A review of commonality models in manufacturing resources planning: state-of-the-art and future directions

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Abstract

Purpose - *The main purposes of this paper are to enhance the understanding of commonality models in manufacturing resource planning by documenting the current state of affairs, and to stimulate fruitful future research by identifying gaps between the relevant issues and available academic literature.*

Design/methodology/approach - *This paper is based on a comprehensive review of the articles from authentic publications on resources commonality for the various product mixes and the pertinent models. The papers are analyzed to identify the current scenarios and draw future research directions in the area.*

Findings – *In real world manufacturing settings, parts commonalities occur in their own ways or can be planned for their preferred occurrences. The use of common components for different products in a company is important for managing product variety and maintaining competitiveness in this age of mass customization and supply chain struggle. The paper finds that development of mathematical model to study the effects of commonality in the multi-stage systems with multiple products and multiple common items are remain in the virgin area of research. Effects of uncertainty factors on the models are other issues not yet covered in literatures. Experiments and empirical studies in this fissure also needed further attention.*

Originality/value – *The contribution of this paper is to provide a summary of the current state of affairs in component commonality and its models, and to point out the future research directions. A review of the work in this expanding and complex area of demand has been provided that identify the issues in this area. This is a comprehensive and up-to-date review of literatures on component commonality in manufacturing resource planning.*

Keywords Commonality, Manufacturing resource planning
Paper type Literature review

Introduction

The underlying ideas for commonality are not really new. As early as 1914, an automotive engineer demanded the standardization of automobile subassemblies, such as axles, wheels and fuel feeding mechanisms to facilitate a mix-and-matching of components and to reduce costs (Fixson, 2007). Commonality, i.e. using the same type of component in different locations of product structure trees, is frequently encountered in manufacturing industries. It has long been known that using a common component can reduce the cost of safety stock. Basically, taking commonality into account can reduce the inventory level, shorten the time for reaching the market, decrease the set-up time, increase productivity, and improve flexibility.

The commonality index is a measure of how well the product design utilizes standardized components. A component item is any inventory item (including a raw material), other than an end item, that goes into higher-level items (Dong and Chen, 2005). An end item is a finished product or major subassembly subject to a customer order.

The beneficial performance characteristics of commonality are simplified by planning and scheduling (Berry et al., 1992), lower setup and holding costs (Collier, 1981, Collier, 1982), lower safety stock (Baker, 1985), reduction of vendor lead time uncertainty (Benton and Krajewski, 1990) and order quantity economies (Gerchak and Henig, 1989, Gerchak et al., 1988). High commonality manufacturing systems are beneficial when system complexity is reduced, leading to lower setup times, and they are detrimental by increasing reliance on fewer parts, leading to higher variations within the production system (Sheu and Wacker, 1997).

The use of common components can decrease lead-time and risk in the product development stage since the technology has already been proven in other products (Collier, 1981, Collier, 1982). Inventory and handling costs are also reduced due to the presence of fewer components in inventory. The reduction of product line complexity, the reduction of set-up and retooling time, and the increase of standardization and repeatability improve processing time and productivity, and hence reduce costs (Collier, 1981, Collier, 1979). Fewer components also need to be tested and qualified (Thonemann and Brandeau, 2000, Fisher et al., 1999).

While commonality can offer a competitive advantage for a company, too much commonality within a product family can also have major drawbacks. First, consumers can be confused between each model if they lack distinctiveness. Commonality can also hinder innovation and creativity and compromise product performance: it increases the possibility that common components possess excess functionality in terms of increased weight, volume, power consumption, complexity, resulting in unnecessary waste (Krishnan and Gupta, 2001). Finally, commonality can adversely impact a company's reputation.

In this paper, the authors have studied the models of commonality in manufacturing resource planning since 1979. Its objective is to twofold, to enhance the understanding of models of commonality in manufacturing resource planning by documenting the current state of affairs, and to inspire fruitful future research by identifying gaps between relevant issues and available literature.

Commonality Perspective

In practice, commonality can be categorized from two perspectives, namely, engineering and management. From an engineering perspective, commonality refers to cases where several different components are replaced by a newly designed component that can perform the function of each one of them, or a cluster of equivalent components, one of which substitutes all the others. The common component must at least provide all the functionality of component it replaces. From a managerial perspective, commonality is present when some stock keeping units (SKUs) of a manufacturing system are used in more than one finished product. The term 'commonality' refers in literature are shown by **Error! Not a valid bookmark self-reference.**.

