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ANALYSIS OF DESIGN FOR GLOBAL MANUFACTURING GUIDELINES

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ABSTRACT

Globalization is motivated by the potential for cost reduction through access to lower labor costs, as well as by the potential for increased sales through access to new markets. A review of cost data indicates the potential savings related to labor as compared to the potential additional costs related to raw materials, shipping, and tariffs. A logistics cost model is then presented that considers purchase cost, shipping cost, inventory holding cost, order cost, and stock out cost subject to demand uncertainty. Four different design for manufacturing and assembly (DFMA) guidelines are then analyzed: 1) minimize total shipping costs, 2) source components globally, 3) standardize product platforms and modularize options; and 4) regionalize final assembly. The results of this case study indicate that global sourcing of components led to the most significant cost reductions, but that all guidelines were significant when considering logistics subject to uncertain demand.

1 INTRODUCTION

The continued development and proliferation of technology has facilitated globalization. Consider manufacturing strategies in different technological eras:

- Before 1400: Transportation was primary on land routes, as for example the silk road. Long delay times and significant expenses made global exchange of goods and information only profitable for high priced, compact, and durable goods as for example silk, precious metals, spices, and gems, affordable only to the wealthiest of the time. Knowledge was if at all usually transported in written form.
- Since 1400: The advent of sailing ships reduced the transportation cost and time by allowing sea routes to access new land and to avoid land routes. This also allowed the exchange of knowledge, since knowledge transfer was now not only limited to written form, but experts were able to travel to foreign countries in greater numbers. Nevertheless, still relatively slow and costly transportation prohibited the trade of non-durable, with much trade still centered on compact durables such as precious metals, furs, and spices. Manufacturing was accomplished through local craftsmen with broader demand around cities supported by cottage industries.
- Around 1900: Railroads enabled distribution of many goods across great land distances, with the development of regional specialized economies such as agriculture, cabinetry, steel, etc. The decrease in logistics cost opens the global market also to the middle class, hence increasing the market volume. Manufacturing increasingly accomplished through vertical integration in large corporations.
- Around 2000: Sustained technological improvements and cost reductions in both transportation and communication facilitate the implementation of globally efficient supply chains, with design and manufacturing accomplished in a distributed network of suppliers chosen to maximize benefits and minimize costs. Global products are now widely affordable, therefore also increasing the need for transportation. Information exchange is almost instantaneous, thereby also reducing uncertainty about product availability, price, and quality.

Today’s level of globalization is not an outcome of governments unilaterally mandating international trade. Rather globalization is the result of many different corporations independently and rationally choosing to globally source and sell their products to increase their economic advantage. There is a significant literature on the development of global supply chains. Handfield [1] indicates that in many corporations the international procurement decision begins as a strategic process ranging from: a) initially, foreign buying is solely a response to a need which cannot be met from domestic sources, to b) ultimately, purchasing develops a proactive inclusion of international sources to maximize buying leverage while serving foreign markets. This type of decision making is analyzed by Antràs [2], who developed a equilibrium model for disintegration. Baily [3] and Kobrin [4] performed empirical analyses to identify the drivers for global integration in different industries; Suh [5] describes how continuing cost and quality pressures drive the outsourcing to China from Korean automobile manufacturers.

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Design for manufacturing and assembly guidelines have been developed to assist product designers to develop higher quality and lower cost products independent of any global sourcing strategy; Dean and Salstrom [6] provided an assessment of the use of DFMA techniques via industry surveys. A recent review of the “state of the art” in DFMA was given by Vliet [7]. Gupta et. al. [8] provided a survey of current state of the art in automated manufacturability analysis including support tools to enhance manufacturability analysis. Kuo [9] provides a review of design for manufacturing along with life cycle design while Amezquita [10] provides a discussion of remanufacturing. Xie [11] provides a review of many such systems that may be used for mass customization in a distributed development environment. Zhang [12] discusses a similar system for optimal concurrent design in a distributed product development cycle. Chincholkar [13] discusses design for production tools to improve product design. Hernandez et. al. [14] provide a method for production modeling and evaluation in a series of products, including the issue of variation in quality. All of these works provide good guidance related to DFMA, but provide little support for global sourcing and logistics.

Krishnan and Ulrich [15] review key product development decisions, including concept design, product design, supply chain design, and project management. One recurring issue is the uncertainty in the demand for a product mix under relatively long lead times in a global supply chain. As lead times increase, the ability to meet demand decreases. In turn, there can be great variance in order quantities, now named as the “bullwhip” effect by Lee [16]. Qureshi [17] discusses the needs to provide product flexibility to meet varying competitive pressures and customer demands. Lee [18] discusses product localization in the context of global development, and compares build to order with build stock strategies.

These business and engineering literatures do not strongly overlap. Perhaps one area of confluence is operations management, which provides rigorous decision support for manufacturing and logistics. In this paper, an inventory (Q) reorder point (R) model (Q,R) is developed to assess the import of four design for manufacturing and assembly guidelines:

1. minimize total shipping costs;
2. source components globally;
3. design product platforms with standard components and modular options, and
4. regionalize final assembly.

Before presenting the model and analysis, however, an assay of current global manufacturing statistic is provided.

