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An investigation into the application of group technology in advanced manufacturing systems

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Abstract. During the last two decades, firms have undergone a great change in their production methods and technologies because of the emergence of new manufacturing concepts and technologies. Traditional concept like group technology (GT) still plays a significant role in new manufacturing concepts such as just-in-time (JIT) and total quality management (TQM), and technologies such as flexible manufacturing systems (FMS), optimized production technology (OPT) and computer integrated manufacturing systems (CIM). In manufacturing systems, GT helps to achieve a reduction in setups, inventory level, and transportation time of goods, and provides an effective control of production. Considering the importance of GT in JIT, FMS, OPT and CIM, the available GT literature has been reviewed in this paper with the objective of studying GT techniques/models and their applications. In addition, frameworks are provided for future research directions in the areas of GT to enhance the applications of GT and its techniques/models.

1. Introduction

Group technology (GT) is a total manufacturing concept which requires identification of part families and machine groups in order to exploit similarities and achieve economies in the entire manufacturing cycle. Implementation of GT may involve the use of a classification and coding system for the direct analysis of production activities. A wide range of benefits are made possible, including design rationalization and variety reduction, and benefits such as reduced setup times, lead time and work-in-process inventory in the shop floor. GT has a wide application and this impacts all areas of manufacturing (Hyer and Wemmerlöv 1982). Alternatively, GT is a manufacturing philosophy that exploits similarities in product design and production process. One of the most important applications of GT in recent years is in the design of cellular manufacturing systems. Formation of part families and machine cells is the first step towards the design of cellular production systems. The resource grouping problem consists of partitioning machine tools of each machine type into machine groups so that each machine in a particular group performs the same set of operations. The part-selection problem involves grouping of parts into families for a simultaneous processing using a set of tools.

In the past GT has been treated as a technique that could be used to reduce the cycle time of a product. But in recent years GT has been treated as a manufacturing strategy to improve the performance of the whole manufacturing system. In particular, the role of the GT concept in advanced production systems is important in order to improve productivity and quality. For example, the application of GT in CIM systems facilitates the process of implementing CIM by simplifying the information control required and providing necessary information about process and production flow. The availability of a coding system for parts and production sequences, together with a database helps to design CAD/CAM and hence the development of CIM. In addition, GT facilitates the process of integrating various functional activities by smoothing out both the material and information flows. As noted earlier, GT cells provide flexibility in terms of process, labour, routes, facilities and routeing; these aspects support the design and implementation process of JIT and FMS. Besides, GT helps to achieve TQM in manufacturing organizations. The coding and classification processes generate data that can be used in quality function deployment (QFD) for improving quality and productivity. However, most of the reports look at GT simply as a technique and they seem to ignore the application of GT as a strategy to improve productivity by creating an environment that fully supports the implementation process of various advanced manufacturing concepts and technologies, such as setup time reduction, clear-cut information flow, integrating various functional areas by providing sufficient

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information, routeing flexibility, control over process and quality, and flexibility of labour force.

Most GT techniques/models consider only a limited number of factors in their criteria for grouping parts and machines that rarely facilitate the application of GT in real manufacturing systems. For instance, part families based on only geometrical configurations of parts may not result in good families, which may lead to an inefficient family of parts. However, other parameters such as batch size, process planning and volume of parts influence the performance of GT cells. Therefore there is a need to consider these factors in GT applications. A number of reports are available dealing with GT procedures and applications, however, most of them deal with developing GT procedures/models, rather than their application. In this direction, many authors seem to have missed the issues involved in GT application while developing models and procedures. In addition, applications of GT in areas other than manufacturing such as marketing, design, distribution and accounting, has not been motivated. Unfortunately, little has been done to study the implications of GT cells in JIT, FMS, OPT, TQM and CIM. In this paper, an attempt has been made to provide an overall review of the techniques/models and application of GT.

The organization of this paper is as follows: Section 2 deals with the application of GT in advanced manufacturing systems. Section 3 reviews the literature available on GT for the purpose of understanding the techniques/models and applications of GT. The scope of GT in advanced manufacturing systems is presented in Section 4. Section 5 deals with the comments on the available GT literature and future research directions in the light of advanced production systems. The conclusions of this research are presented in Section 6.

2. Application of GT in advanced production systems

As noted earlier, GT is one of the most important aspect in the design of cellular manufacturing systems (CMS). Generally, the basic objective in designing a CMS is the identification of part families and machine groups based on the similarity of characteristics. GT cells provide greater ease of automation and facilitate the design and implementation processes of CIM and FMS. Cellular manufacturing has been recognized as one of the most recent technological advances in job-shop or flow-shop type production to: (i) minimize the total material handling costs due to inter-cellular moves; (ii) maximize within-cell utilization of machines; and (iii) minimize the duplication of machines in different cells.

