UNIVERSITY OF
ILLINOIS LIBRARY
AT URBANA-CHAMPAIGN
BOOKSTACKS

CENTRAL CIRCULATION BOOKSTACKS

The person charging this material is responsible for its renewal or its return to the library from which it was borrowed on or before the **Latest Date** stamped below. **You may be charged a minimum fee of $75.00 for each lost book.**

Theft, mutilation, and underlining of books are reasons for disciplinary action and may result in dismissal from the University.

TO RENEW CALL TELEPHONE CENTER, 333-8400

UNIVERSITY OF ILLINOIS LIBRARY AT URBANA-CHAMPAIGN

JUL 28 1998

When renewing by phone, write new due date below previous due date.

L162

330
B385
No 1252 ~~COPY~~ 2
Cop 2

STX

BEBR

FACULTY WORKING PAPER NO. 1252

Strategic Subcontracting for Efficient Disaggregated Manufacturing

K. Ravi Kumar
A. Vannelli

College of Commerce and Business Administration
Bureau of Economic and Business Research
University of Illinois, Urbana-Champaign

BEBR

FACULTY WORKING PAPER NO. 1252

College of Commerce and Business Administration

University of Illinois at Urbana-Champaign

May 1986

Strategic Subcontracting for Efficient Disaggregated Manufacturing

K. Ravi Kumar, Assistant Professor
Department of Business Administration

A. Vannelli
University of Toronto

This Working Paper should not be cited or reproduced in whole or in part without permission of the author.

Comments are solicited.

Digitized by the Internet Archive
in 2011 with funding from
University of Illinois Urbana-Champaign

http://www.archive.org/details/strategicsubcont1252kuma

STRATEGIC SUBCONTRACTING
FOR
EFFICIENT DISAGGREGATED MANUFACTURING

BY

K. RAVI KUMAR *

A. VANNELLI **

Abstract

A new method is presented for using a subcontracting strategy to induce manufacturing efficiency by re-organizing the existing parts and machines into disaggregated cells. Two efficient algorithms are developed which identify the minimal number or minimal total cost of subcontractible parts while achieving disaggregation. The method has the flexibility of letting the designer control the number of cells and cell size thus generating a variety of cellular manufacturing system designs to choose from.

---

* Assistant Professor, Business Administration Department,
University of Illinois, Champaign, Il. 61821, U.S.A.

** Assistant Professor, Department of Industrial Engineering,
University of Toronto, Toronto, Ontario M5S 1A4, Canada

1. Introduction

One of the main reasons for the economic success of mass production is that the material flow in such systems is very simple. This simplicity in flow lines leads directly to simplified management, reduction in throughput times, reduction in investment in inventory and reduced handling costs (Burbidge, 1975). On the other hand, consumer tastes are moving away from mass merchandised products towards more customisation to individual likes and dislikes. Beside the changing tastes, international competition has also forced manufacturers to get into the production of higher value-added products (Reich, 1983). These changes have made small batch manufacturing a large proportion of the manufacturing industry and has lead to more complex flow lines in the factories. These complex flows have increased the complexity of management, lengthened lead-times and vastly increased the investment in inventory.

To regain the efficiencies of the mass production systems, Skinner (1974) advocated the use of the concept of focussed-factories, which advises concentrating on doing a few operations well within a plant and acquiring the rest from outside; i.e. through subcontracting. This manufacturing strategy essentially simplifies the flow lines in the factory and induces higher efficiencies. Such a strategy has been successfully used by the Japanese as part of their manufacturing policy. Statistics show that while purchased materials account for less than 50% of General Motors' sales dollar, they account for more than 80% at Toyota (Abernathy et al, 1981).

One further reason for the simplification of flow lines is the potential for automating entire subsystems or manufacturing cells. For example, group technology can be used to identify parts that require the same group of machines and work centers. This process automatically identifies those parts that cause problems in the simplification of flow lines (Vannelli and Kumar, 1984). When one uses subcontracting of these problem parts as a strategy to disaggregate production flows, one ends up with factories perfectly decomposable into several manufacturing cells that can be, if necessary, automated to obtain flexible manufacturing systems (FMS).

The decision to subcontract is, of course, not to be made solely with the objective of simplifying flow lines. The decision to make-or-buy a single component involves a number of considerations which are both financial and non-financial in nature (Gambino, 1980). Typically, the financial justification involves obtaining estimates of the fixed and variable costs for both internal manufacturing as well as for purchasing the part. These costs typically do not reflect the effect of production flow. Given these estimates, financial techniques such as net present value, internal rate of return and payback periods can be used to evaluate the profitability of each alternative for the single component.

The non-financial considerations, according to a study conducted (Gambino, 1980), are usually the primary determinants of the make-or-buy decisions for a single component. The various factors include level of activity within the factory (or utilised capacity), strategy of production smoothing to maintain level workforce, quality, quantity and dependability of supply. Another significant factor is legal in nature due to the interpretation that large-scale subcontracting can have much the same impact on employees as plant closings or relocation of plants. Therefore, there are labour laws that have been set up to protect the rights of the employees by making unlawful subcontracting subject to collective bargaining (Miscimarra, 1983).

In this paper, we undertake the task of identifying parts that could be analysed for the purpose of making a decision regarding subcontracting. The scenario we choose is that of a factory which is already producing many products and components using several machines and work centers. One of the primary goals to be achieved through subcontracting is the disaggregation of the production in the factory into manufacturing cells, the strategic goal being a focussed factory. The sizes of these cells can be controlled as a management policy parameter.

For example, Toyota prefers to have a maximum of five work centers (Schonberger, 1985). The identification of the problem parts can be guided either by trying to minimize the number of these parts or by assigning costs of subcontracting to each part and minimizing the total subcontracting cost. The first objective indicates a preference for minimal subcontracting based on non-financial reasons while the second objective indicates a preference for objective financial justification.