2 GLOBAL MANUFACTURING STATISTICS

2.1 Labor

The U.S. Department of Labor has statistically characterized labor costs both domestically and abroad [19]. Table 1 lists the national average hourly salary for various manufacturing personnel in the U.S.; this data is solely the hourly wage to the employee and does not represent the total cost to the employer, which would also include health care cost, pension, etc. As should be expected, the wage varied by level of education or skill associated with the position. While not listed in Table 1, the Department of Labor also provides wage data by geographic region within the United States and years of experience.

Table 1: Average U.S. wage by position

Position	Average Wage (US$)
Mechanical engineer	31.88
Tool and die maker	23.94
Precision machine assemblers	20.65
Machinist	19.93
Tool and die maker apprentice	17.92
Lathe setup operator	17.41
CNC Milling operator	16.82
Milling machine operator	16.14
Lathe operator	15.88
Drilling operator	14.21
Machinist apprentice	13.96
Buffing and polishing operator	13.52
Molding machine operator	13.41

Table 2 provides the average wage across all manufacturing personnel for several different nations. As expected the manufacturing wages are highest in the most developed nations, and lowest in the least developed nations. With regard to China, the U.S. Federal Reserve estimated the annual salary of urban workers to be 6,850 Yuan per year in 2003, corresponding to an hourly wage of about $0.43; personal interviews with factory staff in 2005 indicate that the average hourly wage in China is about to $1.00, with engineering wages around $3.00 per hour. This also differs regionally, with highly developed regions near the coast sometimes approaching western wage levels, whereas the underdeveloped hinterland has very low wages and labor skills.

Table 2: Average manufacturing wage by nation [19]

Americas	Compensation (U.S. $)
United States	23.17
Brazil	3.03
Canada	21.42
Mexico	2.50
Asia and Oceania	
Australia	23.09
China	1.00 [20]
Hong Kong	5.51
Israel	12.18
Japan	21.90
Korea	11.52
New Zealand	12.89
Singapore	7.45
Taiwan	5.97
Europe	
Austria	28.30
Belgium	29.99
Czech Republic	5.43
Denmark	33.75
Finland	30.67
France	23.89
Germany	32.52
Hungary	5.72
Ireland	21.94
Italy	20.47
Luxembourg	26.57
Netherlands	30.76
Norway	34.64
Portugal	7.03
Spain	17.10
Sweden	28.42
Switzerland	30.26
United Kingdom	24.71

2.2 Shipping

The cost of shipping miscellaneous goods via various methods from Hong Kong to Los Angeles is provided in Table 3. The majority of cargo is sent via standard shipping containers that are adaptable to ocean, rail, and truck transportation [21]. While specifications can vary somewhat, a standard container is called a twenty foot equivalent unit or “TEU” with a maximum cargo mass and volume of 17,500 kg and 28 m^3, respectively. For products that have a relatively low density, forty foot containers can be more economical with a maximum cargo weight of 24,000 kg and maximum cargo volume of 58 m^3. Air freight is also available, with the cost per unit of mass exceeding the cost per unit volume. The costs of transporting cargo by truck and rail in the U.S. and China are also provided in Table 3.

Table 3: Shipping cost

Shipping Method	**Time (days)**	**Cost per 1000 kg**	**Cost per 1 m^3**
20’ Container [22]	35	144	104
40’ Container [23]	35	133	63
Air freight	3	6750 [24]	1320 [25]
Trucking (US) [22, 26]	N/A	0.3/km	0.12/km
Trucking (China) [27]	N/A	0.1/km	0.04/km
Rail (US) [26]	N/A	0.07/km	0.03/km
Rail (China) [27]	N/A	0.02/km	0.008/km

2.3 Commodity Costs

Some data for various commodities are provided below in Table 4. It is observed that China has a significant advantage on all commodity prices except electricity. In China, there is a shortage of power generating facilities and so the Chinese government regulates a high cost of electricity in an attempt to reduce demand. For this reason, many if not most large manufacturers use on-site generators to increase the reliability and productivity of their operations albeit with increased emissions [28].

Table 4: Commodity costs

	US	China
Electricity ($/kwh)	0.093 [29]	0.32 [30]
Natural gas ($/MMBtu)	7.40 [29, 31]	4.00 [32]
Steel ($/HRB ton)	573 [33]	423 [33]
Cement ($/P425 ton)	75	42.5
Polypropylene ($/IM ton)	1555	1390
Land ($/industrial m^2)	110	58.2

2.4 Operating Costs

Some data are provided below.

Table 5: Business overhead costs

	US	China
Top tax rates (%)	35	33
Indirect cost rates (%)		
Profit Margin (%)		

2.5 Tariffs

The import duties for various items entering the US [34] and China [35] are shown in Table 6. In principle, governments set tariff rates to control industry development. The data in Table 6 indicates that both China and the US generally assess higher duties on finished and technological goods than commodity components and raw materials. By comparison, the import duties for China are significantly higher than the US, but have been consistently declining over the past decade.