In recent years, the application of GT has become a starting point for the design of FMS, JIT, TQM and CIM. Grouping of parts and machines into cells leads to cost savings in setup time, labour, tooling, rework, scrap, machine tool maintenance and work-in-process. Other intangible benefits include highly reliable delivery time, higher management efficiency, lower product throughput time, improved response to customers and better product quality. The standardized setups lead to easy scheduling and control, reduced material handling and fast learning. It is well known that JIT includes a simplified production line and standardized products. GT can be used to form a family of parts and machines which would lead to standardized products and a simplified production line. A GT cell will provide logistic support for employing pull/Kanban material flow in JIT manufacturing systems. The concept of GT can also be extended to supplier's resources as well. The information flow is simplified in GT cells and this supports an easy integration of different workstations in JIT manufacturing systems. Because of this feature, the 'dynamic process quality control' (DPQC) could be established easily in GT cells with minimum effort. DPQC means that whenever a process goes out of control, the process is stopped immediately so as not to produce any defective items. The operation is resumed only after bringing the process to the normal working condition.

The details of the application of GT in JIT, TQM, CIM and FMS are presented in Figure 1. However, these issues are general in nature and may be applicable to any advanced manufacturing system for improving productivity and quality with the help of GT and GT manufacturing cells. Usually, productivity improvement strategies (e.g. new products, improved design and quality, and cost control) are based on business strategies (e.g. increase in market share, new markets, and price

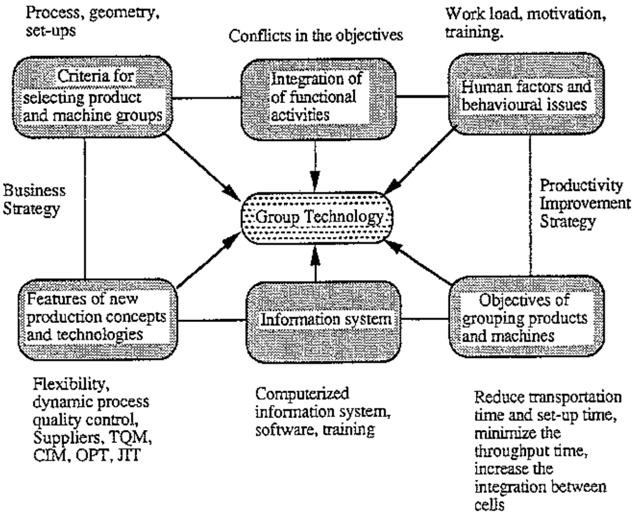

Figure 1. Group technology and applications.

reduction). In order to increase the effectiveness of manufacturing systems, the integration between business and productivity improvement strategies is essential. GT facilitates an easy communication flow between the various functional departments of the manufacturing organization including design, engineering, marketing, suppliers etc. This helps to achieve an easy integration of various functional areas. The criteria selected for machine and product grouping problems in JIT and FMS must satisfy the characteristics of these systems such as Kanban material flow, dynamic process quality control, on-line scheduling, automated tool loading and unloading and automated guided vehicle systems (AGVS).

In FMS, GT cells form the core of the whole system. The purpose of a GT cell in FMS is to provide flexibility, better communication and production control, and layout support for material handling purposes. In addition, GT provides logistic support to integrate different workstations within a cell using computers and softwares. This may help to reduce the level of highly skilled labour required in FMS. The layout issue is very important in GT cell design, especially in FMS. However, most of the available GT literature seems to ignore the characteristics that are directly relevant to JIT and FMS, while designing GT cells in such circumstances. In the light of these circumstances, a review of GT literature may be useful to identify bottlenecks in applying GT, pros and cons of available GT techniques/models, future research directions and applications of GT in advanced manufacturing systems.

3. A brief review of GT techniques and applications

A large number of research reports that deals with the GT concept are available. However, most of them seem to focus on GT techniques/models such as coding and classification schemes. Moreover, the majority of the research reports available appear to be dealing with the GT techniques/models which are based on various procedures such as GT, sequential decision procedures, and mathematical programming. Unfortunately, the practical issues of GT have not been given due consideration in their modelling processes. However, these issues play a significant role in controlling and improving the efficiency of production operations. Most of the GT models/techniques do not given due attention to the selection of suitable criteria for grouping of parts and machines, and other operational and technological constraints. For example, operational and technological constraints, such as type of production control, information flow, material handling, and quality control, should be considered while grouping the items and machines using the GT concept. Furthermore, human aspects of GT (e.g. workload per operator, training and education) should be given due consideration while establishing criteria for coding and classification schemes in the design of GT cells.