This problem is analogous to the tearing problem in graph partitioning (Steward, 1965) wherein one wishes to find the minimal number (or weight) of arcs to be cut to completely disconnect the graph. This problem has been approximated by linear transportation problems (Kumar et al, 1985, Kusiak et al, 1985). If there is initial information on certain parts that will not be subcontracted, then this problem can be approached using dynamic programming (Lee et al, 1979). The latter is the approach taken in this paper and we build on the previous work of Vannelli and Kumar (1984) wherein they implement an algorithm for the case of an unweighted graph. They show how minimal bottleneck machine cells (both parts and machines) or minimal bottleneck machines alone can be identified. In this paper, we explicitly develop an algorithm for the case of identifying minimal number of subcontractible parts with constraints on the number of machines in each cell. We also extend this algorithm to consider the case of weighted graphs and identify the subcontractible parts that minimize total subcontracting cost. We retain the attractive features of the interactive nature of the implementations (as in Vannelli and Kumar, 1984) and allow the manufacturing strategist complete flexibility in the analysis of the production system.

This paper is divided into five sections. Section 2 contains the modelling aspects of the subcontracting problem in the case of minimizing the number of subcontractable parts. The algorithm designed to solve this problem is outlined using an example. An extension of the algorithm to the case of minimizing subcontracting cost is contained in Section 3 along with an example. Applications of the algorithms to a larger sized problem are presented in Section 4. Section 5 presents our conclusions.

2. Minimal Bottleneck Part Problem and Subcontracting

In this section, we outline an approach for identifying parts that may be considered for subcontracting while disaggregating the production of the factory into disconnected manufacturing cells. We develop a greedy heuristic for finding the smallest number of subcontractable parts while disconnecting the plant operation into a fixed number of cells which contain at most k machines.

Although any part may be considered for subcontracting, we focus on the parts which lead to disconnected plant cells. We illustrate these objectives using an example of a job-shop facility which produces five part types on two drilling machines and three milling machines as shown in Fig. 1.

$$\begin{array}{ll|ccccc|}
 & & \multicolumn{5}{c}{\text{parts}} \\
 & & P1 & P2 & P3 & P4 & P5 \\
 & m1 & 1 & & & & 1 \\
\text{Milling department} & m2 & & 1 & & 1 & 1 \\
 & m3 & & 1 & & & 1 \\
\hdashline
\text{Drilling department} & d1 & & 1 & & 1 & 1 \\
 & d2 & 1 & & 1 & & 1
\end{array}$$

Figure 1

Note that a "1" in the ij^{th} position of this matrix indicates that part Pj is processed on machine mi.

Given the traditional process layout using departmental structure, we note that four of the parts are processed in both departments. Typically, this implies excess material handling and complexity in production planning and control. Noting that part P5 complicates the material flow by requiring all the machines for processing, it is a natural candidate for subcontracting. Assuming that this part is subcontracted, the remaining parts and machines can be re-organized as in Fig. 2.

$$
\begin{array}{lc}
 & \text{parts} \\
\begin{array}{rl} & \\ \text{Cell \#1} & \left\{\begin{array}{l} m1 \\ d2 \end{array}\right. \\ \text{Cell \#2} & \left\{\begin{array}{l} m2 \\ m3 \\ d1 \end{array}\right. \end{array}
&
\begin{array}{cc:cc}
\mathbf{P1} & \mathbf{P3} & \mathbf{P2} & \mathbf{P4} \\
1 & & & \\
1 & 1 & & \\ \hdashline
 & & 1 & 1 \\
 & & 1 & \\
 & & 1 & 1
\end{array}
\end{array}
$$

Figure 2

The plant is now re-structured into two manufacturing cells. Cell #1 contains one milling machine and one drilling machine which process parts P1 and P3 only. Cell #2 contains two milling machines and one drilling machine which process parts P2 and P4 only. Moreover, this cellular structure requires no material handling between the two cells unlike the process layout. Production planning and control can now be performed at the individual cell level, thus simplifying organizational complexity.

We describe an approach for achieving the disaggregation of the production in a factory into a fixed number of manufacturing cells via the subcontracting of parts. We proceed by defining the particular parts that achieve this disaggregation.

Definition 2.1 A set of parts whose deletion from a machine-part representation yields disconnected cells is called a bottleneck part set.

As a consequence of Definition 2.1, one would like to find the smallest number of parts whose deletion from the manufacturing process disconnects the factory into a desired number of cells, which contain at most k machines each.

Definition 2.2 A minimal bottleneck part set is the smallest (in cardinality) bottleneck part set whose deletion disconnects a machine-part representation of the factory into m disconnected cells each having at most k machines.

In Vannelli and Kumar (1984), it is shown that the problem of finding a minimal bottleneck part set is equivalent to finding the smallest set of cutnodes in a graph whose deletion disconnects the graph into m subgraphs having at most k nodes. We develop this approach to deal with the outlined subcontracting problem.

Consider the MxP matrix representation A of P parts that are processed on M machines, where

$$a_{ij} = \begin{cases} 1 & \text{if part } j \text{ is processed on machine } i \\ 0 & \text{otherwise} \end{cases}$$

Given that the number of desired cells is m and that k is the maximum number of machines permitted in each cell, then the solution of the minimal bottleneck part set satisfying these constraints is equivalent to permuting the rows and columns of A into a bordered block diagonal from A given in Fig. 3, where the number of columns (i.e. parts) in the border of A is minimized and the number of rows (i.e. machines) in $A_1, A_2, \ldots, A_m$ is less than k.