Table 1: Definition of commonality

Reference	Definition
Eynan (1996)	An approach which simplifies the management and control of inventory and also reduce inventory is component commonality.
Meyer and Lehnerd (1997)	Commonality is a group of related products that share common characteristics, which can be features, components, and/or subsystems. It is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced.
Ma et al. (2002)	Component commonality generally refers to an approach in manufacturing in which two or more different components for different end products (of perhaps the same product family) are replaced by a common component that can perform the function of those it replaces.
Mirchandani and Mishra (2002)	Component commonality refers to a manufacturing environment where two or more products use the same components in their assembly. Commonality is an integral element of the increasingly popular assemble-to-order strategy that inventories certain critical components- typically, with long lead time and expensive- in a generic form.
Labro (2004)	Commonality is the use of the same version of component across multiple

	products. It is a cost decreasing strategy in a stochastic-demand environment because by pooling risks the total volume of the common component can be forecasted more accurately.
Ashayeri and Selen (2005)	Commonality is defined as the number of parts/components that are used by more than one end product, and is determined for all product families.
Humair and Willems (2006)	For manufacturing echelon, commonality refers to the parts or subassemblies that are shared among different items. For distribution echelons, it refers to the end items that are knitted together or bundled as assortments to customers.

Parts commonality measurement

The parts commonality measurement includes the process for evaluation of product commonality and methods to achieve commonality in product family. These measures and methods vary considerably in purpose and process: the nature of the data gathered (some are extensively quantitative while some are more qualitative), the ease of use, and the focus of the analysis. However, they all share the goal of helping designers resolve the tradeoff between too much commonality (i.e. lack of distinctiveness of the products) and not enough commonality (i.e. higher production costs). Commonality index are found in literatures to measure the commonality within a family of products/processes.

Commonality indices

The commonality index is a measure of how well the product design utilizes standardized components. A component item is any inventory item other than an end item, which goes into higher-level items (Dong and Chen, 2005). Several commonality indices are found in reported literatures to measure the commonality within a family of products. Commonality is defined as the number of parts/components that are used by more than one end product and is determined for all product family (Ashayeri and Selen, 2005). Within a product family, commonality index is a metric to assess the degree of commonality. It is based on different parameters like the number of common components, component costs, manufacturing processes, etc. In designing a new family of products or analyzing an existing family, these indices are used very often as a starting point. They are intended to provide valuable information about the degree of commonality achieved within a family and how to improve a system's design to increase commonality in the family and reduce costs. However, there have been only limited comparisons between many of these commonality indices and their usefulness for product family (Thevenot and Simpson, 2006, Thevenot and Simpson, 2004). Several component-based indices are summarized in Table 2.

Table 2: Commonality indices

Name		Developed by	Commonality measure for	No commonality	Complete commonality
DCI	Degree of commonality index	Collier (1981)	The whole family	1	$\beta = \sum_{j=i+1}^{i+d} \Phi_j$
TCCI	Total const commonality index	Wacker and Treleven (1986)	The whole family	0	1
PCI	Product line commonality index	Kota et al. (2000)	The whole family	0	100
%C	Percent commonality index	Siddique et al. (1998)	Individual product with a family	0	100
CI	Commonality index	Martin and Ishii (1996); (1997)	The whole family	0	1

$CI^{(C)}$	Component part commonality	Jiao and Tseng (2000)	The whole family	1	$\alpha = \sum_{j=1}^{d} \sum_{i=1}^{i+d} \Phi_{ij}$
CMC	Comprehensive metric for commonality	Thevenot and Simpson (2007)	The whole family	0	1

Commonality Models

The use of common components in design, production and assembly operations has become more prevalent in the last few years. Research in this area has also blossomed and researchers have addressed a variety of operations related issues. These authors reviewed the papers that are directly relevant and also discuss component commonality issues considered in other research streams in inventory management. The commonality models are summarized in Table 3.

The number of common components, number of products, number of levels in bill-of-material or number of echelons in assembly, number of components used per unit of product, planning horizon, demand distribution of products, costs measure, service level metrics, objective and common component allocation policy can be used to classify the commonality models. From the literatures two streams of research with respect to commonality are distinct. One stream of research is on the design of the system or product and another stream of research covers efficient operation, given the design of the system.