An overall classification scheme of GT literature based on: (i) GT techniques; (ii) applications; (iii) general frameworks, (iv) comparative studies explaining the features of different GT techniques/models; and (v) empirical studies, is presented in Table 1.
This classification reveals that at least 80% of the literature focuses on developing models, procedures, general frameworks, comparative studies of GT methods and empirical studies. We can observe that less than 20% of the GT literature has been devoted to GT applications. However, considering the practical importance of GT in JIT, FMS and CIM, it may be a worthwhile effort to identify the problems involved in applying the GT concept in practice, and develop a framework for the application of GT in advanced manufacturing systems such JIT, FMS, TQM and CIM.

GT is nowadays considered as most appropriate for improving the productivity of large and medium-sized batch production systems. For a long time after its development (Burbidge 1975) it was treated as a set of empirical ideas based on subjective factors, until McAuley (1972), Carrie (1973), Rajagopalan and Batra (1975), and Purcheck (1985) brought a significant turn in the direction of thinking. However, the unavailability of a dependable and efficient algorithm limited the use of GT to specific problems until King and Nakornchai (1982) suggested the rank order clustering algorithm to solve this problem. It is well known that block-diagonalization of the machine-component incidence matrix is the first step in the implementation of GT. The preferred situation, one in which all the ones are in the diagonal blocks and all the zeros are in the off-diagonal blocks, is usually far from perfect. This could be either due to the properties of the data or the inadequacies of the algorithm or both (Kumar and Chandrasekharan 1990). However, powerful algorithms may fail to achieve this if the matrix itself is not amenable to block-diagonalization. Recently, Chandrasekharan and Rajagopalan (1986a,b, 1987, 1989) and Chan and Miller (1982) presented a number of approaches based on GT for grouping parts and machines, which perhaps enriches the literature on GT applications. Strudel and Ballakur (1987) presented a heuristic based on dynamic programming for grouping of machines in manufacturing cell formation. Waghodekar and Sahu (1987) presented machine-component cell formation in GT.

The methods available for solving the resource grouping problem can be classified into three major cate-

Table 1. Classification of available GT literature.

Focus	Literature
1. GT techniques	Adams and Sherali (1986)
	Al-Qattan (1990)
	Askin and Chiu (1990)
	Ballakur and Studel (1987)
	Ben-Arieh and Triantaphyllou (1992)
	Boctor (1989)
	Chan and Miller (1982)
	Chandrasekharan and Rajagopalan (1986a, b, 1987, 1989)
	Frazier and Gaither (1991)
	Harhalakis *et al.* (1990)
	Kaparthi and Suresh (1992)
	Kumar and Chandrasekharan (1990)
	Kusiak (1983, 1987)
	Kusiak and Chow (1985)
	Leskowsky *et al.* (1987)
	Logendran (1992)
	Mulvey and Crowder (1979)
	Okogbaa *et al.* (1992)
	Purcheck (1985)
	Rajagopalan and Batra (1975)
	Shafer *et al.* (1992)
	Shtub (1989)
	Stecke (1983)
	Waghodekar and Sahu (1987)
	Wemmerlöv and Hayer (1984, 1986)
	Whitney and Gaul (1984)
	Wu *et al.* (1986)
2. Applications	Chakravarty and Shtub (1986)
	Choobineh (1988)
	Damodaran *et al.* (1992)
	Dumolien and Santen (1983)
	Globerson and Millen (1989)
	Gupta and Seifoddini (1990)
	Huber and Hyer (1985)
	Hyer (1984)
	Hyer and Wemmerlöv (1982, 1984)
	Kern and Wei (1991)
	Kumar *et al.* (1986)
	Kusiak (1984)
	Nandkeolyar and Christy (1992)
	Savage-Moore (1988)
	Shiko (1992)
	Sule (1991)
	Taheri (1990)
	Tatikonda and Wemmerlöv (1992)
	Ventura *et al.* (1990)
	Welke and Overbeeke (1988)
3. General framework	Burbidge (1979, 1992)
	Burbidge and Dale (1984)
	Choobineh (1988)
	Huber and Hyer (1985)
	Hyer (1984)
	Hyer and Wemmerlöv (1982, 1984)
	Ingram (1934)
	McAuley (1972)
	Ohashi and Hitomi (1991)
	Wemmerlöv (1988)
	Wemmerlöv and Hyer (1987)
4. Comparative studies of GT procedures and applications	Chu and Tsai (1990)
	Flynn and Jacobs (1986)
	King and Nakornchai (1982)
	Sassani (1990)
	Shafer and Meredith (1990)
	Wei and Kern (1989)
5. Empirical studies	Fazakerly (1976)
	Hyer (1984)
	Hyer and Wemmerlöv (1985, 1989)
	Wemmerlöv and Hyer (1987, 1989)

gories: GT (Chakravarty and Shtub (1986), Hyer and Wemmerlöv 1985, King and Nakornchai 1982, Kusiak 1987), sequential decision procedures (Whitney and Gaul 1984), and mathematical programming (Kumar *et al.* 1986, Kusiak 1987, Mulvey and Crowder 1979, Stecke 1983). In general, GT determines part clusters by measuring 'similarities' among parts. For the GT grouping problem, the GT approach needs to code characteristics of the parts and their associated components such as tools, pallets and fixtures. However, GT has to account for the constraints present on the number of part types and associated components in each group. For the sequential decision approach, each decision is based on the magnitude of the product of probabilistic performance criteria designed to trade off many competing attributes (Whitney and Gaul 1984).