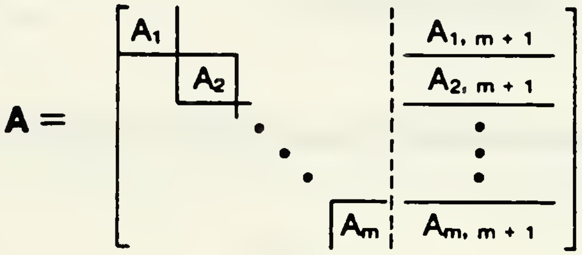

Figure 3

The problem of finding the smallest number of columns in the border of A is equivalent to finding the minimal bottleneck part set.

We propose a variation of the two greedy heuristics developed in Vannelli and Kumar (1984) to solve this problem. The algorithm requires one initial seed (part or machine) to be assigned to each of the m cells. The identification of the seeds, which are parts, may be accomplished simply by considering m parts that are not processed on the same machines. Equivalently, seeds, which are machines, may be found by considering m machines which do not process any common parts. Other more practical situations such as incompatability of machines in a cell may dictate the choice of inital seeding machines.

Algorithm 1

Step 1: $M \triangleq$ number of machines

$P \triangleq$ number of parts

$k_j \triangleq$ maximum number of machines permitted in cell j.

Choose a number of inital cells m.

Step 2: a) Choose m initial parts (one in each cell). Add all the machines attached to these selected parts.

OR

b) Choose m initial machines (one in each cell).

Step 3: Form a boundary part set for each cell j i.e., a set of parts which has not been assigned to any cell and which are processed on machines in cell j. Any node contained in more than two boundary part sets becomes a member of the minimal bottleneck part set and is removed from the list of boundary parts. Note that only part nodes are chosen at this stage.

Step 4: Select a part node from each boundary part set and add it to the corresponding cell with its attached machine nodes such that the sum of part nodes in the resulting bottleneck part set increases minimally and the upper bound on machines is satisfied. If the upper bound for a cell is not satisfiable for any chosen boundary part, then the cell is removed from further consideration.

If two boundary parts are linked by a machine, then only one of them may be added to the existing cells. Add the remaining machine nodes attached to the part nodes that have been added to m cells. The last operation along with the restriction that no two part nodes that have a common machine node are added to each cell assure that only part nodes can be added to the existing minimal bottleneck part set.

Step 5: Repeat Steps 3 and 4 until every node is assigned to a cell or minimal bottleneck part set.

Step 6: Repeat Steps 3 - 5 to find the best solution for other m initial parts or machines.

Example 2.1

Consider the 5 machine - 5 part example given in Fig. 4.

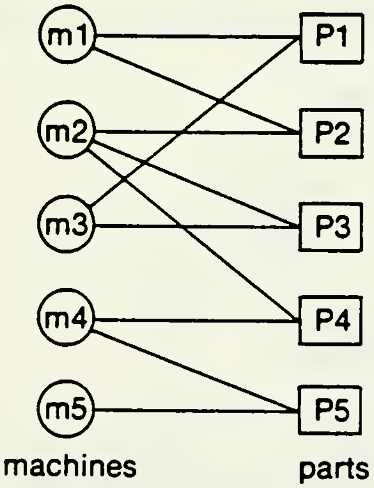

Figure 4

We apply Algorithm 1 to minimize the number of subcontractible parts while disaggregating this arrangement into two cells having at most three machines each.

Step 1: $M=5$, $P=5$, $m=2$, $k_1=k_2=3$.

Step 2: Choose parts P1 and P5 as initial parts in each cell and adding the machines attached to these parts, we obtain

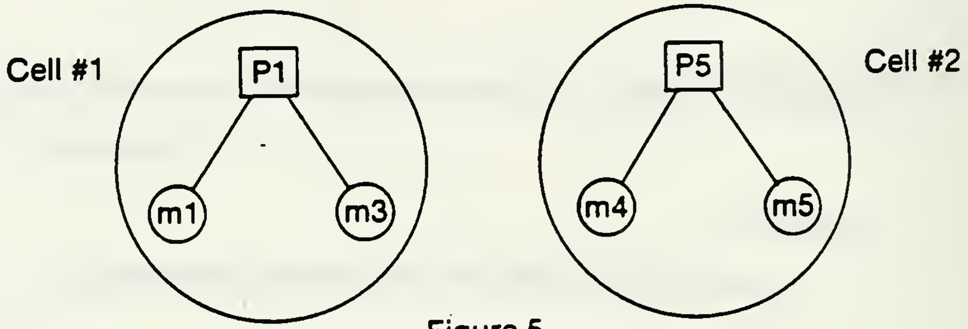

Figure 5

Step3(a): The boundary part set of Cell #1 contains parts P2 and P3 and boundary part set of Cell #2 contains part P4 only, as shown in Fig. 6.

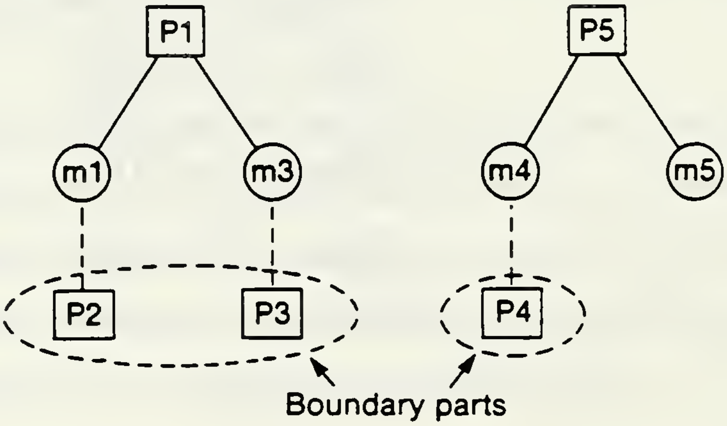

Figure 6

Step 4(a): We consider adding only part P2 or P3 to Cell #1 or part P4 to Cell #2. We do not consider adding part P2 or P3 to Cell #1 and part P4 to Cell #2 since either combination adds machine m2 to the bottleneck part set.