Two product-single common component models

Baker et al. (1986) have studied the effect of commonality in a two-product, two-level model with independent and uniformly distributed demand and service level requirements. Their model minimizes the total components safety stock subject to aggregate and bottleneck required service level constraints. Implicitly they assumed that all components have equal costs and equal usage. Their work showed that under commonality: (a) the total number of units in inventory was reduced; (b) the inventory level (in units) of the common component was smaller than the total inventory levels (in units) of the two components it had replaced; and (c) that the inventory level of the specific components (those that were not replaced) was increased. This study mainly focuses on the service level and safety stocks only. But the scenario of the parts price, quality and uncertainty of their arrival, sensitivity of the finished products etc. are not incorporated in the model. Gerchak et al. (1988) further investigated and extended Baker et at. (1986)'s model to consider general demand distribution for any number of products and minimized the total inventory cost. They found that some important properties do not hold when the components costs are arbitrary. They showed that a decrease in total inventory cost resulted from the use of commonality.

Bagchi and Gutirrez (1992) have maximized the aggregate service level subject to a constraint on the total component availability when the product demands have the exponential or geometric distributions. They found that, for two-product case, replacing product-specific components with common components leads to increasing marginal returns on aggregate service level. They also considered minimizing inventory holding cost subject to service constraints and derive properties of the optimal total cost.

Eynan and Rosenblatt (1996) have studied the economic implications of component commonality in a single period problem. They compared the total component acquisition cost for two products in three different situations, distinguished by the number of common components (none, one and two) subject to an aggregate service level constraint. Eynan (1996) shows analytically that commonality results in larger savings for negatively correlated demand case and small savings for positively correlated demand case when compared with independent demand case. They minimized a cost measure subject to service level constraints.

Kim and Chhajed (2000) have developed a model to examine when modular products should be introduced and how much commonality to offer. The model looks at a market consisting of a high segment and a low.

Desai et al. (2001) have analyzed design configurations by formulating a model that incorporated the marketing and manufacturing trade-offs. They developed model for three possible design configurations: unique, premium-common and basic common. One of the two components can potentially be common between the two products or go as a distinct component in each of the two products.

Mirchandani and Mishra (2002) have developed an optimization model considering a two-stage assemble-to-order system with two products having uniformly distributed demand, one common component and product specific components. Each product has a desired product-specific service level which is also referred to as order fill rate and each component incurs an acquisition cost that equals the product of its unit cost and its order quantity.

Van Mieghem (2004) has analyzed a single unified model with five input and two products under the no-commonality and with commonality. This introduces the revenue-maximization option of commonality as a second benefit that is independent of the traditional risk-pooling benefit. The pure commonality (where each product requires one dedicated and one common component) strategies are never optimal unless complexity costs are introduced. He considered the probabilistic forecast of demand, financial data (price minus any marginal assembly and transportation costs; inventory incurs unit purchasing and holding costs and unmet demand incurs shortage costs) and network data.

Lin et al. (2006) have setup a multi-period model of component commonality with lead time. They analyzed the quantitative relationship between lead time and the inventory level of common component and find some efficient ways to: customization level, optimize inventory management and lower costs.

Multiple product-multiple component models

Baker (1985) has used a two level bill of materials to illustrate that in assemble-to-order situation for multi-products with uncertain demand, commonality reduces the total safety stock. However, component commonality complicates the determination of the product specific service levels. He has studied safety stock issues when the external demands for different items are correlated. He showed the effects of commonality on the inventory levels. His studies indicated that the optimal safety stock strongly depends on the correlation and commonality.

Gerchak and Henig (1986) have modeled a multiple period, multiple product and multiple component problem as a stochastic dynamic program. Their profit maximization objective function considered component acquisition cost and revenue from product sales. They showed that commonality always results in an increase in the safety stock of product-specific components, as compared to the no commonality case. Gerchak and Henig (1989) have further studied the impact of commonality in a more general setting. They showed that the multiple period problems allowing for partial backlog, shortage costs, component dependent holding cost and partial spoilage also has a myopic solution. They identified their model as a stochastic program but do not solve it.

Jonsson and Silver (1989b) have minimized the number of products short, subject to a budget constraint on the number of components in stock. Assuming normally distributed demand, they used numerical integration to determine the optimal solution. They considered a commonality model which maximizes the profit subject to a budget constraint on the value of the components. Jonsson et al. (1993) also considered this problem but used a scenario aggregation approach to formulate the problem and an augmented Lagrangian relaxation to provide good solution to it.