The literature relating to the problem of group, formation has been viewed by King and Nakornchai (1982), Ballakur and Steudel (1987), and Kusiak (1987). The simplest form of group formation problem was suggested by Kusiak (1987) in which a part type can be processed by more than one process plan. Kusiak proved that the group formation problem is similar to the generalized assignment problem (GAP). Mulvey and Crowder (1979), and Kusiak (1983) used Lagrangian relaxation technique to solve a 0 – 1 linear integer programming formulation of the grouping problem which considers only similarities of the objects (parts) for clustering purposes. Stecke (1983) formulated the machine grouping problem as a nonlinear mixed integer program. Several linearization methods (e.g. Adams and Sherali 1986) were applied and computational results showed that the formulation and solution approaches performed well for small problems. Choobineh (1988) proposed a two-stage approach for part families and cell formation problems. However, this approach suffers from its inability to handle exceptional components and it ignores part sequencing and various cost aspects of the system. But part sequencing and the different costs involved decide the design and operational efficiency of FMS, JIT and OPT.

Kumar *et al.* (1986) modelled the machine–part grouping problem as an optimal k-decomposition of weighted networks, which is a 0–1 quadratic program. A modified eigenvector approach was used to approximate the global solution of the quadratic program. Kusiak and Chow (1985) presented an efficient method for solving the GT problem using 0–1 integer programming formulation. Shtub (1989) demonstrated that the simple cell-formation problem is equivalent to the GAP. Further, he has shown that the general case of cell formation, in which several process plans are considered for each part type, is also equivalent to the GAP. Shtub presented an interesting and simple cell formulation problem using the concept of a generalized assignment problem for a computer-aided process planning (CAPP). However, the CAPP is a central part of computer-aided manufacturing (CAM) and its influence on GT and the design of manufacturing cells has to be researched further. This particular research may be useful in the development of CIM to analyse the production flow pattern and corresponding information flow. Moreover, the information obtained by GAP can be used in the analysis of quality function deployment (QFD) and design for manufacturing (DFM).

If we scrutinize the applications of GT in manufacturing firms, the demand for flexibility in terms of frequent product changes and smaller batch quantities in dealing with the desire for shorter throughput times, necessitates reorganization of the existing facilities. Cellular manufacturing system helps to achieve these objectives in manufacturing which is the core part of FMS and JIT. As mentioned earlier, the basis for implementation of cellular manufacturing systems is the allocation of parts or components with certain similarities into groups or families, and the formation of machining cells which are capable of manufacturing one or more part families. This facilitates the control of manufacturing within or between cells, rather than at the individual machines, using a combination of computer-controlled machining and handling devices. Hyer and Wemmerlöv (1989) reported the findings of a survey of 53 US users of GT. These firms have applied GT to design, process planning, sales, purchasing, cost estimation, tooling, scheduling, new equipment sizing, and tool selection. In the majority of the cases, firms used classification and coding systems as tools in applying GT. However, users identified that managerial and technical barriers should be resolved while applying GT. The authors stressed the importance of education and training on GT. Individuals at all levels of the organization should be provided with hands-on training, basic information on GT principles, and payoffs from its use in order to reduce the resistance to GT implementation.

Increased competition has manufacturers receptive to ideas that improve competitiveness. Foremost among the ideas that have achieved widespread acceptance is JIT. In JIT, much attention has been focused on setup reduction, pull systems and the application of statistical process control. On the other hand the aplication of GT, called cellular manufacturing (Burbidge 1963, 1975, 1979, Burbidge and Dale 1984, Hyer and Wemmerlöv 1982, 1984, 1985, Wemmerlöv 1988, and Beeby and Thomson 1979) has not received the same attention. But this process has a tremendous role in achieving JIT material flow. Wemmerlöv and Hyer (1989) presented the analysis of a survey study of 32 US firms involved with cellular manufacturing. They covered areas that include the reason for establishing cells, benefits achieved, types and sizes of cells, extent of cellularization in the plants, methods used to design the cells, changes to planning and control systems, labour-related issues and important experiences gained by the companies. According to their study, many companies have implemented GT cells with an objective of reducing the cost of indirect labour and inspection. In addition, they discussed the problems related to implementation and operation of cells such as operator, resistance, lack of teamwork skills, machine breakdown, volume/capacity imbalance, etc. GT applications other than cellular manufacturing are described in Hyer and Wemmerlöv (1982). Sassani (1990) presented a simulation study on the performance improvement of GT cells. Gupta and Seifoddini (1990) presented a framework based on a similarity coefficient to take into account product demand and other processing parameters in machine–component grouping. This method incorporates relevant production data such as part type production volume, routeing sequences and unit operation time.

