Applied Mechanics and Materials Vols. 110-116 (2012) pp 258-266
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doi:10.4028/www.scientific.net/AMM.110-116.258

Models for Component Commonality in Multistage Production

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Keywords: component commonality; Mathematical model

Abstract. Use of common parts for different products (commonality) is important methods for managing product variety and preserving competitiveness in the age of mass customization and supply chain competition. In literature, the advantages of inclusion of common components in a product family are well established. Unfortunately, most of the works have been conducted via simulation or conceptual thinking. The mathematical models in the premises are not adequate for production, planning and control in multistage production. This paper focuses on the advancement of venerable manufacturing resources planning models by incorporating the part commonality concept in a multiproduct, multi-period and multistage manufacturing system under a deterministic situation. The models are validated with established MRPII models. The material requirement schedule for the basic MRP II and proposed models are compared. It is really a good matching shown between the two schedules. The later bearing additional information of the location where to be available the parts in a time frame. The effects of commonality on cost, capacity and requirement schedule are discussed based on the outcomes of the mathematical models executed with the available live data.

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 [1]. Commonality is the use of identical components in multiple/group of products in a product family. In manufacturing, component commonality refers to the use the same components for two or more products in their final assemblies. Commonality substantially lowers the costs of proliferated product lines, mitigate the effects of product proliferation on product and process complexity [2]. It reduces the cost of safety stock, decreases the setup time, increases productivity, and improves flexibility [3]. The required number of order (or setups) [4-5] pooling effect and lead time uncertainty are also condensed when part commonality is applied. Furthermore, it improves the economy of scale, simplify planning, scheduling and control, streamlines and speeds up product development process [6]. The details about the commonality, its measurements and models are narrated in Wazed et al.[7]. The commonality occurs in its own way in the system or can be planned for its preferred happening as well.

Nowadays, manufacturing companies need to satisfy a wide range of customer desires while maintaining manufacturing costs as low as possible, and many companies are faced with the challenge of providing as much variety as possible for the market with as little variety as possible between the products. Hence, instead of designing new products one at a time, many companies are now designing families. Hence, the component commonality has wide scope to penetrate in the manufacturing and thereby might allow cost-effective development of sufficient variety of products to meet customers' diverse demands. However, too much commonality within a product family can have major drawbacks. Consequently, there is a need of tradeoff between system performance and commonality within any product family.

MRP II is the widely used tool in the manufacturing. Even though the value of the MRP II that can bring to companies is clear, and a few will refuse its potential, numerous organizations have failed or are failing to apply effectively the advantages that this system can give. The same material requirement planning (MRP) logic is used in MRPII, enterprise resources planning (ERP) and extended ERP (ERP II) in their production-planning modules [8], thus their inability to cope and respond to uncertainty is still prevailing and the planned order release (POR) schedules are indifferent to those generated from an MRP system [9-10]. Enns [8] stated that MRP, MRPII or ERP is the ideal system within a batch-manufacturing environment. If resource loading and lead times are identical to those planned in the MRP systems, then the functions of such systems in planning and control will be ideal [11]. However, the production planning systems (viz. MRP, MRP II, ERP and ERP II) were designed and developed to operate within a stable and predictable batch manufacturing environment. Hence they are not capable of tackling uncertainty [12]. For details on the factors and sources of various uncertainties, the authors humbly like to refer the readers to Wazed et al. [13].

In earlier studies [2-4, 6-7, 14-20], the benefits of component commonality in the manufacturing systems associated with a decrease in inventory, lowers the costs of proliferated product lines, mitigate the effects of product proliferation on product and process complexity, reduce the cost of safety stock, decrease the set-up time, increase productivity, improve flexibility, permit greater operating economies of scale, facilitates quality improvement, enhance supplier relationship and reduce product development time, risk-pooling and lead time uncertainty reduction, simplify planning, schedule and control, streamline and speed up product development process, lowers the setup and holding costs, offer high variety while retaining low variety in operations, lower the manufacturing cost and design savings are obtained. However, the commonality issue is completely ignored in the existing manufacturing resource planning models. Furthermore, the analytical research on multistage manufacturing is very few in the present pool of knowledge. Hence, this article will advance the existing MRP II models by integrating component commonality concept.

Component Commonality Model

The component commonality models are developed from venerable MRP II models. This model is a useful starting point for further modeling. MRP II was inspired by shortcomings in MRP. The data requirements are nearly the same as for MRP.