Srinivasan et al. (1992) have considered a multi-period problem in which the inventory holding cost in each period is minimized subject to product-specific service level constraints. First they formulated the problem as a stochastic program with chance constraints. They then reformulated using 'cumulative up to period t' variables that allows a heuristic decomposition of the problem by time period. They showed that in large problems, ignoring commonality can increase the inventory related costs enormously.

Zhang (1997) has studied a general multi-period, multiple product, multiple component model with deterministic lead times. The objective is to minimize acquisition costs subject to product-specific order fill rates. Unsatisfied demand is back-ordered. He used a multivariate normal distribution to characterize the demand in each period.

Hillier (1999a) has developed a simple multiple-period model with service level constraints to compare the effects of commonality in single-period and multiple-period cases. The results are drastically different for these two cases. When the common component is more expensive than the components it replaces, commonality is often still beneficial in the single-period model, but almost never in the multiple-period model.

Hillier (2002a) has developed a model that considers purchasing, ordering, inventory and shortage costs where components are replenished independently according to lot-size, reorder point policy. He showed that order pooling is a significant benefit; in many cases it is much more important than the risk pooling benefit.

Ma et al. (2002) have formulated a multi-period and multistage assembly network model with multiple products and stochastic demands, and proposed a scheme to express the desired base-stock level at each stocking point as a function of the corresponding achieved fill rate. They have demonstrated analytically whether introducing commonality at a particular stage or delaying the point of differentiation by one more stage can be justified. They concluded that a key factor for commonality and postponement decisions is the interactions between processing and procurement lead times.

Chew et al. (2006) have studied the trade-off between the gain through risk pooling and the loss due to component mismatched in a two-echelon assembled-to-stock (ATS) system when component sharing is allowed. They studied these conflicting effects by comparing a particular component sharing policy, namely the equal-fractile allocation policy, with a make-to-stock system which does not allow the allocation of common components.

Nonas (2007) has considered the problem of finding the optimal inventory level for components in an assembly system where multiple products share common components in the presence of random demand. The inventory problem considered is modeled as a two stage stochastic recourse problem where the first stage is to set the inventory levels to maximize expected profit while the second stage is to allocate components to products after observing demand.

Other component commonality models in inventory research

Researchers have included common components in several other studies with substantially different research objectives. These studies describe the implications of commonality, measure the extent of commonality or study inventory problem with common components.

Dogramaci (1979) has investigated detailed mathematical programming formulations and captured more reality, including setup costs and design complexity costs. He showed that commonality is beneficial because it decreased the standard deviation of demand forecast for components and hence reduced inventory costs.

Collier (1981) has studied the effect of degree of part standardization on MRP system performance. He defined a measure called degree of commonality index (DCI), as the average number of immediate parents for each component divided by the number of products. He introduced first the degree of commonality index (DCI) and used statistical methods to show the relationship between DCI and setup and holding costs. In a subsequent study Collier (1982) uses DCI to evaluate the impact of commonality on safety stock. He showed that when a common component replaces product-specific components, the aggregate safety stock reduces by $\sqrt{DCI}$. He showed that same service level can be maintained with reduced safety stock when commonality is increased. Besides saving inventory holding cost and lower component acquisition costs. But the results are based on very restrictive assumptions according to what have pointed out in McClain et al. (1984) and Collier (1984).

Common components are included in the literature on the lot sizing problem when complex bill of material (or general product structures) are studied. Afentakis and Gavish (1986) transform this problem into an expanded assembly structure with additional constraints and solved the problem using a branch and bound approach.

Cohen et al. (1989) have studied stocking policies for spare parts. They used heuristic approaches to determine base stock inventory for each component to minimize expected ordering, holding, shortage and transportation costs. Cohen et al. (1992) proposed extension of their model to develop (s, S) policies for a convergent spare parts logistics system, with item fill rate constraints, to multiple product system with component commonality.

In flexible manufacturing system where cellular layout is used, the problem for planning machines and tools requirements are addressed by Jain et al. (1991). They used a complete-linkage clustering method in making group of parts as part families based on: tool requirements and processing time.

Tang (1992) has developed a production rule for a multistage assembly system containing common components to determine the inventory of the components and their allocation to the products when there is yield loss and uncertain end product demand.

Grotzinger et al. (1993) have considered the commonality problem with a single common component and multiple products, in an assemble-to-forecast environment. The components are allocated to products when the demand is uncertain, but the common component can be re-allocated to different products when demands change.