Raja Gunasingh and Lashkari (1989) addressed the simultaneous consideration of part families (for example, based on geometric configuration and processing requirements) and machine grouping to facilitate an effective cell design. Al-Qattan (1990) offered an efficient method of forming flexible manufacturing cells (FMCs), based on branching from a seed machine and bounding on a completed part. This method treats the formation of machine cells and parts family as a network analysis problem. Further, it can serve as a decision aid to enerate possible grouping and identify the minimal duplicated machines. Boctor (1989) presented an efficient heuristic for the machine grouping problem in FMCs. He also presented a new linear zero-one formulation which seems to have most of the advantages observed in other models. Success or failure of the application of GT to any problem depends upon the characteristics of the basic data, namely machine-component incidence matrix. This point has been stressed by Kumar and Chandrasekharan (1990). Cellular manufacturing is gaining increasing popularity as a means of improving productivity and competitiveness. As a result, much research has been devoted to the development of cell formation techniques. Unfortunately, very little research has been aimed at comparing the numerous cell formation procedures. Considering the importance of this, Shafer and Meredith (1990) compared selected cell formation procedures and offered insights by collecting data from three actual manufacturing plants.

The literature available on GT appears to be ignoring the variation in product mix, product design, market situation and other related technical factors over a time period which force a total system reorganization. The simulation of real existing cells using the concept of intra-cell sub-batch work transfer may improve system utilization through the application of various operational strategies, before resorting to costly cell reorganization. A more recent comprehensive simulation study on manufacturing systems has pointed out several problem areas relevant to the GT philosophy (Flynn and Jacobs 1986). It has been shown that the utilization of a GT cell can be improved through sub-batch workload transfer. In the context of this study, a detailed and practically oriented computer simulation analysis was found to provide a most useful aid to management decision making in sensitive situations. (Refer for detailed discussion on the application of GT to Hyer and Wemmerlöv 1984, 1985, 1989, Wemmerlöv and Hyer 1984, 1986, 1987, Ingram 1984, Kusiak 1984, and Ransom 1972.) Globerson and Millen (1989) developed learning curve models for GT situations which account for shared learning that occurs when multiple products utilize the same process steps. This particular aspect of the learning curve in JIT-GT cells impacts the level of skills and workforce required.

In a flexible manufacturing environment, batch production is necessary not only for satisfying technological constraints but also to obtain potential reductions in processing time, work-in-process and finished goods inventories, and to simplify the production planning process. The central aspect of batch production is grouping part types and required tools into families for simultaneous processing. Wei and Kern (1989) presented a linear clustering algorithm based on the calculation of a commonality score which indicates the similarity in the way two machines are used in the shop for manufacturing the parts. This algorithm's computational complexity is linear and this makes it very easy to code.

During the last few years, a number of research reports have concentrated on the selection of parts, and grouping of parts and machines in FMSs. However, very little effort has been directed at selecting the most suitable method. For example, different clusters may produce conflicting results under different performance measurement criteria. Chu and Tsai (1990) compared three array-based clustering, algorithm—rank order clustering, direct clustering analysis, and bond energy analysis, for manufacturing cell formation. According to their experiments, bond energy analysis performs better than the other two methods, without considering the type of measures or data set used. Rajamani *et al.* (1990) considered a generalized GT problem of manufacturing a group of parts in which each part can have alternative process plans and each operation in these plans can be performed on alternative machines. They presented three integer programming models to successively study the effect of alternative process plans and simultaneous formation of part families and machine groups. However, considering the limit of integer programming capability in modelling this problem, there is a need to develop heuristic or approximate procedures.

Hwan and Shogan (1989) discussed a part selection problem for a FMS with versatile machine tools but with no tool transportation devices. Harhalakis *et al.* (1990) proposed a two-fold heuristic algorithm for minimizing the inter-cell material movement, and addressing the industrial applications. Ventura *et al.* (1990) presented a mathematical formulation for the FMS part-tool grouping problem and proposed an efficient method for determining the optimal solution. Askin and Chiu (1990) presented a mathematical model and heuristic algorithm for the GT configuration problem. They incorporated first the costs of inventory, machine depreciation, machine setup and material handling in a mathematical programming formulation. The proposed heuristic posseses several special features. First, it considers the cost in the model and second, it includes the possibility of machines of a common type being assigned to different cells. Sule (1991) examined the effect of production capacity on machine grouping in cellular manufacturing using GT and developed a procedure for determining the number of machines, their groupings and the amount of material transfer between the groups, so that all components can be processed within the plant with minimum total cost.

