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Delayed product differentiation: a design and manufacturing perspective

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Delayed product differentiation (DPD) is a design concept for improving customer satisfaction and manufacturing performance. In this paper, a methodology for implementing the delayed product differentiation strategy in manufacturing is presented. Three design rules are suggested. The impact of delayed product differentiation strategy on the performance of a manufacturing system is quantified and incorporated in the product design. The problem of selecting designs to minimize the total differentiation and manufacturing cost is formulated and solved. The methodology presented in the paper is illustrated with examples. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: delayed product differentiation, differential design, integral design, assembly time and cost

INTRODUCTION

Background and motivation

Delayed product differentiation (DPD) is a design concept aiming at the increase of product variety and manufacturing efficiency. It is based on delaying the time when a product assumes its identity, i.e. a particular product model at a particular stage of a particular manufacturing process. Although the general concepts of delayed product differentiation have been published in the literature[1–3], its implementation has not been discussed. The concept of delayed product differentiation strategy was discussed in Ref.[3] as a valuable approach to improve performance of a supply chain.

Normally, a manufacturing process involves multiple stages, each requiring different parts or subassemblies. Increasing the level of part commonality at an early stage of manufacturing process may delay the differentiation of products. Commonality here is defined as the use of a component by several different products. The product depicted in Figure 11.14 of Ref.[4], pages 182 and 183, illustrates the application of the DPD concept, where the plastic clamp, plastic feet, terminal rack, guard, shields, upper and lower insulator are common parts which could be used to build 100 different products. When used properly, part commonality may decrease the inventory cost, manufacturing cost, material handling cost, and so on. Otherwise, it may adversely impact the performance of a manufacturing system. In this paper, an implementation approach of the product differentiation concept is developed.

In the delayed product differentiation, common and simple parts are machined and then delivered to the assembly system to form product variants. The delayed product differentiation concept is cited as an assembly-driven strategy in Ref.[2]. Some design strategies, e.g. modular product design, allow for delayed product differentiation by a number common parts serving numerous product models.

Designing parts according to the delayed product differentiation concept is referred to as differential design (see *Figure 1b*) and the design of parts related to the early product differentiation is referred to as integral design (see *Figure 1a*).

Although the number of parts in the differential design is larger than that in the integral design, the total number of different parts can be reduced if common parts are shared by differential designs. Differential design implies breakdown of a unique part into several common parts. *Table 1* summarizes the advantages and disadvantages of differential designs[5].

Most products are designed by the combined differential and integral design concept. While, from the viewpoint of assembly, differential product structures are preferred, a good judgment is needed to ensure that the requirements

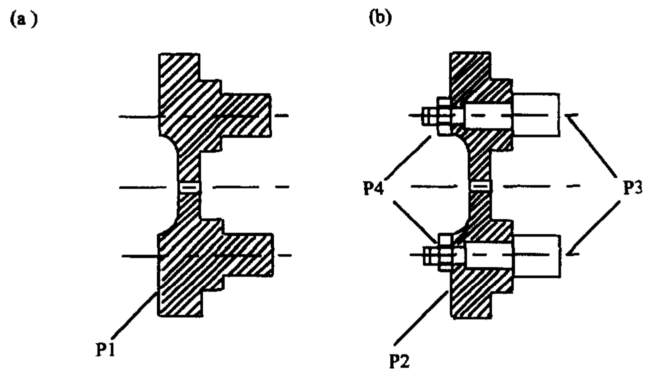

Figure 1 Two designs: (a) integral design; (b) differential design

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Table 1 Advantages and disadvantages of differential designs

Advantages:
(1) Use of favorably priced semi-finished materials and standard parts
(2) Simpler subassemblies and parts
(3) Reduced time and cost of maintaining the products
Disadvantages:
(1) The need for tighter quality control
(2) More interfaces between parts
(3) Higher potential for decreased reliability

for assembly do not override valid requirements of other aspects of manufacture.

Redford and Chal[5] provided qualitative guidelines for the rationalization of product structures. Their guidelines consider one product design at a time. No collective impact of multiple product designs is considered. In this paper, the impact of the delayed product differentiation design on the performance of manufacturing systems is quantified and a quantitative basis for the rationalization of product structures is provided.

The manufacturing performance issue in design of products

One difficulty in implementing the delayed product differentiation strategy is that the management and design teams could be reluctant to proceed with a new design without the evidence of benefits in terms of improved manufacturing efficiency, faster response time to market, reduced manufacturing cycle time, etc. Thus, scheduling methodologies can contribute here.