Table 6: Selected tariff rates

Product Classification	US Duty	China Duty
3902 Propylene polymers	6.5%	10%
3923 Plastics packaging	3.0%	12%
8528 Molded enclosures	3.5%	30%
7308 Steel structures/plates	Free	8.4%
8418 Refrigerators	Free	15%
8501 Electric Motors	4%	24.5%
8532 Capacitors	Free	Free
8541 Diodes, transistors, etc.	Free	Free
8542 Integrated circuits	Free	Free
8703 Motor vehicles	2.5%	25%
9501 Wheeled Toys	Free	7%
9502 Dolls	Free	7%
9503 Other Toys	Free	7%

3 COST/TIME ANALYSIS

Assume that there is an expected demand rate, λ, for a family of products subject to demand variation, σ, which may be assumed Gaussian or some other distribution. The goal of the analysis is to assess the total cost and lead time for the family of products that is globally sourced.

Most products in a product platform have a similar design architecture and supplier network. As such, it is assumed that the cost and lead times of the different members of the product family may be analyzed in parallel with the same model structure and coefficients, albeit with separate demand rates, λ_i, and demand variances, σ_i.

3.1 Global Cost

The cost models are extended from operations analysis for inventory control subject to uncertainty [36]. The demand rate and variance for a given component, j, can be estimated as:

$$\begin{aligned} \lambda_j &= \sum\nolimits_{i=1}^{m} \lambda_i \cdot N_{ij} \\ \sigma_j &= \left(\sum\nolimits_{i=1}^{m} \lambda_i \cdot N_{ij} \cdot \sigma_i^2 \right)^{\frac{1}{2}} \end{aligned} \qquad (1)$$

where N_{ij} is the number of j components required for product i, and m is the number of products in the product platform.

3.1.1 Purchase Cost

The annual purchase cost of a component or assembly is assessed as:

$$G_j^{Purchase} = \kappa_j \left(Q_j, S_j \right) \lambda_j \left(1 + \upsilon_j \right) \qquad (2)$$

where κ is the acquisition cost per unit, including the purchase and shipping costs, which is a function of the supplier, S, the order quantity, Q, and the shipping method, M. After purchase and transport, the products may be subjected to a tariff rate, υ, as previously discussed with respect to Table 6.

3.1.2 Shipping Cost

The cost to ship a component or assembly is estimated as:

$$G_j^{Shipping} = \min \begin{bmatrix} \max\left[\frac{\partial C_{TEU}}{\partial M} M_j, \frac{\partial C_{TEU}}{\partial V} V_j \right] \\ \max\left[\frac{\partial C_{Air}}{\partial M} M_j, \frac{\partial C_{Air}}{\partial V} V_j \right] \end{bmatrix} + C_{Land} \qquad (3)$$

where C_{Air} and C_{TEU} are the cost models for air freight and ocean freight by TEU, M is the mass, V is the volume, and C_{Land} is the additional cost for overland freight. Recent coefficients for the shipping cost models are provided in Table 3. It can be observed that the ocean and air freight will dominate until overland distances exceed 2000 km for rail and for trucking in the US.

3.1.3 Inventory Cost

The cost of holding inventory can represent a significant portion of the product cost, especially when high cost components are shipped via ocean freight. In most inventory control systems, the order quantity, Q, and the reorder point, R, are selected to avoid inventory depletion. Given a demand rate, λ, and a lead time τ from a supplier, S, with shipping method, M, the inventory holding cost for an item, j, is:

$$G_j^{Inventory} = h_j \left(Q_j / 2 + R_j - \lambda_j \tau_j \left(S_j, M_j \right) \right) \qquad (4)$$

where h is the holding cost per unit. In many applications, the holding cost is assessed at the purchase cost of the component times an annual interest rate, which is usually between 15% and 50%, depending on the company policy and longevity of the component.

3.1.4 Order Cost

The cost of placing orders may be significant. The annual number of orders to be placed is:

$$n_j^{orders} \left(Q_j \right) = \lambda_j / Q_j \qquad (5)$$

For an order cost, K, the annual expected ordering cost is:

$$G_j^{Order} = K_j \, \lambda_j / Q_j \qquad (6)$$

3.1.5 Stock Out Cost

In the event of inventory depletion, there may be different penalties assessed dependent upon the nature of the depleted component. If the component, such as a fastener, can be readily acquired, then the penalty cost may, for example, include the 1) cost of purchasing the component from a different supplier at a higher cost, 2) the cost of expediting the acquisition of the component by personal transport or air carrier, and 3) the cost of overtime and other factory resources to make up for lost production time to meet the demand rate. If, however, the component is unique, then the shortage of the component will result in a shortage of the finished product. In this case, the penalty cost may include: 4) the loss in profit due to the lost sales as well as 5) the loss in future profits due to loss in goodwill or future sales.

The cost of inventory depletion is estimated as:

$$G_j^{Penalty} = p_i n_i \left(R_j \right) \lambda_j / Q_j \qquad (7)$$

where p_i is the penalty cost associated with a shortage in the supply of product i, and n_i is the expected demand shortage in product i occurring per order cycle for component j. Assuming a Gaussian distribution in the demand of product i with a demand variance of σ_i, the expected demand shortage is:

$$n_i = \sigma_i L\left(\frac{R_j - \lambda_j \tau_j}{\sigma_j}\right) \qquad (8)$$

where L is the partial expectation function defined as:

$$L(z) = \frac{1}{\sqrt{2\pi}}\exp\left(-0.5z^2\right) - z\left(1-\Phi(z)\right) \qquad (9)$$

It should be noted here that in a product family, demand rates (λ_i, σ_i) will vary by product member and give rise to different rates of demand (λ_j, σ_j) for the underlying components. Clearly, the supplier, S_j, shipping method, M_j, order quantity, Q_j, and reorder point, R_j, must be selected to provide a minimum total product cost without holding an excess of inventory in the supply chain.