Using classic MRP II software, problem MRP II would not be solved directly. Instead, problem MRP would be solved and then the capacity constraint for the MRP II model would be checked. In other words, the result of solving problem MRP provides values for the decision variables. Once these values are known, they become data for subsequent processing. Direct solution of the optimization model is a much better idea. In practice, the problem is bigger and harder to solve than the simple MRP II models that have presented. However, MRP II provides us with a good jumping off point for more sophisticated models because it mimics a widely used planning tool. We can and will embed these constraints in a model that captures costs and constraints that are important to the manufacturing organization or the supply chain. Especially the dashing thought of component commonality is to be incorporated.

Multistage Production Models in Deterministic Conditions

In this section we introduce a class of models that is based on the simplest assumption: demand, lead time, quality and breakdowns are deterministic and stationary. We concentrate primarily on the case where the information of the factors is constant and not anticipated to change. Although the assumption of deterministic and stationary factors seems quite restrictive, models requiring that assumption are still important for the following reasons. First, many results are quite robust with respect to the model parameters, such as the demand rate and costs. Second, the results obtained from these simple models are often good starting solutions for more complex models.

We consider an K-stage assembly/manufacturing line that produces $ENDP$ products as illustrated in Figure 1 (a- end product, b- component and c- manufacturing/assembly line). The production/assembly process of a product starts at stage 1. When a component moves along the line, component (module) is added onto it at some of the K stages. In general each production line is specified for a product if sharing of resources is not permitted. The resources are identified by the product, P it producing and stage, K of the system. Component C_{Pkit} is assembled to the product $i\,(i=1,..,N)$ in period $t\,(t=1,..,T)$ at resource $WC(P,K)$ $\;for\; P=1,..,ENDP \;\; and\; k=1,..,K$.

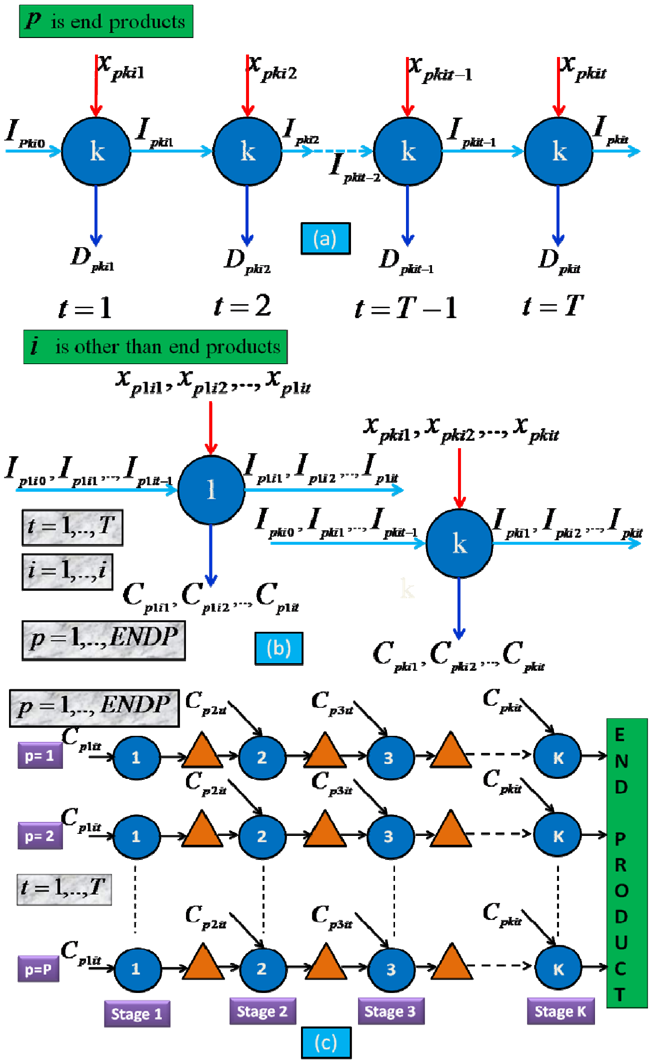

Figure 1. A multistage production system

We assume that components are purchased from external suppliers with deterministic replenishment lead-times. The lead-time is $LT(p,k,i)$ for component/module i at $WC(p,k)$. Based on the illustration, the demand and component requirement constraints can be written as

$$I_{pkit-1} + \sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau} - IP_{pkit} \ge D(p,k,i,t)$$