Balakrishnan et al. (1996) have studied an assembly release planning problem in an assemble-to-forecast environment. Given the inventory availability information and demand distribution in the time corresponding to the procurement and assembly lead times, they determined integer assembly release quantities. They developed bisection algorithms for their model which included commonality and suitability among the components.

Vakharia et al. (1996) have used simulation to investigate the impact of component commonality on the work-load of a firm using an MRP system. They found that it decreases the average shop load, particularly when the number of setups is high, but increases the variability in loadings and system disruption.

Lee and Tang (1997) have proposed standardization, i.e. use of common components or processes, besides modular design and process restructuring, as means to postpone the point of product differentiation. They illustrated the costs and benefits of these approaches using a simple model.

Ha (1997) has studied allocation of common components in a make-to-stock production system with two priority demand classes and backordering. Ha (1999) also studied a similar problem for several demand classes with lost sales. He showed that for each demand class there exists a stock rationing level below which it is optimal to start rejecting the demand of this class in anticipation of future arrival of higher priority demands.

Hillier (1999b) has considered the possibility of replacing a number of different parts by a single common part. In the single period case, it is shown that even when the common part is somewhat more expensive, it might still be cost-effective to utilize. However, in the multi-period case, it is shown that the break-even cost of the common part is often just a few percent more expensive than the unique parts. The added purchasing costs over multi-periods quickly dominate any holding cost savings achieved through risk pooling.

Thonemann and Brandeau (2000) have modeled the component design problem as a mathematical program that considers production, inventory holding, setup and complexity costs (the cost in indirect functions caused by component variety). They formulated the problem as an integer program and applicable to components that are invisible to the customer, that has additive functionality. They showed that an optimum design achieves high cost saving by using significantly fewer variants than a no-commonality design but significantly more variants than full commonality design.

Hillier (2000) has developed a multi-period single-stage model for multi-product scenario with single common item under general demand distribution. He considered an uncapacitated, periodic review, Assemble-to-order (ATO) inventory system in which components are stocked at the beginning of each period according to forecast and the objectives of minimizing production, holding and shortage costs.

Hillier (2002b) has analyzed the effect of commonality on costs when the common part is more expensive than the parts it would replace in a multi-period case. He investigated the possibility of using both cheaper unique parts and a more expensive common part. Initial demand is met with unique part. The common part is used as only backup, when one or more of the unique parts stocks out. He developed a multi-period model that considered purchasing, shortage and holding costs. He concluded that the strategy of using commonality as backup dominates the strategy of no commonality or pure commonality and it is worthwhile even if the common part is significantly more expensive than the unique parts.

Labro (2004) has reviewed the component commonality literature through a management-accounting lens, focusing on the cost effects of an increase in the use of same version of a component across multiple products. He presented a review of the OM literature and reconciled it with management-accounting literature on cost drivers and cost of complexity. ABC is introduced as a framework to classify the effects on an increase in component commonality on costs indentified in the existing literature.

Zhou and Grubbstrom (2004) have focused on the effect of commonality in multi-level production–inventory systems, especially assembly systems. They have considered deterministic demand and ignored capacity constraints and assume that no backlog is allowed. They confined their attention to two cases of different complexity, the first when commonality only involves purchased items with lead times that can be disregarded. The second is when commonality affects items which are subject to some kind of processing, the simplest sub-case being when purchased items are not available until after some delay.

Mohebbi and Choobineh (2005) have studied the impact of introducing component commonality into an assemble-to-order environment when demand is subject to random variations, and component procurement orders experience random delays. By using simulated data, it shows that component commonality significantly interacts with existence of demand and supply chain uncertainties, and benefits of component commonality are most pronounced when both uncertainties exist. They consider a two-level ATO environment that produces three finished products only.

Heese and Swaminathan (2006) have analyzed a stylized model of a manufacturer who designs a product line consisting of two products for sale to two market segments with different valuations of quality. They investigated what circumstances support component sharing as a profitable strategy and, more specifically, which components are the best candidates for commonality. The manufacturer determines the component quality levels, the amount of effort to reduce production costs and whether to use common or different components for the two products.