3.2 Global Lead Time

The lead time for ordering a component j is:

$$\tau_j = \tau_0\left(\Gamma_j, S_j\right) + Q_j \gamma_j\left(S_j\right) \qquad (10)$$

Here, τ_0 is the minimum lead time for the component given the supplier, S, and the shipping method, Γ. There is also a marginal term that increases the lead time based on the order quantity, Q, and the supplier production rate, γ. It should be noted that the same form of the lead time may be used for internal assembly operations.

The total lead time for a product is:

$$\tau^* = \sum_{k=1}^{o} \tau_k(Q) \qquad (11)$$

where k is an index across the o critical jobs [37] in the project schedule required to produce the product family members.

4 DESIGN GUIDELINES

Some guidelines will now be provided with appropriate analysis. Consider the hypothetical design of a fourth generation gaming console for which a simplified assembly sequence is shown in Figure 1. As shown, the product's manufacturing and assembly consists of:

A. Procuring the plastic housing;
B. Procuring the PCB motherboard;
C. Procuring the CPU;
D. Assembling the above items;
E. Procuring one of two different types of kitted peripherals; and
F. Packaging and shipment of two different products.

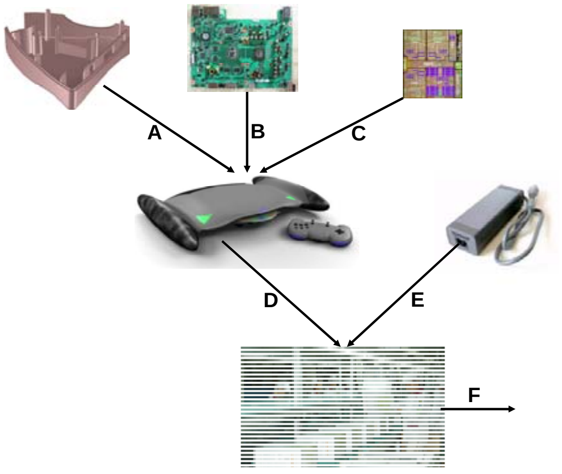

Figure 1: Assembly sequence

To exemplify the analysis, we assume these steps can be executed solely in the US and/or China. Some estimated costs and the associated mass and volume of the resulting components are provided in Table 7. In this case study, the CPU can only be procured from the US while the peripherals can only be procured from China. These restrictions emulate the lack of component availability due to technological or cost limitations.

The expected demand rates and variances for the two products are provided in Table 8; subsequent analysis will assume that the penalty cost for a stock out is $100 per unit of unmet demand. The cost of placing an order is also set to $100, which is necessary to avoid the analysis driving the economic order quantity to 0. This order cost assumption has a small effect when order volumes are high and the price per component is set by contract. To assess holding cost, an interest rate of 30% is applied to the value of the inventory, which also equals the net profit margin of one seller of gaming consoles.

Table 7: Product sourcing options

	US			China		
Step	Cost ($)	Mass (g)	Vol (cc)	Cost ($)	Mass (g)	Vol (cc)
A. Housing	6	300	2000	4	300	2000
B. PCB MB	15	300	600	11	300	600
C. CPU	80	20	50	N/A	N/A	N/A
D. Assembly	8	620	3000	4	620	3000
E1. Option 1	N/A	N/A	N/A	20	1000	3000
E2. Option 2	N/A	N/A	N/A	40	2000	6000
F1. Box 1	8	2000	15000	4	2000	15000
F2. Box 2	8	3000	15000	4	3000	15000

Table 8: Product demand

	US		China	
Option	Annual Demand Rate (MM/yr)	Weekly Demand Variance (K/week)	Annual Demand Rate (MM/yr)	Weekly Demand Variance (K/week)
Box 1	4	80	2	40
Box 2	4	80	1	20

4.1 Shipping Method

Assume that the supplier for a component is selected, and the price of the component is independent of the shipping method. Then a rule for shipping is that **the shipping cost should be selected that minimizes the total inventory and shipping cost**. While ocean freight is significantly cheaper than air, the previously described analysis will take the cost of long lead times into account by increasing the reorder point to account for demand uncertainty during the component's shipment.

Specifically, the optimal order quantity is:

$$Q^* = \sqrt{\frac{2\lambda\left(K + p \cdot n(R)\right)}{h}} \qquad (12)$$

To demonstrate the analysis for one component, let us examine the $4.00 housing made in China to be imported into the US. In this instance, the economic order quantity is:

$$Q^* = \sqrt{\frac{2 \cdot 8 \cdot 10^6 \, housings/yr \cdot \left(\$100/stockout \cdot n(R)\right)}{30\%/yr \cdot \$4.00}} \qquad (13)$$

The number of stock outs is, $n(R)$ is effected by the lead time demand and the lead time demand variance as [38]:

$$n(R) = \left(\sigma\sqrt{\tau}\right) L\left(\frac{R - \lambda\tau}{\sigma\sqrt{\tau}}\right) \qquad (14)$$

The number of stock outs is a function of the reorder point, R. Economics dictates that the reorder point should be selected to balance inventory costs with penalty costs related to stock outs. This objective can be achieved by selecting the reorder point such that:

$$1 - F(R) = \frac{Qh}{p\lambda} \qquad (15)$$

where F is the inverse normal cumulative distribution function of the critical ratio between the cost of holding inventory and the cost of stock outs. Iteration is required until the economic order quantity and the reorder point converge.

