory-tracking cost, or inventory-ordering cost. We observed that the optimum commonality changed with motor cost difference, inventory-tracking cost, and inventory-ordering cost. Thus, the optimum commonality is sensitive to underlying business conditions.

In this study, we assumed that high-performance components are more expensive than low-performance components. Thus, commonality leads to a higher material cost. This assumption may be most applicable when components are purchased from suppliers. In contrast, if components are designed and manufactured in-house, commonality may not necessarily increase material costs if the cost of designing a common component for multiple products is lower than the total cost of designing unique components for each model. This may suggest that the benefit of commonality may be larger if commonality is considered at the early stage of product design and development. Furthermore, we investigated commonality for one component (i.e., motor). In many cases, designers may wish to consider commonality simultaneously for more than one component, e.g., commonality of motors and commonality of batteries in the case of e-bikes. Finally, this study focused on a relatively small number of supply chain variables. Thus, future work includes (1) simulating commonality decisions starting at the design stage, (2) determining commonality for multiple components, and (3) conducting a comprehensive analysis incorporating all decisions, variables, parameters, and uncertainties in Fig. 1.

References

[1] Collier, D. A., 1981, "The Measurement and Operating Benefits of Component Part Commonality," Decis. Sci., **12**(1), pp. 85–96.
[2] Lee, H. L., 1993, "Design for Supply Chain Management: Concepts and Examples," *Perspectives in Operations Management*, R. K. Sarin, ed., Kluwer Academic Publishers, Boston, MA, pp. 45–65.
[3] Fixson, S. K., 2005, "Product Architecture Assessment: A Tool to Link Product, Process, and Supply Chain Design Decisions," J. Oper. Manage., **23**(3–4), pp. 345–369.
[4] Kota, S., Sethuraman, K., and Miller, R., 2000, "A Metric for Evaluating Design Commonality in Product Families," ASME J. Mech. Des., **122**(4), pp. 403–410.
[5] Martin, M. V., and Ishii, K., 2002, "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," Res. Eng. Des., **13**(4), pp. 213–235.
[6] Alizon, F., Shooter, S. B., and Simpson, T. W., 2009, "Assessing and Improving Commonality and Diversity Within a Product Family," Res. Eng. Des., **20**(4), pp. 241–253.
[7] Thevenot, H. J., and Simpson, T. W., 2007, "A Comprehensive Metric for Evaluating Component Commonality in a Product Family," J. Eng. Des., **18**(6), pp. 577–598.
[8] Lee, H. L., and Tang, C. S., 1997, "Modelling the Costs and Benefits of Delayed Product Differentiation," Manage. Sci., **43**(1), pp. 40–53.
[9] Huang, G. Q., Zhang, X. Y., and Liang, L., 2005, "Towards Integrated Optimal Configuration of Platform Products, Manufacturing Processes, and Supply Chains," J. Oper. Manage., **23**(3–4), pp. 267–290.
[10] Hillier, M. S., 2002, "The Costs and Benefits of Commonality in Assemble-to-Order Systems With a (Q,r)-Policy for Component Replenishment," Eur. J. Oper. Res., **141**(3), pp. 570–586.

[11] Chiu, M.-C., and Okudan, G., 2011, "An Integrative Methodology for Product and Supply Chain Design Decisions at the Product Design Stage," ASME J. Mech. Des., **133**(2), p. 021008.
[12] Chung, W.-H., Kremer, G. E. O., Richard, A., and Wysk, R. A., 2014, "A Modular Design Approach to Improve Product Life Cycle Performance Based on the Optimization of a Closed-Loop Supply Chain," ASME J. Mech. Des., **136**(2), p. 021001.
[13] Huang, G. Q., Zhang, X. Y., and Lo, V. H. Y., 2007, "Integrated Configuration of Platform Products and Supply Chains for Mass Customization: A Game-Theoretic Approach," IEEE Trans. Eng. Manage., **54**(1), pp. 156–171.
[14] Zhang, X., and Huang, G. Q., 2010, "Game-Theoretic Approach to Simultaneous Configuration of Platform Products and Supply Chains With One Manufacturing Firm and Multiple Cooperative Suppliers," Int. J. Prod. Econ., **124**(1), pp. 121–136.
[15] Fujita, K., 2014, "Global Product Family Design: Simultaneous Optimal Design of Module Commonalization and Supply Chain Configuration," *Advances in Product Family and Product Platform Design: Methods & Applications*, T. W. Simpson, J. Jiao, Z. Siddique, and K. Hölttä-Otto, eds., Springer, New York.
[16] Thonemann, U. W., and Brandeau, M. L., 2000, "Optimal Commonality in Component Design," Oper. Res., **48**(1), pp. 1–19.
[17] Ramdas, K., 2003, "Managing Product Variety: An Integrative Review and Research Directions," Prod. Oper. Manage., **12**(1), pp. 79–101.
[18] Howard, R. A., and Matheson, J. E., 2005, "Influence Diagrams," Decis. Anal., **2**(3), pp. 127–143.
[19] Chopra, S., and Meindl, P., 2015, *Supply Chain Management: Strategy, Planning, and Operation*, 6th ed., Pearson Education Limited, Harlow, UK.