Design for manufacturing requires design engineers to take a broader perspective than the product functionality and performance. It also requires generalization of the definition of cost used for evaluation of alternative designs, which often includes only the material cost of a product and direct labor in assembly.

Youssef[6] pointed out that timeliness in creating goods and services is essential in the competitive environment. Stephen and Tatikonda[7] showed that the product introduction time affects its competitiveness. Therefore, the time required to manufacture products should be incorporated into the evaluation of alternative designs. The impact of design decisions on manufacturing performance should be considered at the early product design stage.

Andreasen *et al.*[8] showed that from an assembly point of view, the optimal design of a part can only be achieved by considering various design alternatives, thus providing some degree of design freedom. The design alternatives can be created by considering various form divisions.

In this paper, it is assumed that a fixed number of standard parts is available. Designers intend to replace the unique (integral) designs of parts with differential designs which contain some standard parts. They face the decision of selecting appropriate differential designs that improves manufacturing performance. For example, consider the integral design of product C in *Figure 2*.

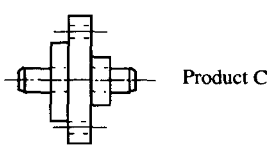

Figure 2 The integral design of product C

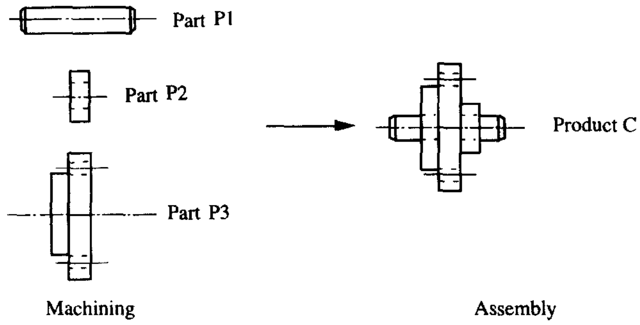

Figure 3 The differential design of product C in *Figure 2*

The design in *Figure 3* contains three parts. If these parts are standard and available or can be delivered from suppliers, then the design and manufacturing time could be significantly reduced. However, if the assembly time required by the design in *Figure 3* is relatively long, then this design may not be appropriate. A decision has to be made what type of a design to select. Here, only a single design was considered. For large number of designs, the decision problem becomes complex.

Differential designs may increase the number of assembly operations to be performed and the assembly time and hence require additional stations in the system or affect balancing of the system. The degree of this impact depends on the structure of the assembly system.

In this paper, a qualitative and quantitative approach is developed to guide the design of products to improve manufacturing performance. The reminder of the paper is organized as follows. In Section 2, a graph representation of product structures is presented. Based on this representation, a part classification scheme is developed. The structure of the assembly system and its operations are defined in Section 2. Qualitative design rules for improving efficiency of the assembly system are developed. In Section 3, a mathematical model for selecting differential designs is developed. The impact of differential designs on manufacturing cycle time is quantified based on an aggregate scheduling model. An integer programming formulation for selecting optimal differential designs is presented. The methodology presented in this paper is illustrated with a numerical example in Section 4. Section 5 concludes the paper.

BASIC ANALYSIS

Graph representation of product structures

A product can be represented by a digraph G, where each node represents a part or a subassembly, and each arc represents a precedence relationship between two nodes. In

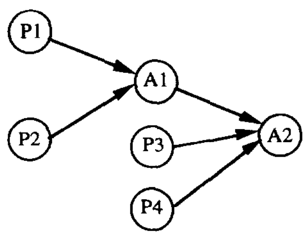

Figure 4 The digraph of a product

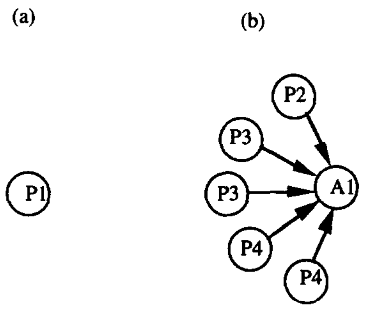

Figure 5 Graph representations of the designs in *Figure 1*

the digraph G, any node of degree 1, i.e. with the number of edges incident to the node equal to 1, denotes a part; any node of degree greater than 1 denotes a subassembly. For example, a product with four parts P1, P2, P3, and P4 and two subassemblies A1 and A2 is shown in *Figure 4*.