If we add P4 and its attached machine m2, then the minimal bottleneck part set contains the two parts P2 and P3 as shown in Fig. 7.

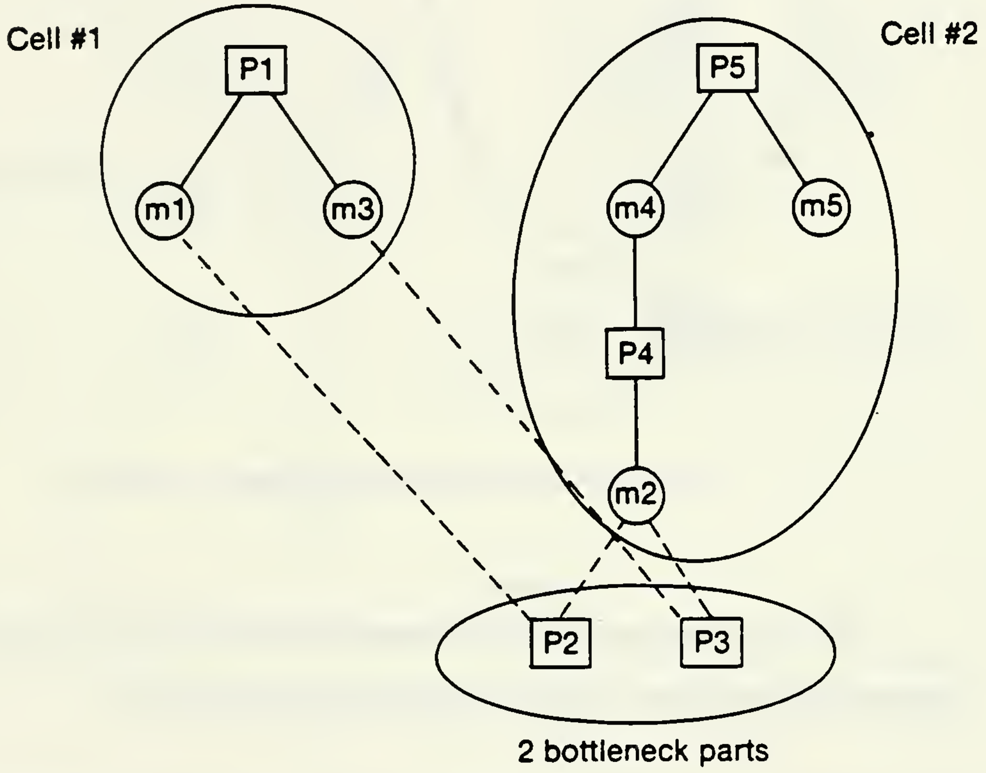

Figure 7. Cell groupings after adding P4 to Cell #2

However, if we add parts P2 or P3 (say P2) and its attached machine m2 to Cell #1, then the minimal bottleneck part set contains only part P4 as shown in Fig. 8.

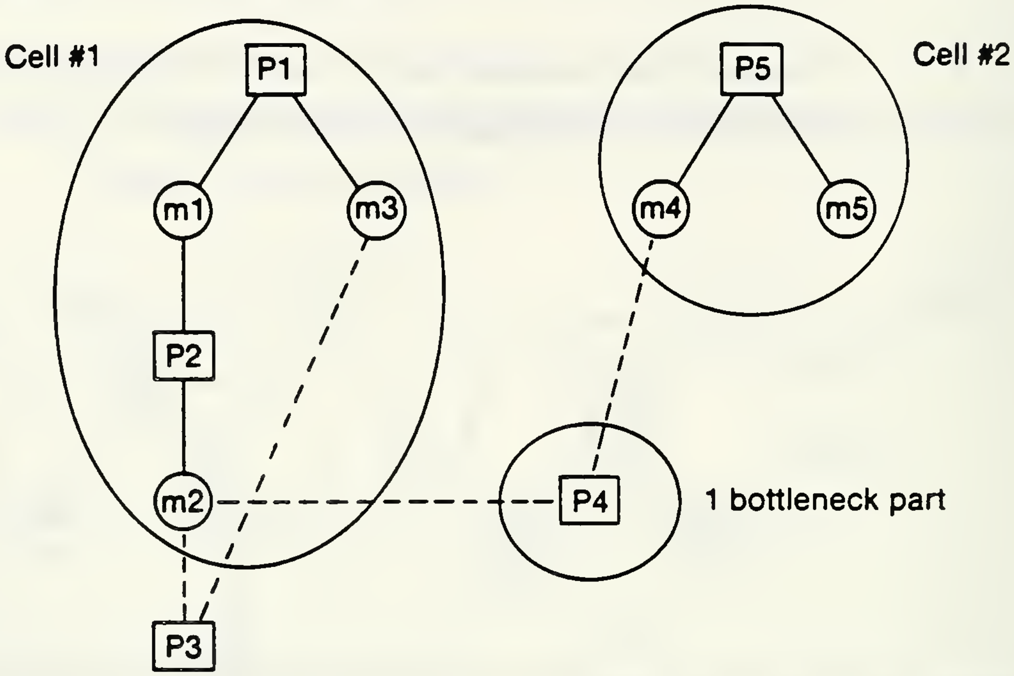

Figure 8. Cell grouping after adding P2 to Cell #1

Thus, we assign part P2 and its attached machine m2 to Cell #1 since it minimizes the number of bottleneck parts. Part P4 is assigned to bottleneck part set.