Using the previously described analysis with the data included in this paper, a comparison of ocean (TEU) and air shipping methods for the housing and CPU are respectively provided in Table 9 and Table 10. In both cases, the use of air freight provides for a lower order quantity, reduced lead time, and hence reduced penalty costs. However, the preferred shipping method varies by component, and for a surprising reason. One might expect that the inventory holding costs make ocean shipping undesirable for high cost components, such as the CPU. However, the analysis demonstrates that the inventory levels in this case are dominated by the reorder point necessary to avoid excessive stock outs. As such, the inventory costs here due not determine the selection of shipping method. Instead, it is the high order quantity and long lead time of the ocean freight for the CPU that increases the penalty costs enough to make the air freight preferable as shown by the bottom line in Table 10. The underlying reason is the scaling [38] of the demand and demand uncertainty with lead time, which can lead to a “bull whip” effect on supply chain inventories as elsewhere discussed in the operation research literature [16].

Table 9: Shipping cost comparison – housing

	Ocean (TEU)	**Air**
Order Quantity	493,763	42,817
Reorder point	1,679,646	660,735
Stock out per order	132.0	0.00000
Average inventory	657,297	470,605
Inventory costs	$788,756	$564,726
Penalty costs	$294,030	$0
Shipping costs	$2,288,000	$29,040,000
Total logistics cost	$3,370,786	$29,604,726

Table 10: Shipping cost comparison – CPU

	Ocean (TEU)	**Air**
Order Quantity	160,506	9,574
Reorder point	1,644,801	637,712
Stock out per order	280.0	0.00000
Average inventory	455,823	430,961
Inventory costs	$10,939,751	$10,343,066
Penalty costs	$1,919,223	0
Shipping costs	$57,200	$1,485,000
Total logistics cost	$12,916,174	$11,828,066

4.2 Global Sourcing

Assume a competitive market in which all competitors have access to the same network of characterized suppliers; the term “characterized” means that the performance and cost of the supplier components is known by the system integrators. Then, a rule for global sourcing suggests that **components should always be sourced globally to provide minimum total product costs**. While this rule suggests a pure cost basis for decision making, it is possible to include penalty costs to model the loss in profit due to potential adversities such as reduced product quality and lost sales volume due to selection of the low cost supplier. A properly developed economic model should suggest that the selection of a global supplier based purely on lowest component costs can be undesirable when:

- Long lead times incur high holding costs due to necessarily high reorder points (required to avoid lost sales due to demand variance);
- Long lead times incur high penalty costs due to high uncertainty in demand (in which the previously high inventory was consumed and the sales channels were starved);
- Lack of supplier control may permit the unintended disclosure of product specifications, product technology, or sales information to competitors; or
- The technological capability or product quality of suppliers is uncertain, and this uncertainty may contribute to the commercial failure of the finished products.

The impact of global sourcing can be demonstrated using the case study. Figure 2 provides a graph of all the sourcing alternatives, as well as the graphs corresponding to “Made in the USA” and “Made in China.” These latter two graphs are logical outcomes of supply chain designs that attempt to minimize cost, lead time, and inventory levels through the selection of available local suppliers.

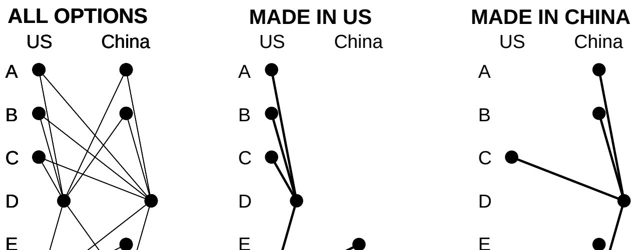

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Figure 2: Sourcing alternatives

Applying the previously described analysis, the impact of global sourcing can be demonstrated using the case study. Here, the analysis was performed for all product mixes according to the demand schedule of Table 8. It should be noted that when production of multiple products share components, the demand variance is pooled across the demand of all products per the moment matching method.

Table 11 provides the logistics breakdown when all products are produced in the US; Table 12 provides similar data for the products made in China.