The level of assembly (h) is assigned as follows: the value 0 is assigned to the root node (final assembly or subassembly), and working backwards from the root node, values of increment 1 are assigned to each subassembly node, e.g. in *Figure 4*, the assembly level at node A2 is 0 and that at node A1 is 1. The level of a part is the same as the corresponding subassembly node plus one, e.g. in *Figure 4*, the assembly level of parts P3 and P4 is 1, and that of parts P1 and P2 is 2.

The graph representations of the two designs in *Figure 1* are presented in *Figure 5*.

Based on the values of the node degree h corresponding to a part and the maximum node degree H, parts can be classified into three classes (see *Table 2*).

The three classes A, B, C, of parts are illustrated in *Figure 6*. In *Figure 6*, part P3 of class A, part P5 of class B, and part P12 of class C.

Note that the digraphs in *Figures 4* and *5* are simple digraphs. A simple digraph is a digraph with only one assembly node at each level of assembly. A digraph other than simple is complex. In this paper, differential designs represented by linear assembly structures (simple digraphs) are considered.

The precedence relationship between assembly operations is represented by a superimposed assembly graph Gs. The superimposed assembly graph Gs is obtained by combining digraphs of individual products. For simplicity, part nodes and their arcs to the assembly and subassembly nodes are ignored in Gs, i.e. only the relationships between assemblies and subassemblies are captured.

Note that an arc (i,j) in G is redundant if in addition to the arc itself a chain of arcs exists from node i to node j. The redundant arcs are omitted. The superimposed assembly graph for the two products in *Figure 7* is illustrated in *Figure 8*.

Table 2 The part classification scheme

	Maximum node	
Node degree h	$H = 1$	$H > 1$
$h = 1$	Class A	Class C
$h > 1$	N.A.	Class B

The assembly system

In this section, the assembly system is briefly discussed. The assembly system has no buffers between stations and is paced, for example, as an automated assembly line. Thus, all jobs advance to the next station in one direction when all operations at proceeding station are completed. Each station performs one job at a time. The job processing time is the total assembly time of all operations at that station. The time between a job entering and leaving the system is the cycle time, c.

It is assumed that the assembly system is balanced for a given target throughput rate q. Therefore, the cycle time of the assembly system is given by $c = 1/q$. Jobs advance to the next station every c time units. The throughput of the assembly system is therefore $1/c$ products per time unit.

A typical assembly line balancing procedure assigns assembly operations to the stations while maintaining the precedence constraints of the superimposed assembly graph and works as follows. Starting with station 1, assign as many successive operations as possible without exceeding the cycle time, c. Perform the assignment for station 2, 3, and so on, until all operations are assigned. Depending on the structure of the superimposed assembly graph, the computational complexity of the assembly line balancing problem can range from polynomial to NP-hard[9,10]. For the review of the assembly line balancing literature, the reader is referred to Nahmias[11].

Extensive research has been done on the assignment of assembly operations to stations to minimize the number of stations in the assembly system for a given cycle time c (e.g. see Refs[10,12–14]. It is assumed that the assembly system is balanced, i.e. assembly operations are assigned to stations, after the final design of all products is completed. Therefore, it is not possible to balance the assembly system without considering the collective impact of all designs. Qualitative rules are developed to guide the design process in order to improve the efficiency of the assembly process.