Ohashi and Hitomi (1991) discussed the effective use of a single NC machine with multiple functions with an objective to pursue fully-automated, unmanned production. They considered limited capacity for the tool magazine, available processing time and restricted machining force. Frazier and Gaither (1991) studied whether the seed machine selection rules have any appreciable impact on the performance of cell formation heuristics. They identified that the best of the random seeds approach yielded the optimal solution on the sample problems with which it was compared. This approach can be used on any personal computer and only requires a few minutes of processing time. Logendran (1992) developed a two-phase methodology leading to the development of a realistic binary linear programming model which takes into account the sequence of operations and budgetary restrictions to carry out the duplication process in manufacturing problems. The purpose of this model is that once the part-machine assignments to cells have been determined in a cellular manufacturing problem, the process of duplicating bottleneck machines is usually performed as, in the long run, it significantly reduces the material handling costs incurred by parts creating inter-cell moves. Ben-Arieh and Triantaphyllou (1992) identified two types of fuzzy features: qualitative features, and quantitative ones with subjective meaning. They presented a methodology to deal with crisp and fuzzy data in a unified manner. Also, some clustering approaches which process the quantified features are discussed. They offer the advantages that, first, it allows adoption of the GT approach to specific features and specific needs, and, second, the user can define the importance of the features in the specific scenario of interest.

Kern and Wei (1991) presented a method to identify the opportunities for reducing the number of inter-cell transfers caused by the existence of exceptional elements. Nandkeolyar and Christy (1992) concluded from their investigation that more flexibility is not necessarily better than less flexibility, and that as product diversity increases, for a given system there is a level of flexibility that will optimize system performance and minimize the rate of its deterioration. Kaparthi and Suresh (1992) presented a neural network custering method for the part-machine grouping problem in GT. They used a Carpenter-Grossberg network because this clustering method utilizes binary-valued inputs and it can be trained without supervision. This approach can handle very large problems. However, further research is required to investigate and improve the performance of this algorithm in the case of imperfect data. Shafer *et al.* (1992) developed a mathematical programming model that deals with exceptional elements which can be eliminated by changing the design or the process plans of the parts. This idea can be used in TQM. Their model considers three important costs: (i) inter-cellular transfer; (ii) machine duplication; and (iii) subcontracting. This model is an optimization model that recognizes possibly advantages using mixed strategies which are ignored by previous approaches. Shiko (1992) reported on constrained hierarchical clustering applied to similarity analysis, the grouping of process plans and, consequently, the parts manufactured in accordance with them. This approach has contributed to solving the family formation problem in CAPP.

Rajamani *et al.* (1992) considered cell formation in a manufacturing environment where there are significant sequence-dependent setup times and costs. The trade-off between the savings on sequence-dependent setup costs and additional investment on new machines has been identified and modelled by them. However, the reported mixed integer programming model is applicable only for repetitive cycle production. Okogbaa *et al.* (1992) developed a new heuristic for part families and machine cell formation that provides alternative solutions. Also, they developed a simulation model of a GT system using the new heuristic and compared this with that of a traditional process layout system. Damodaran *et al.* (1992) considered the problem of assigning operations of part types to one or more machines in a cellular manufacturing system. They developed a mixed integer linear model considering the trade-off between refixturing and material handling movement. However, the resulting formulation cannot be implemented for large size problems. Therefore, there is a need for heuristic or approximate solution procedures.

Table 2 gives the classification of available literature on GT which is based on the techniques used in grouping of products and machines. It is noticeable that most of the literature belongs to clustering and mathematical programming models. However, the application of mathematical programming models seems to be limited from the view that they consider only a limited size of problem and this may not represent the real situation. The GT clustering method appears to be dominating the GT techniques owing to the fact that it uses numerical weight for various subjective factors in resource grouping problems. However, the clustering method does not consider many operational and technological constraints as compared to that of mathematical programming models. Many subjective factors that represent realistic situations have not been included in both procedures. Therefore, a number of researchers have proposed simulation models, fuzzy theory, and AI and expert systems to consider more realistic, qualitative and quantitative factors. Nevertheless, the human factors and behavioural and managerial issues have been simply ignored in their modelling approaches. Therefore, one must consider these factors in order to enhance the applications of GT in practice.

Welke and Overbeeke (1988) argue that cellular manufacturing is the best technique available to achieve JIT manufacturing philosophies and report the experiences at Deere & Co. The use of GT at this company has allowed engineers to group parts into smaller part families by geometric similarities or part/product likeness. The most successful efforts at implementing manufacturing cells included unified and well-defined objectives. At Deere, these were communicated and became goals for all members of the manufacturing team. Simulation has increased by providing alternative routes. However, grouping of machines based on process similarity may not be very efficient from a product flexibility point of view. Therefore, considerations should be given to process similarity and product flexibility when designing manufacturing cells for FMSs.