Table 11: Cost of all products made in the US

	US Consumption			China Consumption		
Component	All but E1/2	E1	E2	F1	F2	Total
Made At	US	China	China	China	China	N/A
Weekly Demand	211,538	115,385	96,154	38,462	19,231	N/A
Weekly Variance	60,828	63,246	58,310	40,000	20,000	N/A
Purchase cost/unit	117	20	40	137	157	N/A
Shipping cost/unit	0.000	0.312	0.624	1.560	1.560	N/A
Freight Method	N/A	TEU	TEU	TEU	TEU	N/A
Order Quantity	7,917	712,014	536,245	270,527	128,493	N/A
Reorder point	634,633	962,716	803,114	332,946	165,624	N/A
Stock out per order	0	2534	3450	7519	3887	N/A
Average inventory	427,053	626,416	494,313	237,440	114,486	N/A
Purchase costs	1,287,000,000	120,000,000	200,000,000	N/A	N/A	1,607,000,000
Inventory costs	14,989,560	3,758,494	5,931,759	9,758,797	5,392,274	39,830,883
Penalty costs	0	2,135,200	3,216,537	5,558,591	3,025,230	13,935,558
Shipping costs	0	1,872,000	3,120,000	3,120,000	1,560,000	9,672,000
Tariff costs	0	0	0	10,960,000	6,280,000	17,240,000
Total costs	1,301,989,560	127,765,694	212,268,295	29,397,388	16,257,503	1,687,678,441

fraction of purchase costs out of total costs 95.22%

Table 12: Cost of all products made in China

	China Consumption			US Consumption		
Component	C	All E1 but C	All E2 but C	F1	F2	Total
Made At	US	China	China	China	China	N/A
Weekly Demand	211,538	115,385	96,154	76,923	76,923	N/A
Weekly Variance	60,828	63,246	58,310	80,000	80,000	N/A
Purchase cost/unit	80	43	63	123	143	N/A
Shipping cost/unit	0.135	0.000	0.000	1.560	1.560	N/A
Freight Method	Air	N/A	N/A	TEU	TEU	N/A
Order Quantity	9,574	9,647	7,280	563,592	532,335	N/A
Reorder point	637,712	454,056	393,764	668,529	664,834	N/A
Stock out per order	0	0	0	14650	15195	N/A
Average inventory	430,961	343,495	301,250	488,787	469,463	N/A
Purchase costs	880,000,000	258,000,000	315,000,000	N/A	N/A	1,453,000,000
Inventory costs	10,343,066	4,431,079	5,693,633	18,036,224	20,139,968	58,643,971
Penalty costs	0	30	122	10,397,563	11,417,845	21,815,560
Shipping costs	1,485,000	0	0	6,240,000	6,240,000	13,965,000
Tariff costs	0	0	0	19,680,000	22,880,000	42,560,000
Total annual costs	891,828,066	262,431,109	320,693,755	54,353,787	60,677,813	1,589,984,531

fraction of purchase costs out of total costs 91.38%

It is observed that when the products are made in the US, the cost of all products is approximately 1.69 billion dollars, with the purchase cost of the products representing over 95% of the product costs. By comparison, the same products made in China would cost only 1.59 billion dollars, saving the original equipment manufacturer one hundred million dollars. Is should be noted that the fraction of the components' costs decreased due to significant increases in the inventory costs and penalty costs associated with the cost and delays of air shipping CPUs from the US and ocean shipping finished boxes back to the US. Even so, the decision to make the products in China would result in a 6% reduction in costs.

The above results and associated issues are highly representative of other outsourcing studies [39]. In this example, the cost reductions may not seem worth the added risk of implementing a global supply chain. In many cases, the component costs for parts made in China may be significantly less than what is suggested in this example. In other cases, the cost savings may be marginalized by fluctuations in currency or tariff rates. In yet other cases, the motivation for global sourcing may not be cost reduction but rather entry to foreign markets restricted by foreign corporations. In most large product development efforts, the decision to outsource will have political and tax ramifications. As such, the decision to globally source components has long term consequences, especially when capital expenditures are required to enable overseas manufacturing operations.

4.3 Standardization/Modularization

Design for manufacturing guidelines suggest that standard components should be utilized when custom components do not add significant value. With respect to global manufacturing and assembly of products, **components in a product platform should be standardized across different members of a product family**. Differentiation of products in a product mix is often accomplished by:

- Low cost physical components to provide aesthetic differentiation or localization. Examples may include instruction manuals, face plates, etc.;
- Higher cost physical components or modules to provide different levels of performance. Examples may include print cartridges for different print qualities in printers, engines/interiors in vehicles, etc.; or
- Software modules to control electromechanical functions. Examples may include language selection, print density on printers, emission control systems on cars, etc.

There are several benefits to this approach. First, standardization of components across a product platform reduces the total number of components to be designed and thus the total development cost of all products. Second, the use of standard components allows higher quantities of fewer components to be purchased, which can result in volume discounts and also lower inventory management costs. Third, the use of standard components enables the pooling of demand variance across multiple products in the products platform mix.

The foregoing analysis can be used to analyze the effect of standardization on total product cost. Here the analysis assumes that there are four discrete products corresponding to products F1 and F2 being released to the US and China markets. The analysis will also assume that the cost of all components in the four products is the same as that of the previously described products that share components as specified in Table 7. As such, this analysis focuses solely on logistics cost and does not consider changes in the product development cost or volume pricing.

Table 13 lists the total cost of producing four discrete products, assuming a lead time of 1 week within China for the procurement of local components. This cost structure can be compared directly to the results of Table 12 corresponding to the two product mix with standard components. It is observed that the purchase costs of the components are identical, but the inventory and penalty costs have increased. The reason is that the disaggregation of the component demands has simultaneously resulted in lower weekly demand and a higher weekly order variance.