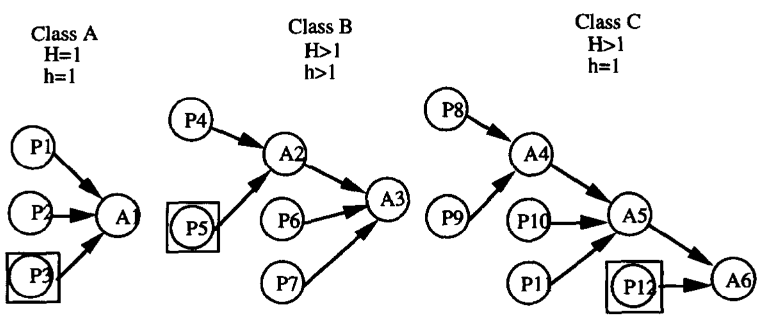

Figure 6 The product structure

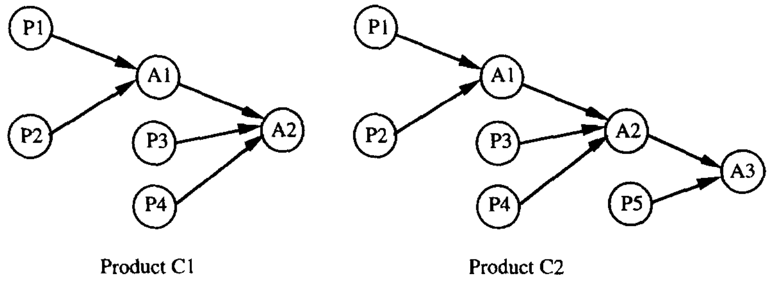

Figure 7 The digraphs of two products

Design rules for delayed product differentiation

Three design rules for delayed product differentiation are proposed next. As discussed in Ref.[2], machining parts normally requires a longer lead time than their assembly. The integral design results in complex parts that are more difficult to manufacture, more costly, require more inspection, and fail more in test and use. On the other hand, the differential design of a part with linear assembly structure has more robust scheduling characteristics which is crucial in assembly time and cost minimization. The design rules presented next are heuristic and are developed around the concept of products with linear assembly structures and assembly line balancing.

Rule 1. Avoid differential designs of parts in the presence of a subassembly at the assembly level $h < H$

The reason behind this rule is that in this case differential parts may lead to a product structure represented with a complex digraph. As discussed before, a product represented by a simple digraph leads to a linear assembly structure with robust scheduling characteristics. Another reason for avoiding subassemblies at assembly level $h < H$ in differential designs is obvious as the assembly time is eliminated.

Assume that part P3 in *Figure 9* needs to be redesigned, e.g. due to difficulties in complying with tolerances. Note that the assembly level of part P3 is $h = 1$ and the maximum assembly level of the digraph is $H = 2$.

Figure 10 shows two possible differential designs of part P3. The differential design in *Figure 10a* is preferred over the differential design in *Figure 10b* based on rule 1, as the former has a linear assembly structure.

Rule 2. Avoid differential designs of a part if the assembly time of the differential design is greater than the cycle time of the assembly system

Differential designs of parts normally require subassembly (see *Figure 11*). From the assembly balancing standpoint, a differential design is not preferred over integral design if the assembly time of the differential design is greater than the cycle time of the assembly system. Note that, the assembly time of the differential design include machining time of parts and assembly time of subassembly.

There are two reasons behind this rule. First, the assembly operations of a differential design cannot be performed within the established cycle time without rebalancing the assembly system. Second, the assembly system has to be rebalanced with a larger cycle time. As a consequence, the throughput rate of the system will decrease.

To illustrate design rule 2, two designs in *Figure 1* are considered. In *Figure 1a*, the cycle time which includes machining time of parts P1, P2, P3 and assembly time of subassemblies A1 and A2 of 20 units is assumed. In *Figure 1b*, the differential design of a part P2 is selected. The assembly time of the differential design is equivalent to 22 (see *Table 3*) which is greater than the cycle time of the assembly system. So, the differential design is not preferred in this case.

Rule 3. In differential designs of parts avoid cycles in a superimposed assembly graph

The example in *Figure 12* shows products with assembly operations producing cycles in a superimposed assembly graph. This example illustrates that designing products without considering precedences among operations may impact manufacturing performance. Cycles in a superimposed graph need to be avoided.

A cycle in a superimposed assembly graph implies a backtracking flow in the assembly system. Backtracking increases the material handling cost and decreases manufacturing productivity as it makes the material movement similar to the job shop[15]. Furthermore, more diverse material handling equipment may be required, and queues may develop[16].

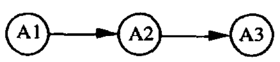

Figure 8 The superimposed assembly graph for the products in *Figure 7*

SELECTION OF OPTIMAL DESIGNS

If a part can serve different designs, then the indirect cost can be dramatically reduced. The indirect cost may include the following components: creating and maintaining parts drawing; designing and manufacturing tooling; multiple setups; extra handling; ordering; delivery; and servicing.

Designers are faced with a decision of when the delayed product differentiation strategy should be implemented. Thus the problem of identifying the designs which could be most effectively served by a common part

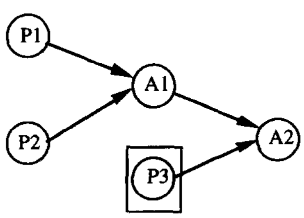

Figure 9 The product structure represented by a simple digraph

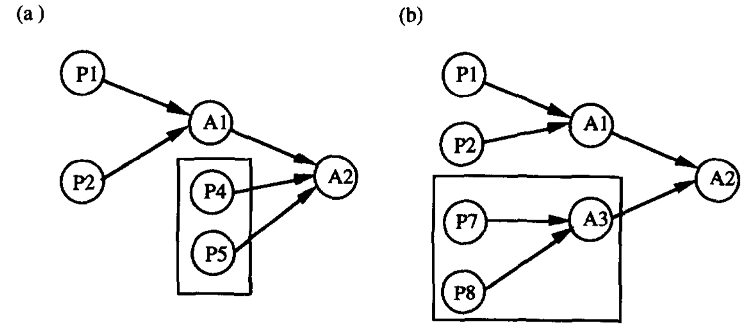

Figure 10 Two differential designs of part P3 in *Figure 9*: (a) differential design of part P3 without assembly; (b) differential design of part P3 with a subassembly

becomes an interesting though complex issue discussed next.