$$p=1,..,ENDP;\quad k=1,..,K;\quad i=p;\ t=1,..,T$$

$$I_{pkit-1} + \sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau} - I_{pkit} \ge \sum_{\tau=1}^{t}\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau} + IP_{pkit}\right)$$

$$p=1,..,ENDP;\quad i=1,..,N \setminus ENDP;\quad k=1,..,K;\quad t=1,..,T$$

$$C_{pkit} \ge \sum_{\tau=1}^{t}\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau} + IP_{pkit}\right)$$

$$p=1,..,ENDP;\quad i=1,..,N \setminus ENDP;\quad k=1,..,K;\quad t=1,..,T$$

The complete model for multistage system under ideal conditions is shown in Figure 2. Component purchasing cost, variable production cost and inventory costs for products and components and setup cost of the machines are taken into consideration.

Objective function

$$Minimize \quad z=\sum_{WC(P,K)}\sum_{I}\sum_{T}\left(v_i x_{pkit}+q_i I_{pkit}\right)+\sum_{WC(P,K)}\sum_{I}\sum_{T} f_{pk}\left(y_{pkit}-\gamma_{pkit}\right)+\sum_{WC(P,K)}\sum_{T} c_{WC} OT_{pkt}$$

Subject to

$$I_{pkit-1}+\sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau}-I_{pkit}\geq D(p,k,i,t) \quad p=1,..,ENDP; \quad k=1,..,K; \quad i=p; t=1,..,T$$

$$I_{pkit-1}+\sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau}-I_{pkit}\geq \sum_{\tau=1}^{t}\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau}+I_{pki\tau}\right)$$

$$p=1,..,ENDP; \quad i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$C_{pkit}\geq \sum_{\tau=1}^{t}\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau}+I_{pki\tau}\right) \quad p=1,..,ENDP; \quad i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$x_{pkit}-ny_{pkit}LS(i)=0 \quad p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$x_{pkit}\leq My_{pkit} \quad p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$LS(i)\leq My_{pkit} \quad p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

The capacity constraints:

$$\sum_{I}\left\{U(p,k,i)x_{pkit}+ST(p,k,i)\left(y_{pkit}-\gamma_{pkit}\right)\right\}-OT_{Pkt}+UT_{pkt}\leq 1 \quad p=1,..,ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$OT_{Pkt}\times UT_{pkt}=0 \quad p=1,..,ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$y_{pkit-1}+y_{pkit}\geq 2\gamma_{pkit} \quad p=1,..,ENDP; i=1,..,N; \quad k=1,..,K; \quad t=1,..,T$$

$$\gamma_{pkit}\leq MU(p,k,i) \quad p=1,..,ENDP; i=1,..,N; \quad k=1,..,K; \quad t=1,..,T$$

$$\sum_{i=1}^{N}\gamma_{pkit}\leq 1 \quad p=1,..,ENDP; k=1,..,K; \quad t=1,..,T$$

Non-negativity constraints:

All variables ≥ 0; $\quad y_{pkit}=\{0,1\}$; $\quad n=Integer$

Figure 2. Model for multistage system under deterministic situations

The third equation of the capacity constraints allow γ to be one for i on machine $WC(p,k)$ only if there is production of p in both periods. The fourth constraints ensure that we only set γ to one for i that are to be routed to machine $WC(p,k)$, which is done mainly to avoid spurious values of γ that can be confusing when reading the solution. The last constraints ensure that at most one product can span the time boundary on a specific resource $WC(p,k)$.

If backlog is allowed, the demand/component requirement constraints and the cost function will be change.

$$Minimize \quad z=\sum_{WC(P,K)}\sum_{I}\sum_{T}\left(v_i x_{pkit}+c_i C_{pkit}+q_i I_{pkit}+b_i B_{pkit}\right)+$$
$$+\sum_{WC(P,K)}\sum_{I}\sum_{T} f_{pk}\left(y_{pkit}-\gamma_{pkit}\right)+\sum_{WC(P,K)}\sum_{T} c_{WC} OT_{pkt}$$

Demand and component requirement constraints

$$I_{pkit-1}+\sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau}-I_{pkit}+B_{pkit}-B_{pkit-1}\geq D(p,k,i,t)$$
$$p=1,..,ENDP; i=p; \quad k=K; \quad t=1,..,T$$

$$I_{pkit-1}+\sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau}-I_{pkit}+B_{pkit}-B_{pkit-1}\geq$$
$$\sum_{\tau=1}^{t}\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau}+I_{pkit}+B_{pkit}\right)$$
$$p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$I_{pkit}\times B_{pkit}=0 \quad p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