Table 13: Cost of all custom products made in China

	China Consumption					US Consumption		
Component	C	US/E1-C	US/E2-C	China/E1-C	China/E2-C	F1	F2	Total
Made At	US	China	China	China	China	China	China	N/A
Weekly Demand	211,538	76,923	76,923	38,462	19,231	76,923	76,923	N/A
Weekly Variance	60,828	80,000	80,000	40,000	20,000	80,000	80,000	N/A
Purchase cost/unit	80	43	63	43	63	123	143	N/A
Shipping cost/unit	0.135	0.000	0.000	0.000	0.000	1.560	1.560	N/A
Freight Method	Air	N/A	N/A	N/A	N/A	TEU	TEU	N/A
Order Quantity	9,574	8,180	6,831	5,736	3,352	563,592	532,335	N/A
Reorder point	637,712	431,154	426,783	211,896	102,928	668,529	664,834	N/A
Stock out per order	0	0	0	0	0	14650	15195	N/A
Average inventory	430,961	358,321	353,276	176,302	85,373	488,787	469,463	N/A
Purchase costs	880,000,000	172,000,000	252,000,000	86,000,000	63,000,000	N/A	N/A	1,453,000,000
Inventory costs	10,343,066	4,622,335	6,676,913	2,274,300	1,613,553	18,036,224	20,139,968	63,706,359
Penalty costs	0	3,856	6,002	2,135	1,849	10,397,563	11,417,845	21,829,251
Shipping costs	1,485,000	0	0	0	0	6,240,000	6,240,000	13,965,000
Tariff costs	0	0	0	0	0	19,680,000	22,880,000	42,560,000
Total costs	891,828,066	176,626,192	258,682,915	88,276,435	64,615,402	54,353,787	60,677,813	1,595,060,610

At first, the total “bottom line” cost for the two different product platforms may seem insignificantly different. The are many arguments to the contrary, however. First, the difference is already over five million dollars, which is significant relative to the engineering expense. Second, these cost differences consider only the logistics costs and are truly conservative since they do not consider potential saving associated with the pooling of product development efforts or cost reductions due to volume discounts. Third, these results correspond to a lead time of only one week and the cost differences will increase significantly with increases in lead times; to quantify this effect, the lead times were varied in the analysis to obtain the results shown in Figure 3. It is observed that costs increase and diverge since an increased lead time increase the demand uncertainty, the inventory reorder point, the inventory level, the inventory holding costs, and the penalty costs due to stock out.

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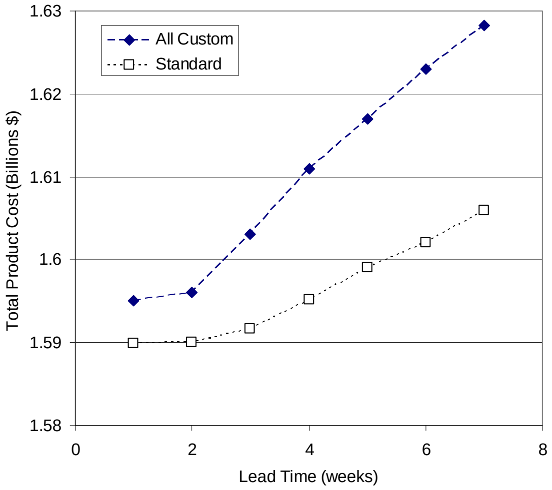

Figure 3: Sourcing alternatives

4.4 Final Regional Assembly

In the previous examples, the product was assembled in either the US or China, and subsequently shipped as a finished good to the market where it was not produced. However, guidelines for mass customization suggest that **the best product and supply chain design uses final assembly to provide mass customization and localization to the regional markets**. Some of the typical customizations provided during final assembly include:

- Incorporation of physical modules that modify the performance of the product according to local market demands and/or government regulations;
- Software programming to enable or disable product features, or to specify the language of the operating interface;
- Bundling of the product with other region-specific products; and
- Packaging and labeling of sealed boxes for regional distribution.

There are several advantages for regional final assembly. While not a requirement, the final assembly usually operates with a standard product platform into which modular options are integrated. As such, the first benefit of final regional assembly is the aggregation of demand for the product platform, which will tend to reduce purchasing and logistical costs. Second, the supply chain "tact time" and logistical costs can be significantly reduced when the product platform is shipped in high volumes and the lower cost (and hopefully smaller) product modules may be sent via air freight at relatively low cost. As a result, very large demand fluctuations across the product mix may be managed. Finally, the importation of lower cost components will usually reduce the tariff costs compared to the importation of finished goods for two reasons: a) the valuation of the components is less than that of the finished goods and so provides a lower basis for the application of the tariff, and b) the tariff rate on components is often lower than finished goods to encourage regional manufacturer development.

The analysis was again applied to estimate the cost reduction associated with regional assembly of the finished product. The results of the analysis are provided in Table 14. Specifically, all product platforms with the exception of the CPU and peripheral options (E1 and E2) are made in China. Only those CPUs incorporated into the products to be released to China are shipped to China and incorporated with E1 and E2. The partially assembled product platforms are then sent by TEU to the US separately from peripheral options E1 and E2. The CPU and the peripherals are then assembled in the US for US distribution. The results of Table 13 can be compared to those of the previous analyses. It is observed that the costs associated with regional assembly are about fifty million dollars less than those costs associated with making the finished product in China as previously shown in Table 12.