Boothroyd[17] suggested that in design of products for assembly, the minimum part count rule should be applied. Reducing the number of different part types yields a multitude of benefits, including decreased material cost, reduced assembly and fixturing cost and improved quality[17]. The reduction in the number of parts is enhanced by the increase in the level of part sharing among products. Therefore, minimization of the part count differentiation cost is to be included the objective function. The part count differentiation cost is defined next.

THE IMPACT OF DIFFERENTIAL DESIGNS ON MANUFACTURING CYCLE TIME

A factor to be considered the design selection problem is the impact of a design on the manufacturing cycle. The manufacturing cycle time is measured by the makespan of an aggregate schedule of the manufacturing system. The change in manufacturing cycle time can be converted into production cost by multiplying it by the unit cost.

In order to compute the change in manufacturing cycle time due design modifications, the following notation is defined:

$t(*)$ = processing (machining or assembly) time of a part or subassembly
h = assembly level index
$Q(h)$ = the set of parts at assembly level h
A_h = subassembly at level h
H = the maximum assembly level of a digraph
P_j = part j of differential design of part P
$SP(P)$ = the set of parts in the differential design of part P
$A(P)$ = subassembly of the differential design of part P
$C_{max}(i)$ = the makespan of aggregate schedule when part P (corresponding to integral design i) is integral
$C'_{max}(i)$ = the makespan of aggregate schedule when part P is designed as differential design i.
$\Delta C_{max}(i) = C'_{max}(i) - C_{max}(i)$ = the change in the makespan due to the differential design i.

If differential design i of part P of class A contains no subassemblies, then $\Delta C_{max}(i)$ can be computed as follows:

$$\Delta C_{max}(i) = \sum_{p_j \in SP(P)} t(P_j) \tag{1}$$

If differential design i of part P of class A contains a subassembly $A(P)$, then $C_{max}(i)$ can be computed as follows:

$$\Delta C_{max}(i) = \max\left\{ t(A(P)) - \sum_{P_j \in Q(1)-P} t(P_j), 0 \right\} + \sum_{P_j \in SP(P)} t(P_j) - t(P) \tag{2}$$

For differential design i of part P of class B, $C_{max}(i)$ is computed as follows:

$$\Delta C_{max}(i) = \sum_{p_j \in SP(P)} t(P_j) - t(P) \tag{3}$$

For differential design i of part P of class C, $C_{max}(i)$ is computed as follows:

$$\Delta C_{max}(i) = \sum_{p_j \in SP(P)} t(P_j) + \max\left\{ t(A_2) - \sum_{P_j \in SP(P)} t(P_j) - \sum_{P_j \in Q(1)-P} t(P_j), 0 \right\} - \max\left\{ t(A_2) - \sum_{P_j \in Q(1)} t(P_j), 0 \right\} \tag{4}$$

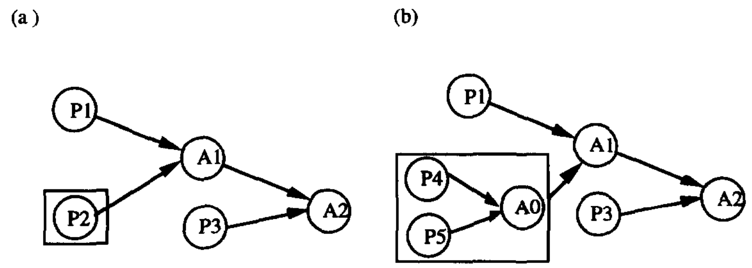

Figure 11 Two subassembly systems: (a) non-differential design of part P2; (b) differential design of part P2

Table 3 The machining and assembly times

Part number	4	5
Machining time	6	6
Subassembly number	0	
Assembly time	10	

Table 4 The machining and assembly times

Part number	1	2	3	4	5	6	7	8	9	10	11
Machining time	5	10	2	9	8	8	2	6	5	2	2
Subassembly number	1	2	3	4	5	6	–	–	–	–	–
Assembly time	2	2	3	2	6	3	–	–	–	–	–