The influence of human factors has not been given due attention in GT applications to manufacturing. For instance, if there are a large number of machines and products with different characteristics such as imbalance in capacities, demand, and skills required, the attitude of the workers may be negative. This may result in lower labour productivity in a manufacturing cell. Therefore, considerations should be given to human factors such as workload per operator, training and education level when designing a GT cell for JIT and FMS.

Layout and material handling systems play a significant role in decisions related to the design of GT cells in FMS. However, this issue has not been given due consideration when designing GT cells for FMS and JIT. For instance, JIT demands a U-shaped layout with a view to increasing the efficiency of operators in controlling the production process and process quality. Now, the question is whether GT can accommodate a U-shaped layout in JIT manufacturing systems. This issue should be addressed very carefully, taking into account material handling cost, Kanban material flow, and human operator performance. In the case of FMS, AGVS is important for material handling purposes. The problem of synchronization between the speed of machines and AGVS should be considered when designing a GT cell for FMS. This should also include the operational and layout aspects of robots in GT cell design for FMS, JIT and CIM.

The interaction between cells is important whether in terms of processing or production planning or information flow, and must be considered when designing a manufacturing cell in FMS or JIT with the objective of facilitating the application of GT techniques. The design of a GT cell should be based on the level of independency of other associated cells. Also, the level of independency between cells in JIT or FMS should be addressed from the viewpoint of the amount of information flows between cells and the integration of cells using computers, considering the trade-offs between associated costs, such as cost of information system, inventory cost and material handling cost.

In FMS, the application of GT in tool management and storage of jigs and fixtures might also result in significant savings in administration costs related to location and identification. Similarly, other operational and technological constraints in JIT and FMS should be considered when designing a GT cell. Also, GT should support integration of various functional activities with a minimum amount of information flow between cells and within cells. This would also facilitate the processes of design and implementation of CIM.

The concept of GT should be extended to subcontractors with the objective of integrating the activities of various cells in a manufacturing organization including those of suppliers. GT cells at the supplier's system may act as an integration tool to achieve JIT production and maintain high quality both at the purchasing and supplier systems.

OPT can be used to eliminate bottleneck operations in JIT manufacturing systems and FMS. This bottleneck operation/stage can be considered in the GT cell using the trade-off between cost of capacity and bottleneck operations or machines. This concept can be integrated at the design stage of JIT and FMS.

There are very few techniques of GT that consider the batch size, processing time, and setup time while selecting parts. Similar situations exist in machine grouping problems also. Various aspects such as capacity, cost of machines and integration between various machines, including human aspects of processing the part in a cell, have not been included in resource grouping problems using the GT concept.

5. Future research directions in the areas of GT

Reducing the gap between theoretical and practical aspects is very important in today's manufacturing environment. In this section, future research directions are presented in order to enhance the applications of GT models/techniques in the light of advanced manufacturing systems.

Future research is needed to compare the available cell formation procedures in different situations. The main aim of this research would be the development of guide lines pertaining to the selection of cell formation procedures based on objectives, environments and characteristics of specific firms. In addition, pointers for new cell formation procedures based on the deficiencies discovered in current techniques may result from this research. For example, currently similarity coefficients typically rely on substitute measures, such as common machines required in processing, to evaluate the similarity between parts. Similarity coefficients that employ more direct measures, such as similarities between parts in terms of setups and tooling, may yield better results. Another possible way cell formation procedures might be improved is through the use of part volume data. Research such as this is clearly relevant and timely to a large number of manufacturing organizations. The extension of group analysis to the generalized group formation problem and the proposed GAP formulation adds the dimension of computer-aided process planning to the analysis. It is a part of computer-aided manufacturing, and its impact on group technology and the design of technology cells should be subject to further research.

Despite numerous economic benefits and operational advantages offered by the GT concept, its real potential has not been fully explored. A number of factors, including vulnerability to machine breakdown, underutilization of resources and eventual unbalanced workload distribution in a multi-cell plant, present some problems when designing GT cells. These problems come mainly from the standard principles of GT, such as the avoidance of interaction between cells, and the tendency to setup permanent idealistic cells. These particular interactions between cells can be incorporated by treating each cell as a machine, then applying GT to incorporate the interaction between cells which is based on the relationship/interaction weight assigned between different cells. Similarly, other practical constraints should be considered when grouping resources, such as (i) due dates and (ii) part quantities. The extent of variation in product mix, product design, market situation and other technical factors over a period of time influence the design of a GT cell considerably. The major problem in achieving the full potential of GT in manufacturing are managerial rather than technical. They often have inadequate infrastructure facilities like lack of technical support, efficient information systems, cost accounting systems, and suitable incentive schemes.