Table 14: Cost of all regionally finished products

	China Consumption				US Consumption			
Component	All-C,E1/2	+C	+E1	+E2	All-C,E1/2	+C/E1	+C/E2	Total
Assembled at	China	China	China	China	China	US	US	N/A
Weekly Demand	211,538	57,692	38,462	19,231	153,846	76,923	76,923	N/A
Weekly Variance	60,828	31,623	40,000	20,000	56,569	80,000	80,000	N/A
Purchase cost/unit	23	80	20	40	23	80/20	80/40	N/A
Shipping cost/unit	0.000	0.135	0.000	0.000	0.270	0.312	0.624	N/A
Freight Method	N/A	N/A	N/A	N/A	TEU	NA/TEU	NA/TEU	N/A
Order Quantity	17,856	5,002	8,313	4,174	264,358	1,141,480	869,080	N/A
Reorder point	647,548	221,406	216,179	104,262	1,218,229	707,836	693,816	N/A
Stock out per order	0	0	0	0	825	9771	11329	N/A
Average inventory	444,937	166,215	181,874	87,118	427,331	817,037	666,818	N/A
Purchase costs	253,000,000	240,000,000	40,000,000	40,000,000	N/A	416,000,000	496,000,000	1,485,000,000
Inventory costs	3,070,066	3,989,159	1,091,245	1,045,417	8,076,565	4,902,225	8,001,816	30,176,493
Penalty costs	0	39	882	1,090	2,495,162	3,424,089	5,214,020	11,135,282
Shipping costs	0	405,000	0	0	2,160,000	1,248,000	2,496,000	6,309,000
Tariff costs	0	0	0	0	0	0	0	0
Total annual costs	256,070,066	244,394,198	41,092,127	41,046,508	12,731,726	425,574,314	511,711,836	1,532,620,775

The reduced costs stem from many sources, not including the purchase costs. In fact, the purchase costs increased due to the increase of four dollars per unit to perform step F of assembly in the US rather than in China (refer to Table 7). As such, the net cost savings are derived from:

- a $28,500,000 savings due to reduced inventory costs (associated with lower inventory levels and a lower value of the inventory due to exclusion of the CPU from the work in progress);
- a $10,700,000 savings due to the lower penalty costs of stock outs (associated with the aggregation of the product platform and greater availability of lower cost peripherals E1 and E2);
- a $7,700,000 savings due to lower shipping costs (associated with a) reduced volumes of air freight for the CPU, and b) lower TEU rates due to the lower cubic volume of the work in process as compared to a larger finished box); and
- a $42,600,000 savings due to the elimination of import tariffs (associated with a zero tariff rate for components and a 4% tariff rate for finished electrical consoles).

5 CONCLUSION

This paper provided four guidelines directed to design for global manufacturing and assembly. Models of the logistical costs associated with global supply chains were developed, including the purchasing cost, inventory holding cost, the ordering cost, shortage cost, and tariff cost. A detailed analysis of the effect of each design guidelines was demonstrated for a hypothetical gaming console that could be produced domestically or overseas. A comparison of the cost savings associated with the four guidelines is provided in Figure 4.

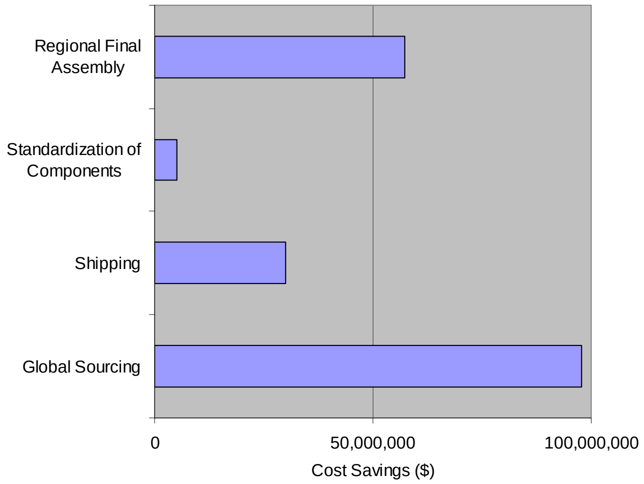

Figure 4: Sourcing alternatives

It appears that the global sourcing is most important to reduce product costs, followed by regional final assembly, optimization of shipping methods, and standardization of components. In total, the total cost savings through application of the design for manufacturing guidelines approached approximately 20% of the total product cost. These savings are significant in both relative and absolute terms, especially since these cost savings will bring about proportionally greater increases in the profit margins of the sold products. Furthermore, the parameters in the case study are conservative and underestimate the potential savings associated with the application of these guidelines. For example, the global sourcing of components may provide much lower costs than those suggested in this study. As another example, the standardization of components can yield cost savings associated with increased sales volumes as well as reduced product development costs.

The presented case study is relatively simple compared to the typical product and supply chain designs. However, the described model provides useful decision support for product design and procurement engineers. While the presented concepts and models have existed in different research literatures for some time, this paper has integrated the techniques to assess the value of design for manufacturing guidelines. There is no significant barrier to the adoption of these methods by design and manufacturing engineers to actively optimize the product and supply chain designs. Indeed, it is foreseeable that future product development environments will have access to cost models and supplier databases, facilitating the optimization of global manufacturing during and after product development.

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