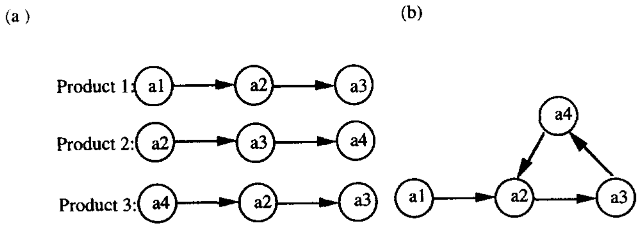

Figure 12 Cycles in a superimposed assembly graph: (a) assembly operation structures of three products; (b) superimposed assembly graph

THE PART COUNT DIFFERENTIATION COST

Let M be the total number of part types available. For each differential design i, define the following incidence column vector:

$$\mathbf{e_i} = [e_{i1}, \cdots, e_{im}, \cdots, e_{iM}]^T$$

where

$$e_{im} = \begin{cases} 1, & \text{if differential design } i \text{ uses part type } m \\ 0, & \text{otherwise} \end{cases}$$

For any two differential designs, i and j, define the part count differentiation cost

$$d_{ij} = \sum_{m=1}^{M} w_m q(e_{im}, e_{jm}) \quad (5)$$

for all i and j

where

$$q(e_{im}, e_{jm}) = \begin{cases} 1, & e_{im} \neq e_{jm} \\ 0, & \text{otherwise} \end{cases}$$

w_m = the most cost efficient of part type m

The part count differentiation cost d_{ij} measures the dissimilarity between two differential designs. Due to different importance of each part type, the part count differentiation cost has been weighted by introducing the cost coefficient w_m for each part type m. The cost coefficient assigned to a part can be set to be proportional to the manufacturing cost or procurement cost of the parts. Note that, in eqn (5), d_{ij} must be computed for all i and j.

THE INTEGER PROGRAMMING FORMULATION

Before the problem of selecting modular designs is formulated, the following notation is defined:

K = set of parts
N_k = set of differential designs for part k
$N = \sum_{k \in K} N_k$, set of all differential designs
A = set of connections from the set N_v to set N_w, $(v,w) \in K \times K$ and $v \neq w$
d_{ij} = part count differentiation cost for designs i and j defined in eqn (5)
u = unit manufacturing cost
$r_i = u\Delta C_{max}(i)$ = manufacturing cost change due to differential design i

$$x_i = \begin{cases} 1, & \text{if differential design } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1, & \text{if differential design } i \text{ and } j \text{ are selected} \\ 0, & \text{otherwise} \end{cases}$$

$$\text{Min} \frac{1}{2} \sum_{(i,j) \in A} d_{ij} y_{ij} + \sum_{i \in N} r_i x_i \quad (6)$$

s.t. (7)

$$\sum_{i \in N_k}, \quad k \in K$$

$$x_i + x_j - 1 \leq y_{ij}, \quad (i,j) \in A \quad (8)$$

$$x_i = 0, 1, \quad i \in N, \quad (9)$$

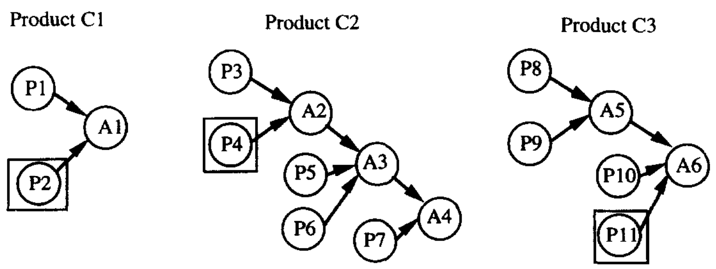

Figure 13 The product structures

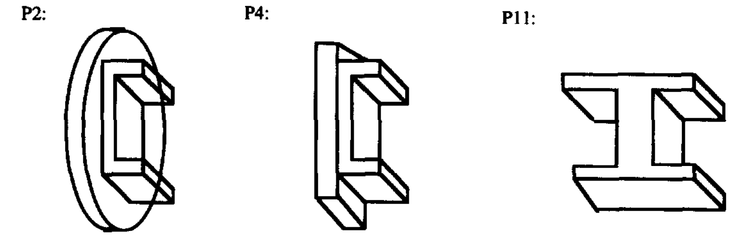

Figure 14 The integral designs of parts P2, P4, and P11

$$y_{ij} \geq 0, \quad (i,j) \in A \qquad (10)$$

The objective function eqn (6) minimizes the total part count differentiation cost and manufacturing cost. Note that maximizing the total part differentiation cost has a positive impact on minimizing the total part count. Additionally, from the definition $y_{ij} = y_{ji}$ and the term $d_{ij}y_{ij} = d_{ji}y_{ji}$ appear twice in eqn (6), so a factor 1/2 has been introduced. Constraint eqn (7) ensures that for each complex part exactly one differential design is selected. The consistency of decision variables is imposed by constraint eqn (8). Constraints eqn (9) ensure integerality. Constraint eqn (10) imposes non negativity.