It is clearly evident that development of GT concepts will undoubtedly produce many interesting and challenging research problems. It has been suggested that in order to make the design and operation of GT cells efficient, one has to consider the interaction of the GT with the storage and CAD systems. There are number of other issues which should be the subject of future research programmes, such as: (i) developing models for solving the design problems, in particular, those which have not been investigated yet; (ii) developing planning and scheduling procedures for each class of GTs; (iii) studying interactions between GT and its environment; and (iv) experiment on the suitability for GT of the currently used tools and techniques, and design a more focussed hybrid approach.

Most of the solutions offered for practical problems by different methods are only applicable for specific situations. However, in order to enhance the application of models, one has to develop a generalized formulation of the GT problem. Most of the techniques that are currently available for the design of cells assume that each part has fixed process plans and are processed on predetermined machines or group of operations. If bottleneck machines are present, most of the available GT methods can produce acceptable grouping of parts or machines without extensive additional computational effort. Hence, there is a need for further research to identify the bottleneck machines/operations in the system. In addition, the following research problems can be identified in the areas of GT techniques and applications, in particular for advanced production systems:

(i) The aspect of grouping of workers has not been given due attention in JIT and FMS. The human aspects of cellular manufacturing should be studied carefully with reference to motivation and co-operative behaviour between different employees. (Fazakerly 1976 Huber and Hyer 1985). In evaluating the workforce required in a GT cell, the magnitude of the difference between the traditional product-based learning curve approach and the GT process-based learning curve approach should be considered for more accurate decision making. GT simplifies the information system within the GT cells and this may help to implement a CIM system.

(ii) When grouping parts or machines, other associated resources such as tools, jigs, fixtures, pallets and storage systems should also be taken into account for grouping in order to make the cell more productive.

(iii) Clear guidelines for selecting a particular cell formation method based on the company's objective, characteristics and environment, internal knowledge, skills, and experience should be developed (Shafer and Meredith 1990). Part-selection problems using GT must address the problems arising from new types of flexibilities due to advanced FMS technology. More flexibility is not necessarily better than less flexibility, and as product diversity increases, for a given system there is a level of flexibility that will optimize system performance and minimize the rate of its deterioration (Nandkeolyar and Christy 1992). Therefore, there is a need to develop models to optimize the level of flexibility required in GT cells considering various trade-off measures.

(iv) There are some disadvantages that may result due to poor implementation of GT concepts in manufacturing, such as reduction in machine utilization, increase in number of machines used and increase in tooling cost. These problems should be considered when developing models to study different alternatives using various trade-offs between associated costs.

(v) Application of fuzzy theory to the range of GT applications such as feature-based design (and grouping), assembly design and operation may provide opportunities to consider more qualitative and subjective factors. Artificial intelligence (AI) and expert systems (ES) should be developed for GT (Leskowsky *et al.* 1987, Wu *et al.* 1986). These would help to improve the design performance of cellular manufacturing systems using GT.

(vi) Models should be developed for the application of GT in design and engineering, sales, marketing, purchasing, vendor selection and personnel. In addition, The application of GT in activity based costing (ABC) may be an interesting area for future research. Furthermore, more realistic criteria such as batch size, processing time, setup time and human performance should be considered when grouping products and machines using GT.

6. Concluding remarks

The literature available on GT has been reviewed in order to identify the applications, gap between theory and practice, and future research problems. The available GT techniques/models are incapable of modelling many realistic manufacturing systems including JIT, FMS and CIM. The interaction between different manufacturing cells should be included when grouping machines or parts. The scheduling of tool movement in GT cells can be considered for further study and improvement. Simulation can be the most powerful tool to study the implication of GT and for the design of GT cells. The constraints on capacity of machine tools, tool magazine, number of pallets and buffer capacity, and machine breakdowns should be incorporated when designing GT cells. The size of GT cells is very important in controlling the cost. Therefore, appropriate models should be developed for optimizing the number of machines and labour force required with a view to achieving the full benefits of GT in cellular manufacturing systems. In addition, the effect of lot-sizing policies and flexibility should be incorporated when designing GT cells.

The application of GT cells in advanced manufacturing systems such as JIT, FMS and CIM will certainly enhance the design and operational efficiency of such systems. The literature available on GT has been reviewed with an emphasis on developing models/techniques of GT with a view to facilitating the application of GT in advanced manufacturing situations. Also, an attempt has been made to offer suitable frameworks on how GT can be utilized to improve the design and operational aspects of advanced manufacturing systems. Finally, future research directions are indicated in the areas of GT with a focus on JIT, FMS and CIM.

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