<u>Step 3(b)</u>: The boundary part set for Cell #1 contains P3 and boundary part set for Cell #2 is empty. Therefore one disconnected cell (Cell #2) has been found.

<u>Step 4(b)</u>: Since the addition of part P3 does not increase the size of the minimal bottleneck part set, we add part P3 to Cell #1.

<u>Step 5</u>: Every part and machine has been assigned to either a cell or the bottleneck part set as shown in Fig. 9.

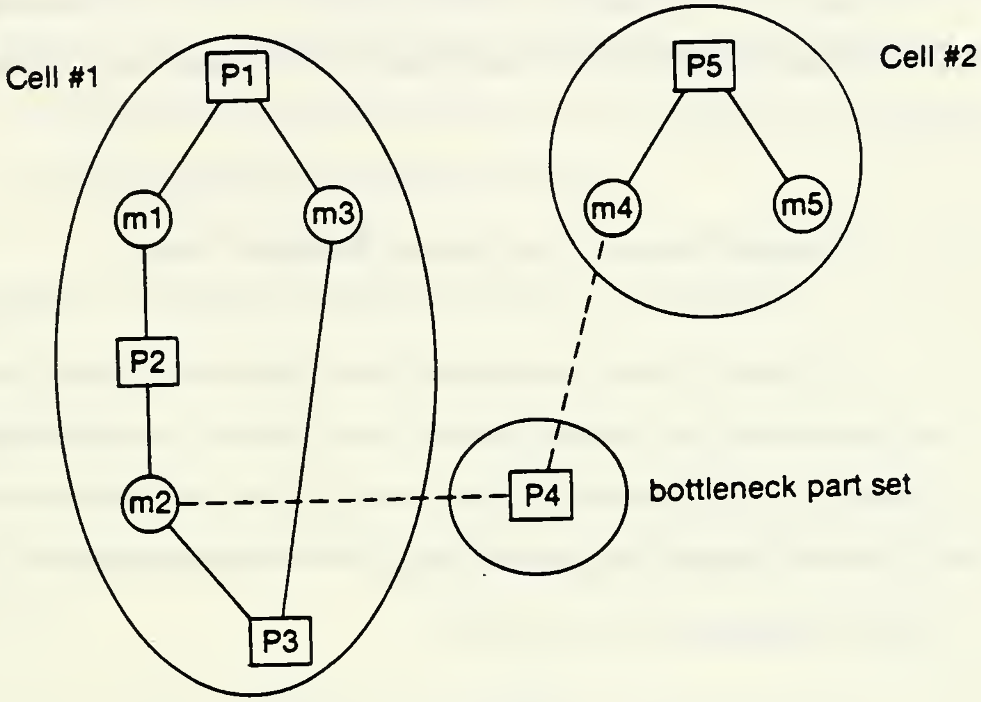

Figure 9

Algorithm 1 retains many of the desirable interactive features of the original version presented in Vannelli and Kumar (1984). It allows the designer to consider several disaggregated cell possibilities via subcontracting; this is achieved by allowing the designer flexibility in the choice of the number of cells m, cell size limits k_j and initial starting points. Similarly, Algorithm 1 is a polynomialy bounded heuristic. It can be shown that the algorithm requires $0 (v^m)$ storage and $0(v^m \log (v^m))$ running time, where v is the average number of edges attached to any node in the part-machine network. Since part-machine networks are sparse, the average number of edges v and the number of groups m tend to be small.

However, it differs in the assignment of parts and machines to the individual cells. Specifically, the new algorithm attempts to delete the smallest number of parts while satisfying cell size limits on machines; the minimal bottleneck machine algorithm (Vannelli and Kumar, 1984) attempts to delete the smallest number of machines while satisfying the same constraints. The concept of a generalized edge which considers the parts as just linkages between machines in the bottleneck machine problem is inappropriate in this new problem context.

3. Finding Minimal Total Cost of Bottleneck Parts

Algorithm 1 allows the plant designer to disaggregate a factory into manufacturing cells by subcontracting the smallest number of parts. However, in other circumstances, it is more desirable to consider the costs of subcontracting each part and minimize the total-subcontracting cost. Thus, one may subcontract more parts but the total cost of subcontracting these parts to achieve disaggregation may be much less.

This situation can be modelled by assigning a cost c_j to each part p_j. The costs are influenced by several factors. One of the components of the subcontracting cost is the difference between the average cost of producing the part internally and the purchase cost of buying the part from an outside vendor. Other qualitative and non-financial factors also affect the cost. For example, if a strategic goal is to maintain high quality control and/or a dependable supply of such a part, and if such aspects are unavailable from outside vendors, the designer may wish to impute a higher cost to this part. A designer could also shield proprietary parts from being subcontracted by assigning an infinite cost to this part.

Algorithm 1 can be easily modified to deal with the situation of subcontracting costs c_i being assigned to parts p_i.

Algorithm 2

This algorithm is the same as Algorithm 1 except we change Step 4 to:

Step 4': Select a part node from each boundary part set and add it to the corresponding cell with attached machine nodes such that the sum Σc_i of the costs of the parts in the resulting bottleneck part set increases minimally.

Note that Algorithm 1 is embedded in Algorithm 2 when $c_i = 1$ for each part p_i.

Example 3.1

We illustrated Algorithm 2 on the following modification of Example 2.1 shown in Fig. 10.