Kranenburg and Houtum (2007) have developed a multi-item, single-site/stage spare parts inventory model with multiple groups to study the effect of commonality on spare parts provisioning costs for capital goods. The objective of the model is to minimize the spare parts provisioning costs, i.e., inventory holding and transportation costs, under the condition that all service level constraints are met. It is a spare parts model where demand occurs for individual items whereas in manufacturing model, it occurs for all items. They developed a heuristic solution procedure using a decomposition approach as in Dantzig–Wolfe decomposition, in order to obtain both a heuristic solution and a lower bound for the optimal costs. They have shown that the savings obtained by shared stocks are significantly affected by the commonality percentage and the degree to which the commonality occurs in the expensive SKU-s.

Jans et al. (2008) have proposed a mixed integer nonlinear optimization model to find the optimal commonality decision in an industrial production-marketing coordination problem. They focused on production and development cost savings instead inventory cost savings and integrate information from different functional areas such as production, marketing and accounting. They formulated the problem as a net-present-value investment decision.

Process modeling

Process models are often multi-stage procedures to conduct all or portions of the design process when designing products with commonality, plat-forms, or product families in mind. For example, Jiao and Tseng (1999) present a detail process to establish product families and Germani and Mandorli (2004) propose a procedure leading to self-configuring components in product architecture design. Another five-step model for product family design is presented by Farrell and Simpson (2003). Yet a different approach to commonalize product subsystems has been suggested by Qin et al. (2005). They use actual data on critical parameters of existing products to construct similarity matrices with in turn enable cluster formation, i.e. common platform definition. In general, the engineering literature, and in particular text books, tend to provide detailed step-by-step advice on how to proceed when designing modular products and products with common components (Kamrani and Salhieh, 2002, Ulrich and Eppinger, 2000).

Table 3: Commonality models

Study	Number of common components	Number of products	Number of time periods	Product demand distribution	Costs considered	Service level metric	Allocation policy
(Baker, 1985)	One	Two	Single	Uniform	Component acquisition	Product specific	Prioritized (not solved optimally)
(Baker et al., 1986)	One	Two	Single	Uniform	Component acquisition	Aggregate; Bottleneck	Smallest demand first
(Gerchak and Henig, 1986)	Multiple	Multiple	Multiple	General	Component acquisition, product revenue	-	Stochastic program (not solved)
(Gerchak et al., 1988)	One	Two; Multiple	Single	Uniform; General	Component acquisition	Aggregate; Bottleneck	Randomized
(Gerchak and Henig, 1989)	Multiple	Multiple	Multiple	General	Component acquisition, product revenue	-	Stochastic program (not solved)
(Jonsson and Silver, 1989a)	Multiple	Multiple	Single	Discrete (Binomial)	Component acquisition, product revenue	-	Stochastic program (Bender's decomposition; heuristic)
(Jonsson and Silver, 1989b)	One	Two	Single	Normal	-	Expected units short	-
(Bagchi and Gutierrez, 1992)	One	Two	Single	Exponential; Geometric	-	Aggregate	-
(Jonsson et al., 1993)	Multiple	Multiple	Single	Discrete (Binomial)	Component acquisition, product revenue	-	Stochastic program (Scenario aggregation)
(Eynan and Rosenblatt, 1996)	One	Two	Single	Uniform	Component acquisition	Aggregate	-
(Eynan, 1996)	One	Two	Single	Uniform; Correlated	Component acquisition	Aggregate	-
(Ma et al., 2002)	Multiple	Multiple	Multiple	Random and independent for other period for other products	Purchasing, inventory holding (work-in-process, component and product) costs	-	-
(Mirchandani and Mishra, 2002)	One	Two	Single	Independent and uniformly distributed	Acquisition cost	Product specific service level	
(Hillier, 2002b)	One	Multiple	Multiple	General distribution	Purchasing, inventory and shortage costs	-	-
(Hillier, 2002a)	Multiple	Multiple	Multiple	Stochastic	Purchasing, ordering, holding and shortage costs	-	-
(Van Mieghem, 2004)	One	Two	Single	Probabilistic	Assembly, transportation, inventory (purchasing & holding) and shortage costs	-	-
(Chew et al., 2006)	Multiple	Multiple	Single	Random	Trade-off between gain through risk pooling and loss due to component mismatch	-	Equal-fractile allocation policy
(Lin et al., 2006)	One	Two	Multiple	Followed a specific distribution	Responsive costs	Considered	-
(Kranenburg and Van Houtum, 2007)	Multiple	Multiple	Single	Random	Inventory holding and transportation costs	Product section	Triggered
(Nonas, 2007)	Multiple	Multiple	Single	Random	Profit maximization	-	Deterministic program

N.B. Unless mentioned otherwise, product demands are independent and default service level is order fill rate.