Note that the structure of the formulation eqns (6)–(10) is the same as that of the formulation (6.31)–(6.35) in Ref.[18]. Hence, the formulation eqns (2)–(6) can be solved efficiently by the construction algorithm developed in Ref.[18]. For a problem with 100 differential designs and 40 parts, it can be solved with the construction algorithm in 0.6 s.

The implementation methodology for the delayed product differentiation strategy is summarized as follows:

Step 1. Generate alternative differential designs.
Step 2. Apply the delayed product differentiation design rules to eliminate undesirable differential designs.
Step 3. Solve formulation eqns (2)–(6) to obtain optimal differential designs.

The numerical example presented next illustrates the implementation methodology of the delayed product differentiation strategy.

ILLUSTRATIVE EXAMPLE

Consider the three products C1, C2, and C3 in *Figure 13* to be produced in a manufacturing system. Assume that the cycle time of the assembly system for a target throughput rate is set to $c = 7$ time units. Note that A1, A4, A6 represent the 'assembly node' because those assembly nodes are corresponding to products (see *Figures 14* and *15*).

A7, A8, A9, A10, A11 in *Figure 16* represent the 'subassembly nodes' generated for each part. For example, A7 (D1) and A8 (D2) in *Figure 16* are two differential (alternative) designs of part P2. Note the cycle time of the assembly system of 13 time units is assumed.

The values of machining and assembly times are given in *Table 4*.

Assume that parts P2, P4, and P11 of class A, B, and C, respectively are considered to be redesigned as differential. Again, the differential design of a part may involve or not assembly. The graph representations of the differential designs of parts P2, P4, and P11 are shown in *Figure 16*. Note that differential designs D1 and D2 of parts P2 involve subassembly (see *Figure 16a*). While, differential designs D5 and D7 of part P11 do not involve assembly (see *Figure 16a*).

The values of machining and assembly times are provided in *Table 5*.

Applying the design rules 1–3, differential designs D2 and D6 are eliminated as D2 violates rule 2 and D6 violates

Table 5 The machining and assembly times

Part number	12	13	14	15	16	17	18	19	20	21
Machining time	4	1.5	0.5	0.5	4.5	1	1.5	3.5	2.5	1
Subassembly number	7	8	9	10	11	–	–	–	–	–
Assembly time	2	8	4	5	3	–	–	–	–	–

Table 6 The values of ΔC_{max}

	D1	D3	D4	D5	D7
ΔC_{max}	−3.5	−2.5	−1	4.5	5

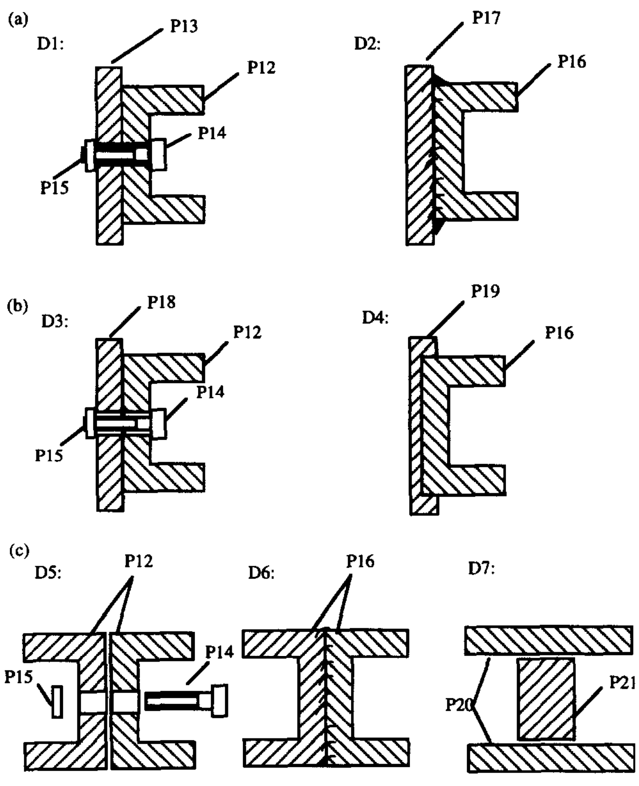

Figure 15 The differential design of three parts: (a) part P2; (b) part P4; (c) part P11