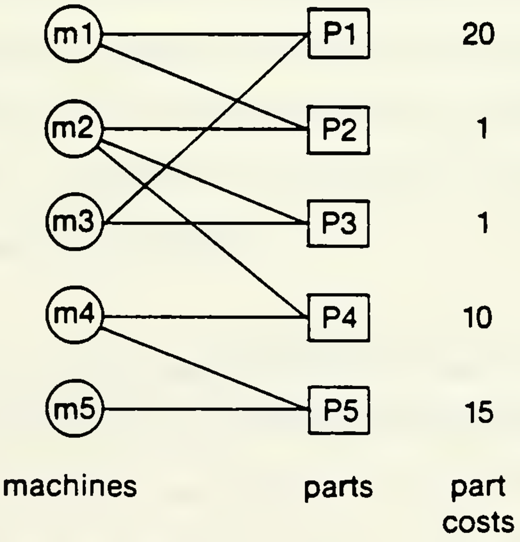

Figure 10

Step 1: $M=5$, $P=5$, $k_1=k_2=3$, $m=2$

Step 2: Choose parts P1 and P5 as initial parts in each cell. As before, by attaching the machines to these parts, we obtain the starting cells shown in Fig. 5.

Step 3: As in Step 3 (a) in Example 2.1, the boundary part set of Cell #1 contains parts P1 and P3 and the boundary part set of Cell #2 contains part P4 only as shown in Fig. 6.

Step 4: If we add part P4 and its attached machine m2 (see Fig. 7) to Cell #2, the total cost of subcontracting parts P2 and P3 is 2. However, if we add part P2 and its attached machine m2 (see Fig. 8) to Cell #1, the total cost of subcontracting part P4 is 10. Unlike Example 2.1, we now add part P4 and machine m2 to Cell #2 and obtain the two disconnected cells given in Fig. 7 with minimal bottleneck part set containing parts P2 and P3.

4. Numerical Results

Algorithms 1 and 2 have been coded in APL and are presently running on an IBM 4341 computer at York University Computing Centre. We tested the preceeding algorithm on a 30 machine-41 part example shown in Fig. 11. Subcontracting costs (which are given in thousands of dollars) for each of the parts were generated using a uniform distribution. This example is used to show the flexibility that a designer is given by using Algorithms 1 and 2.

Algorithm 1 is first applied on the unweighted parts problem (c_i=1 for all parts). The starting nodes are machines #17 and 30, m=2, $k_1 = k_2 = 20$. The minimal bottleneck part set contains parts 7,14, 18 and 28. Thus, by subcontracting these four parts (total subcontracting cost of $229,000), we disaggregate the factory into two cells having 20 and 10 machines respectively in each cell. The resulting two cells and minimal bottleneck part set is shown in Fig. 12. The same minimal bottleneck part set is obtained using Algorithm 2 on the weighted part problem (costs included) and using same initial seeds.

However, when the seed machines #1 and 30 are selected, m=2, $k_1=k_2=20$, the minimal total cost part set found using Algorithm 2 contains parts 5,6,19,24 and 37. The total subcontracting cost of $217,000 is a $12,000 saving over the grouping obtained in Fig. 12. However, this is achieved by subcontracting one more part. The two disaggregated cells and minimal bottleneck part set are shown in Fig. 13.

Finally, Algorithms 1 and 2 are applied using the starting machines #1, 17 and 30, m=3, $k_1=k_2=k_3=15$. The same bottleneck part set is found using both algorithms. It contains the six parts 6, 7, 14, 18, 19 and 24. The total cost is $233,000 to achieve the disaggregated cells and the minimal total cost bottleneck part set shown in Fig. 14. Although the given company would spend $16,000 more to subcontract these parts as compared to the two-cell representation given in Fig. 13, the production control advantages that three disaggregated cells afford may outweigh the subcontracting cost disadvantage.

The algorithms suggested are very efficient. Although the algorithms are presently coded in APL, they exhibit reasonable running times (in the range of 10-30 sec.) for the various problem scenarios tested. Any APL code can be accelerated by an order of magnitude by coding it in a high-level language. More important, the example also illustrates the flexibility that a designer is given in considering subcontracting strategies. For instance , using Algorithm 2 and changing the number of cells from two to three leads to a marginal increase in subcontracting cost and parts while potentially decreasing organizational complexity.

PARTS AND SUBCONTRACTING COST

MACHINES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
(part cost x $1000)	15	50	19	71	68	46	47	380	26	165	232	229	22	33	121	132	34	39	46	108	21	25	80	18	91	45	68	110	47	42	49	55	249	44	60	41	35	46	116	34	52
1										1																					1	1	1						1		1
2											1	1						1														1	1						1		1
3												1											1								1	1							1	1	
4							1								1									1	1			1							1						
5					1												1																	1		1					
6						1																				1															
7																1											1							1		1					
8	1							1	1					1															1												
9			1										1								1																				
10		1										1								1			1																1		
11										1																							1						1		1
12											1	1							1	1			1	1															1	1	
13																			1						1													1			
14				1	1													1								1											1				
15																	1																				1				
16						1																						1													
17							1									1											1									1					
18														1		1											1							1							
19	1		1																		1	1								1											
20	1		1																		1	1																			
21										1		1																			1	1	1							1	
22										1		1											1								1	1							1	1	
23		1										1											1								1								1		
24																																						1			
25				1																																					
26																1											1							1		1					
27								1							1																										
28								1																					1						1						
29	1		1						1				1								1									1											
30	1		1																		1	1																			

Figure 11

PARTS

Minimal Bottleneck Part Set

MACHINES

	10	41	32	33	31	40	11	23	39	12	19	24	38	25	15	35	8	29	9	13	30	22	21	1	3	20	2	4	37	5	26	17	6	36	27	16	34	18	7	28	14
1	1	1	1	1	1				1	1																															
21	1		1	1	1	1				1																															
11	1	1		1					1																																
2		1	1	1			1		1	1																												1			
22	1		1		1	1		1	1	1																															
12						1	1	1	1	1	1	1														1															
3			1		1	1		1	1	1																															
23					1			1	1	1																	1														
10								1	1	1																1	1														
24													1																												
13											1		1	1																											
4												1		1	1	1																							1	1	
27															1		1																								
28																1	1	1																							
8																	1	1	1					1																	1
29																			1	1	1		1	1	1																
9																				1			1		1																
19																					1	1	1	1	1																
20																						1	1	1	1																
30																						1	1	1	1																
14																												1	1	1	1							1			
5																														1		1		1			1				
25																												1													
15																													1			1									
6																															1		1								
16																																	1							1	
18																																		1	1	1	1				1
26																																		1	1	1	1				
7																																		1	1	1	1				
17																																			1	1			1		