When common component is introduced in manufacturing

$$I_{pkct-1}+\sum_{\tau=1}^{t-LT(p,k,c)} x_{pkc\tau}-I_{pkct}+B_{pkct}-B_{pkct-1}\geq$$
$$\sum_{\tau=1}^{t}\left[\sum_{j=1}^{N} R(c,j)\left(x_{pkj\tau}+I_{pkj\tau}+B_{pkj\tau}\right)\right]$$
$$p=1,..,ENDP; c=1,..,C; \quad k=1,..,K; \quad t=1,..,T$$

$$I_{pkit-1}+\sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau}-I_{ikt}+B_{pkit}-B_{pkit-1}\geq$$
$$\sum_{\tau=1}^{t-LT(i,k)}\left[\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau}+I_{pkj\tau}+B_{pkj\tau}\right)\right]$$
$$i\neq c; \quad p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$C_{ikt}\geq \sum_{\tau=1}^{t-LT(i,k)}\left[\sum_{j=1}^{N} R(i,j)\left(x_{pkj\tau}+I_{pkj\tau}+B_{pkj\tau}\right)\right] i\neq c;$$
$$p=1,..,ENDP; i=1,..,N\setminus ENDP; \quad k=1,..,K; \quad t=1,..,T$$

$$C_{ckt}\geq \sum_{\tau=1}^{t}\left[\sum_{j=1}^{N} R(c,j)\left(x_{pkj\tau}+I_{pkj\tau}+B_{pkj\tau}\right)\right]$$
$$p=1,..,ENDP; c=1,..,C; \quad k=1,..,K; \quad t=1,..,T$$

Validation of Mathematical Models

The fundamental MRP II models are used to make a requirement list with deterministic information like demand, lead time of products and component, etc. on an existing production line of a Malaysian company. The company, namely ABC (a given name), is producing air filter products for diverse air filtration system. The details of the company are found in Wazed et al. [21]. The same data with the layout information is also employed in proposed mathematical models to prepare a timely requirement schedule of the systems under investigation. Both the models are solved in Lingo systems with global solver, and the outputs are compared.

Primary data collected from the floor are used to compare the outcomes of the MRP II and proposed mathematical models. Validation of data were performed to ensure that these are for the right issue and useful. Data validation checks that the data is sensible before it is processed. The recorded data were scrutinized by the production engineers who are familiar with the specific processes and adjustment has been taken. The model validation is performed to test the overall accuracy of the model and the ability to meet the real value. Table I and Table II are showing the timely requirements of components generated respectively by the basic MRP II and mathematical models for the company.

Table I. Timely requirement of parts based on Basic MRP II

Part/Product	Period								
	1	2	3	4	5	6	7	8	9
AAI	0	0	0	0	0	0	0	50	0
Assembly	0	0	0	0	50	0	0	0	0
Gasket	0	0	0	0	0	0	200	0	0
Assembly A	0	0	0	50	0	0	0	0	0
Al Separator	0	0	200	0	0	0	0	0	0
Al Foil	0	100	0	0	0	0	0	0	0
Media	150	0	0	0	0	0	0	0	0

It is really a good matching found between the two schedules generated by the basic MRP II and modified models. The later bearing additional information of the location where to be available the parts in a time frame.

Table II. Timely requirement schedule generated by mathematical models

Machine /Stage	Part/ Product	Period								
		1	2	3	4	5	6	7	8	9
Folding	Al Foil	0	100	0	0	0	0	0	0	0
Folding	Media	150	0	0	0	0	0	0	0	0
Assembly	Assembly A	0	0	0	50	0	0	0	0	0
Assembly	Al Separator	0	0	200	0	0	0	0	0	0
Strapping	Assembly	0	0	0	0	50	0	0	0	0
Gasketing	Gasket	0	0	0	0	0	0	200	0	0
Packaging	AAI	0	0	0	0	0	0	0	50	0

Effect of Component Commonality

The basic mathematical models for multistage manufacturing are validated in a production line. In this section, the effect of component commonality is observed using the proposed commonality models and the outcomes are compared with their basic forms. The models are executed for 18 periods under various created scenarios. For the commonality models, we assumed two different scenarios (Table III). The complete mathematical models for commonality of the multistage system are shown in Figure 3:

Table III. Commonality design

Scenario	Component in Line 1	Component in Line 2	Common component	Layout
1	C	H	C	Figure 4a
	D	I	D	
2	A	E	A	Figure 4b
	B	F	B	

Effect of Commonality on Production Cost and Capacity Requirement

The authors have executed the models in Lingo system to observe the impact of common parts in production. It is considered that the demand (Table IV) and procurement lead time are known and constant. The cost of the product specific components and common components are known. Common parts usually require higher cost and processing time (i.e. processing cost) than the others. It is assumed that the common parts are able to fulfill the purpose of the replaced component. The other cost parameters are considered same under any scenario. Figure 5 shows the effect of cost of common parts on the total cost incurred and capacity. The timely requirement schedules of the dependent items for both of the cases are generated from the models.