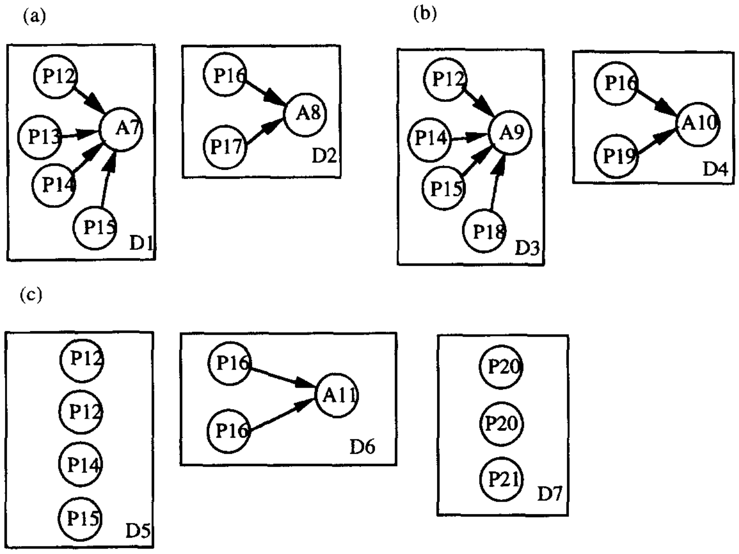

Figure 16 Graph representations of differential designs of three parts: (a) part P2; (b) part P4; (c) part P11

rule 1. The part count differentiation cost $[d_{ij}]$ is provided in matrix eqn (12) based on the incidence matrix eqn (11).

	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21
D1	1	1	1	1	0	0	0	0	0	0
D3	1	0	1	1	0	0	1	0	0	0
D4	0	0	0	0	1	0	0	1	0	0
D5	2	0	1	1	0	0	0	0	0	0
D7	0	0	0	0	0	0	0	0	2	1

(11)

	D1	D3	D4	D5	D7
D1	-	2	6	2	6
D3	2	-	6	2	6
D4	6	6	-	5	4
D5	2	2	5	-	5
D7	6	6	4	5	-

(12)

Applying the part classification scheme in *Table 2*, parts P2, P4, and P11 are classified as of class A, B, and C, respectively. Based on eqns (2)–(5), the change ΔC_{max} in makespan is shown in *Table 6*.

Solving the formulation eqns (6)–(10) with $w_m = 1$ and $u = 1$, the optimal designs D1, D3, and D5 are selected.

The final structures of products C1, C2, and C3 are shown in *Figure 17*.

CONCLUSION

In this paper, a methodology for implementing the delayed product differentiation strategy in manufacturing was presented. Three design rules were introduced to improve performance of a manufacturing system. The impact of delayed product differentiation strategy on the manufacturing system performance was quantified and incorporated in the product design process. The problem of selecting designs to minimize the number of parts and manufacturing cycle time was formulated and solved. An illustrative example was presented.

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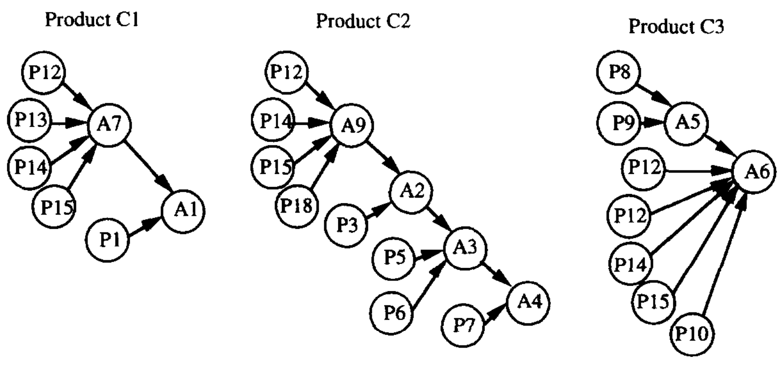

Figure 17 The final designs of products C1, C2, and C3

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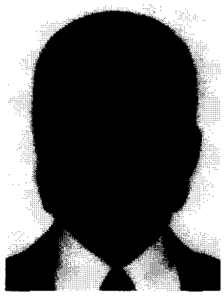

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