Cell #1

Cell #2

Figure 12

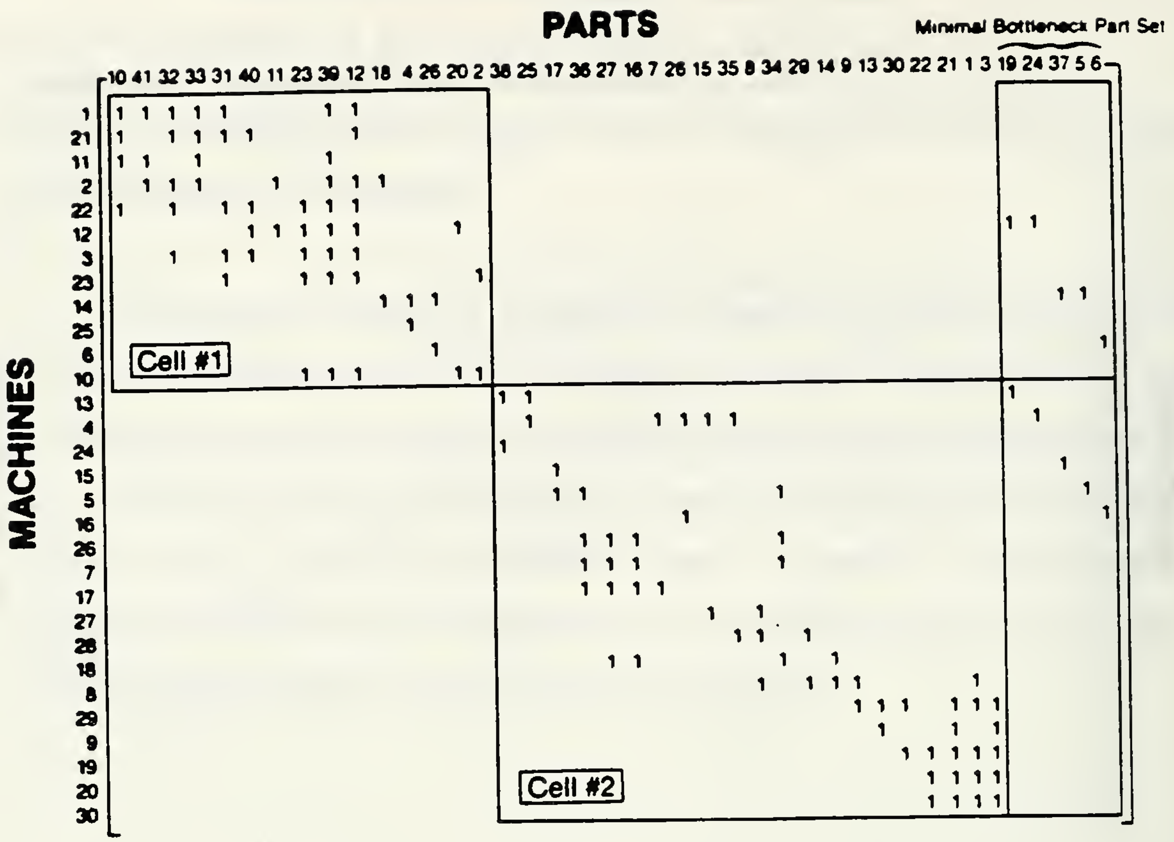

Figure 13

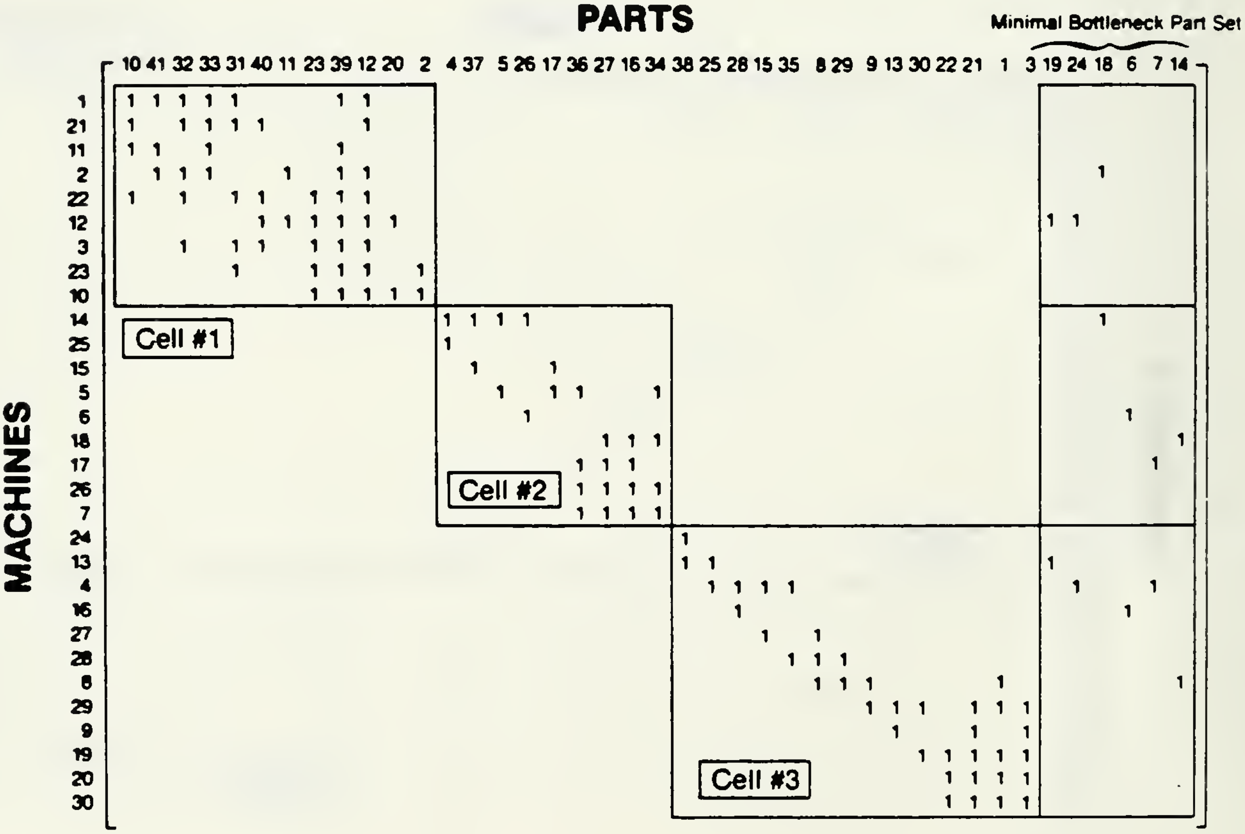

Figure 14

5. Conclusions

Subcontracting has been used as a strategic tool for production smoothing to maintain level workforce (Schonberger, 1985). Subcontracting has also been used in the form of make-or-buy decisions when new products or components are designed (Gambino, 1980). The former use of subcontracting reduces capacity levels and risks involved with seasonality, while the latter attempts to reduce the new capacity requirements using financial and non-financial considerations.

In this paper, we have used subcontracting as a new tool for re-designing an existing manufacturing system into a cellular manufacturing system. The aim of this subcontracting strategy is to reduce capacity and induce manufacturing efficiency by re-organizing the existing machines and parts into disaggregated cells. These disaggregated cells are a realization of Skinner's (1974) concept of a focussed factory, which can be automated to obtain a flexible manufacturing system.

We initially developed an algorithm to identify the minimal number of subcontractible parts while disaggregating the parts and machines into a fixed number of cells. The designer has the flexibility of choosing the number of cells and constraining the individual cell sizes, that is, the maximum number of machines permitted in each cell. The algorithm is extended to the case where a subcontracting cost is associated with each part. These subcontracting costs can be assigned by the designer through explicit consideration of financial costs, as well as non-financial factors such as quality, dependability and proprietary design. The second algorithm minimizes the total cost of subcontractible parts while disaggregating the parts and machines into a fixed number of cells.

The algorithms are presently coded in APL and performed very efficiently when tested on a 30 machine-41 part example. Any APL code can be accelerated by an order of magnitude by coding it into higher level language. This is currently being undertaken for Algorithms 1 and 2. The efficiency and flexibility of the proposed algorithms may serve as an important decision aid in production system design.

Acknowledgements