Table IV. Timely demand of the end products

Period	9	10	11	12	13	14	15	16	17	18
Product SL	120	120	120	120	120	120	120	120	120	120
Product DL	140	140	140	140	140	140	140	140	140	140

Objective function

$$\text{Minimize} \quad z = \sum_{WC(P,K)} \sum_{I} \sum_{T} \left(v_i x_{pkit} + c_i C_{pkit} + q_i I_{pkit} \right)$$

$$+ \sum_{WC(P,K)} \sum_{I} \sum_{T} f_{pk} \left(y_{pkit} - \gamma_{pkit} \right) + \sum_{WC(P,K)} \sum_{T} c_{WC} OT_{pkt}$$

Subject to

$$I_{pkct-1} + \sum_{\tau=1}^{t-LT(p,k,c)} x_{pkc\tau} - I_{pkct} + B_{pkct} - B_{pkct-1} \geq$$

$$\sum_{\tau=1}^{t} \left[\sum_{j=1}^{N} R(c,j) \left(x_{pkj\tau} + I_{pkj\tau} + B_{pkj\tau} \right) \right] \quad p = 1,..,ENDP;\ c = 1,..,C; \quad k = 1,..,K; \quad t = 1,..,T$$

$$I_{pkit-1} + \sum_{\tau=1}^{t-LT(p,k,i)} x_{pki\tau} - I_{ikt} + B_{pkit} - B_{pkit-1} \geq \sum_{\tau=1}^{t-LT(i,k)} \left[\sum_{j=1}^{N} R(i,j) \left(x_{pkj\tau} + I_{pkj\tau} + B_{pkj\tau} \right) \right]$$

$$i \neq c; \quad p = 1,..,ENDP;\ i = 1,..,N \setminus ENDP; \quad k = 1,..,K; \quad t = 1,..,T$$

$$C_{ikt} \geq \sum_{\tau=1}^{t-LT(i,k)} \left[\sum_{j=1}^{N} R(i,j) \left(x_{pkj\tau} + I_{pkj\tau} + B_{pkj\tau} \right) \right] i \neq c; \quad p = 1,..,ENDP;\ i = 1,..,N \setminus ENDP; \quad k = 1,..,K; \quad t = 1,..,T$$

$$C_{ckt} \geq \sum_{\tau=1}^{t} \left[\sum_{j=1}^{N} R(c,j) \left(x_{pkj\tau} + I_{pkj\tau} + B_{pkj\tau} \right) \right] \quad p = 1,..,ENDP;\ c = 1,..,C; \quad k = 1,..,K; \quad t = 1,..,T$$

$$LS(i) \leq M y_{pkit} \quad p = 1,..,ENDP;\ i = 1,..,N \setminus ENDP; \quad k = 1,..,K; \quad t = 1,..,T$$

$$I_{Pkit} \times B_{pkit} = 0 \quad p = 1,..,ENDP; \quad k = 1,..,K; \quad i = 1,..,N \setminus ENDP;\ t = 1,..,T$$

The capacity constraints:

$$\sum_{I} \left\{ U(p,k,i) x_{pkit} + ST(p,k,i) \left(y_{pkit} - \gamma_{pkit} \right) \right\} - OT_{Pkt} + UT_{pkt} \leq 1 \quad p = 1,..,ENDP; \quad k = 1,..,K; \quad t = 1,..,T$$

$$OT_{Pkt} \times UT_{pkt} = 0 \quad p = 1,..,ENDP; \quad k = 1,..,K; \quad t = 1,..,T$$

$$y_{pkit-1} + y_{pkit} \geq 2\gamma_{pkit} \quad p = 1,..,ENDP;\ i = 1,..,N; \quad k = 1,..,K; \quad t = 1,..,T$$

$$\gamma_{pkit} \leq MU(p,k,i) \quad p = 1,..,ENDP;\ i = 1,..,N; \quad k = 1,..,K; \quad t = 1,..,T$$

$$\sum_{i=1}^{N} \gamma_{pkit} \leq 1 \quad p = 1,..,ENDP;\ k = 1,..,K; \quad t = 1,..,T$$