Connecting both product and process, Jiao et al. (2000) proposed a data structure that integrates the bill-of-materials with the bill-of-operations. Jiao and Tseng (2000) developed a process commonality index that incorporates concerns as process flexibility, lot sizing and scheduling sequencing into their measurement instruments. Balakrishnan and Brown (1996) viewed 'commonality across products as shared set of processing steps from ingot casting to some intermediate hot or cold forming step' in their work on aluminum tube manufacturing.

Simulation, Experiments and Empirical studies

Three types of simulation can be identified in the selected set of references. The first type is found in paper using mathematical modeling approaches that supplement and test their models with numerical simulations. For example, considering downward substitution in their multi-period model Rao et al. (2004) demonstrate the size of the inventory cost saving that their model predicts with simulation. Similarly, Dong and Chen (2005) illustrate the impact of component commonality on order fill rate, delivery time and total cost via simulation. A second type of simulation that has experienced an increase in popularity recently is agent-based modeling. A number of recent studies use agent-based modeling in the framework of complex adaptive system (Kuauffman, 1995). For example, Ethiraj and Levinthal (2004) explore the performance effect of what they called under and over commonality. Finally, a third type of simulation study uses real data to simulate effects of commonality. For example, Lin et al. (2000) study the inventory reduction effects on different complexity reduction approaches, such as feature elimination, feature substitution and feature postponement with data of a IBM midrange computer family with over 200 members and hundreds of feature codes.

The use of experiments in the study of commonality is atypical. The impact of parts commonality on customers' product valuation with the help of an experiment, so far an available example, is studied by Kim and Chhajed (2001). Studying the effects of commonality in vertical line extensions from both low-end and high-end products, they find that the use of commonality can increase the valuation of the low-end product but decrease the value of the high-end product.

Commonality and its effects have been studied empirically in rare cases. Safizadeh et al. (1996) have studied the product-process matrix. In their empirical study, they find that part commonality allows sustaining high plant performance despite violating the alignment between product and process. The view that increasing component commonality in real organizations can actually be quite difficult due to the lack of downstream information and often mis-fitting incentive structures is supported through a couple of case studies by Nobelius and Sundgren (2002).

Discussions and future research directions

In preceding sections, we have reviewed commonality models. All the studies have focused on single and/or two-stage assembly models. Most papers that developed analytical solutions assumed that only one unit of a common component were used to assemble a product. The distribution of product demand was often assumed to be uniform for analytical solutions. Most of the studies assumed that the product demands are independent to reduce the complexity of analysis.

The various costs considered in the component commonality literature are purchase cost, holding cost and shortage cost. Most models considered the price of components when the objective was cost minimization or profit maximization. Holding cost or inventory carrying cost included the material handling and storage cost, opportunity cost of locked capital, insurance, taxes, and cost of obsolescence, deterioration and additional staffing. A shortage cost is incurred when the product demand cannot be met due to stock-out of one or more components. Ordering or fixed setup costs incurred to either procure or produce component.

The most common service metric used in component commonality studies that modeled a service constraint is the order fill rate, defined as the probability of no stock-out during a replenishment cycle. It is also called cycle fill rate or α – service level. This metric could be applied to individual product or, simultaneously, to all products. Product specific and aggregate service levels are reported in literature. Other popular service metrics in inventory literatures are (Schneider, 1981): item fill rate (β – service level) which is the fraction of the demand satisfied (not lost or backordered from stock) and γ – service level which is the mean cumulative fraction of demand satisfied each period.

Parts commonality is a neglected topic in most of the studies in milieu of manufacturing. Many advantages of parts commonality in the manufacturing and inventory systems are reported as well as number of models are proposed/developed. Most of the mathematical models studied earlier hardly considered two-stage cases with single common component. Therefore, developments of mathematical model to study the effects of commonality in the multiple-stage systems with multiple products and multiple common items are still remaining in the virgin area of research.

Uncertainty is another issue that was completely ignored in the models of commonality. However, in some models products demand distributions are considered as stochastic, but they treated it as an independent variable. Assimilation of other uncertainty factors (like lead time, workforce, quality etc.) in commonality model demands further research. Experiments and empirical studies in this fissure also need further attention.

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