Part of the research of the second author (A. Vannelli) is funded by the Natural Sciences and Engineering Research Council of Canada grant no. U0381. The authors would like to thank the York University Computing Centre staff for making IBM's APL2 language available so that the outlined algorithms in this paper could be coded and tested.

REFERENCES

Abernathy, W.J., Clark, K.B. and Kantrow, A.M. (1981) "The New Industrial Strategy", Harvard Business Review, September-October, pp. 68-81.

Burbidge, J.L. (1975) The Introduction of Group Technology, Halsted Press, John Wiley and Sons, New York.

Gambino, A.J. (1980) The Make-Or-Buy Decision, National Association of Accountants, New York.

Kumar, K.R., Kusiak A. and Vannelli, A. (1984) "Grouping of Parts and Components in Flexible Manufacturing Systems", Working Paper #84-14, Department of Industrial Engineering, University of Toronto, to appear in a Special Issue of European Journal of Operations Research on Flexible Manufacturing Systems.

Kusiak, A., Vannelli, A. and Kumar, K.R. (1984) "Grouping Problem in Scheduling Flexible Manufactturing Systems", Working Paper #84-16, Department of Industrial Engineering, University of Toronto, to appear in Robotica.

Lee, J.G., Vogt, W.G. and Mickle, M.H. (1979) "Optimal Decomposition of Large-Scale Networks", IEEE Transactions on Systems, Man and Cybernetics, SMC-9, 7, pp. 369-375.

Miscimirra, P.A. (1980) "The NRLB and Managerial Discretion: Plant Closings, Relocations, Subcontracting and Automation", Labour Relations and Public Policy Series, No. 24, Industrial Research Unit, The Wharton School, University of Pennsylvania.

Reich, R.B. (1983) "The Next American Frontier, I and II", The Atlantic Monthly, March (pp. 43-58), April (pp. 97-108).

Schonberger, R.J. (1985) Operations Management, Business Publications, Plano, Texas.

Skinner, W. (1974) "The Focussed Factory", Harvard Business Review, May-June, pp. 113-121.

Steward, D.V. (1965) "Partitioning and Tearing Systems of Equations, "Journal of Numerical Analysis, Vol. 2, pp. 345-365.

Vannelli, A. and Kumar, K.R. (1984) "A Method for Finding Minimal Bottleneck Cells for Grouping Machine-Part Families", IBM Research Report RC 10763 (#48225), to appear in International Journal of Production Research.

HECKMAN
BINDERY INC.
JUN 95
Bound-To-Please® N. MANCHESTER,
INDIANA 46962

UNIVERSITY OF ILLINOIS-URBANA
3 0112 042410578