Non-negativity constraints:

All variables ≥ 0; $y_{pkit} = \{0,1\}$; $n = Integer$

Figure 3. Commonality Models for multistage production

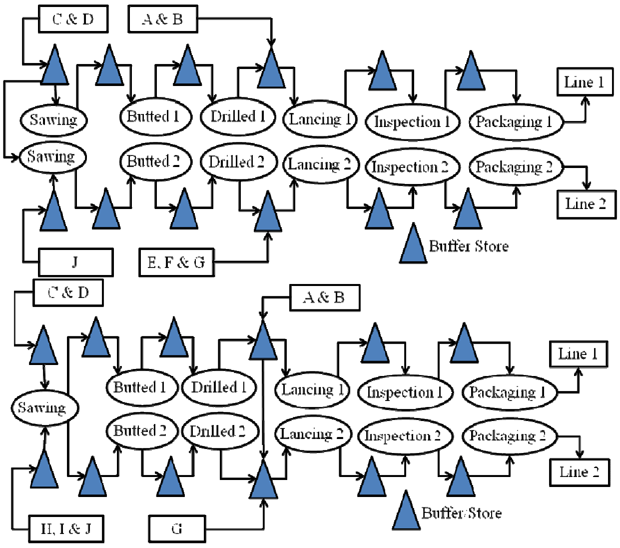

Figure 4. Production layout for commonality (a-Scenario1 and b-Scenario2)

Figure 5 shows that the cost of production and capacity requirements is always less for commonality cases. The cost increases with the cost ratio for both of the scenarios. Cost ration represents how much expensive the common parts in comparison to the substituted parts. For example, 1.10 means that the cost (both purchasing and processing) of common parts is 10 percent higher than the cost of the components it replaced. It is observed that commonality offers a better choice even if the cost (both purchasing and processing) of the common parts is 60 percent higher than the substituted parts (Scenario 1). The disparity in cost with cost ratio is not much sensitive in scenario 1 over the scenario 2. The cost saving in commonality models mainly comes from the processing cost. Inclusion of common parts at the lower level (Scenario 1) is always beneficial over the upper level (Scenario 2). Generally at the downstream of a production requires less parts and processing than the upstream components. This is the main reason of higher cost saving offer comes from the inclusion of common part at lower level than its successor. Since the commonality models require less setup due to less variety of parts, the capacity requirement is less.

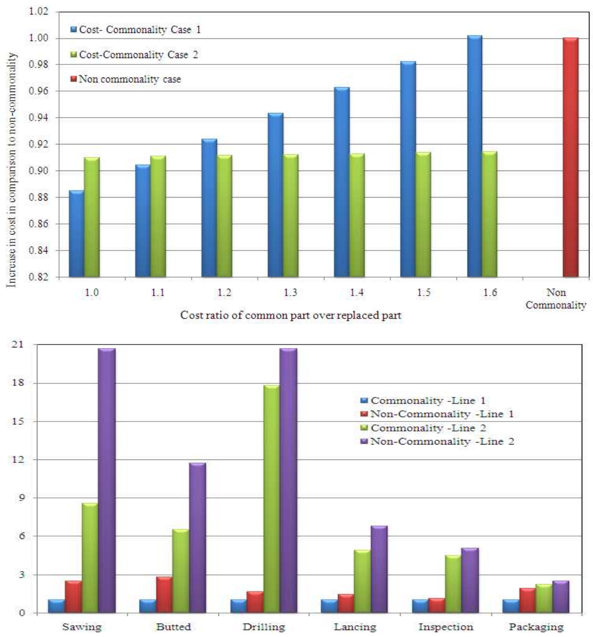

Figure 5. Effect of common parts on (a) costs and (b) capacity requirement (same setup and processing time)

Conclusion

From this study and analysis, the authors like to conclude that –

i. Under stable and stationary condition, the proposed models can provide exact planning like MRP II. Additionally, the parts routes are easily traced in the floor for each planning period.
ii. Use of common parts in manufacturing is always better over the non-commonality scenario in term of production cost and capacity requirements.
iii. The requirements of common parts are always higher than the individual part it replaces.
iv. The impact of applying component commonality at different stages is different due to the lead time dynamics in the system. Inclusion of common parts at the upstream is always beneficial than at the downstream of the production line.

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