Faculty of Mathematical Sciences

University of Twente
The Netherlands

P.O. Box 217
7500 AE Enschede
The Netherlands
Phone: +31-53-4893400
Fax: +31-53-4893114
Email: memo@math.utwente.nl
www.math.utwente.nl/publications

MEMORANDUM NO. 1604

Design and analysis of reconfigurable layout systems

S. HERAGU,[1]G. MENG[1],
W.H.M. ZIJM AND J.C.W. VAN OMMEREN

DECEMBER 2001

ISSN 0169-2690

---

[1] Decision Sciences and Engineering Systems Department, Rensselaer Polytechnic Institute, Troy, NY, 12180, USA

Design and Analysis of Reconfigurable Layout Systems

Sunderesh Heragu[1], Gang Meng[1]and Henk Zijm[2], Jan-Kees van Ommeren[2]

1. Decision Sciences and Engineering Systems Department, Rensselaer Polytechnic Institute, Troy, NY
2. Faculty of Mathematics, University of Twente, Enschede, The Netherlands

Abstract

In this paper, we present a framework for determining the layout in a manufacturing environment characterized by constantly changing product volumes and mix. Much of the production equipment is assumed to be relatively light weight and therefore their location can be easily changed to suit the current production environment. The framework allows several alternate layouts to be developed and evaluated with respect to deterministic (material flow and machine relocation) criteria as well as stochastic (queuing) criteria. We present an open queuing network modeling approach to estimate performance measures of a given layout. It is assumed a layout and production data for a specified planning period of specified length are available. The production data takes into account, processing and handling set-up times as well as transfer and process batch size information of multiple products that flow through the system. Two sets of discrete material handling devices are used for inter-cell and intra-cell material transfer, respectively. Experimental results are provided to demonstrate the effectiveness of the queuing network approach.

Key words**: cellular manufacturing, open queuing network, performance analysis, re-configurable layout**

2000 Mathematics subject classificstion: **90B15, 90B30**

1. Introduction

The current day manufacturing environment is characterized by numerous challenges and changes. A typical manufacturing company faces constantly changing product volumes and mix. Simultaneously, the production environment has seen rapid advances take place in materials engineering and manufacturing technology. Composite materials are replacing traditional material such as cast iron and steel. Not only are these materials light weight, they also have excellent mechanical and structural properties. For example, these materials can be made so as to have strong tensile and vibration absorbing properties. Machining technology is also advancing rapidly. Non-abrasive manufacturing technology such as electron beam welding and laser cutting are replacing traditional machining processes. This trend is likely to continue well into the next two decades. In fact, through a workshop and a delphi survey, the committee on Visionary Manufacturing Challenges for 2020 has identified adaptable processes and equipment and reconfiguration of manufacturing operations as two key enabling technologies that will help companies overcome two of the six grand challenges or fundamental goals to remain productive and profitable in the year 2020 (National Research Council, 1998). These grand challenges are to "*achieve concurrency in all operations*" and to "*reconfigure manufacturing enterprises rapidly in response to changing needs and opportunities*".

A direct result of the advances in the materials and machining fields is that machines need not be heavy requiring elaborate foundation. Also, since the payload is light weight, material handling systems can also be designed to be relatively light weight. One can envision a manufacturing system of the future to be made of light weight manufacturing and materials handling equipment that can configured and reconfigured as and when needed - perhaps even on a monthly or weekly basis! A primary advantage of reconfiguring a layout when warranted by changes in product mix and volume is that material handling cost can be minimized because equipment can be reconfigured to suit the new production mix and volume. Of course, this cost must more than offset the cost of moving equipment from its current location to a new one. In addition, due to the short term life of a given layout and availability of production data for this time period, it is possible to consider optimizing operational performance measures such as minimizing part cycle times and work in process inventory. To summarize, the potential to frequently alter layouts, therefore, in a sense, transforms the modern layout problem from a strategic problem in which only long term material handling costs are considered to a tactical problem in which operational performance measures such as reduction of product flow times, work in process inventories, and maximizing throughput rate are considered in addition to material handling and machine relocation costs when changing from one layout configuration to the next.

In the next section, we provide motivation for this research topic and also provide specific industrial examples of re-configurable facilities. In section 3, we review the relevant literature. In section 4, we develop a framework for generating and evaluating different layout configurations. We also discuss the importance of generating alternate machine cells and layout configurations so that the resulting grouping and layout will exhibit good operational performance characteristics. In section 5, we discuss an open queuing network modeling approach to analyze a given layout with respect to the usual operational performance measures – product flow times, work-in-process inventories and machine/material handling device utilization. To demonstrate the validity of the open queuing network model, experimentation, numerical results, comparison with simulation and discussion of results are provided in section 6. Conclusions are drawn in section 7.

2. Motivation and Industry Trends

The technological developments taking place in the manufacturing processes and materials arena point towards next generation manufacturing systems that are inherently agile, adaptable and quickly re-configurable. In many industries such as consumer electronics, home appliances and garment manufacturing, the fabrication and assembly workstations can be physically moved rather easily because they are light in weight. Furthermore, as discussed in Heragu and Kochhar (1994), composites are the primary choice for many discrete manufactured components. Aluminum composites, for instance, can now replace cast iron parts and phenolics are replacing aluminum parts (Arimond and Ayles, 1993 and Fujine et al., 1993). Not only are these light, but they can be engineered to have excellent mechanical properties such as hardness, heat resistance, tensile strength and vibration absorption. The last property permits machine tool designers to design functionally equivalent, but lighter tools that do not require an elaborate foundation, making them easily movable. Non-abrasive manufacturing process technology such as laser cutting, electron beam hardening and molecular nano-technology is also supporting machine tool designers' quest for making light weight machining equipment (Asari, 1993). Permanent magnetic chucks that facilitate quick mounting and dismounting of tools are being developed (Editor, 1993). In fact these chucks do not magnetize the cutting tool, carry their own energy source and do not obstruct machining. Once again, these features in and of themselves support rapid equipment reconfiguration.

Benjafaar et al. (2001) point out a few examples in industry practice and academic research that support the migration of next generation systems towards highly adaptable and quickly re-configurable systems. For example, a multi-national initiative on *Intelligent Manufacturing Systems* is focused on developing multifunctional machine tool technology that is also capacity adjustable. In fact, by simply plugging in modular hardware and software, the basic functionality, capacity and efficiency of the tools are upgraded to suit a changed production environment (Ikegaya, 2000). Turmatic Systems already markets a product that allows simultaneous machining using up to 7 machining units and retrofitting of additional machining units. Southwestern Industries, Inc. manufactures a compact and mobile milling machine that can be transported through narrow doors in a manufacturing plant. A casting which serves as the machine tool foundation is designed to be moved from any side with a pallet jack. A rigid frame eliminates levelling the tool after each relocation. The tool is even designed to plug quickly and efficiently into power and coolant lines.

Climax Portable Machine Tools, Inc. manufactures portable machine tools for repairing turbines, paper machinery and other heavy equipment (Benjafaar et al. 2001).

Northern Telecom, in one of its manufacturing facilities facing constant product design changes, employs conveyor-mounted work cells that can be readily relocated just before a scheduled production/assembly change (Editor, 1996). These cells are relatively independent of the main assembly line and can therefore be unplugged and moved to a new location depending upon the current product assembly. The constant commissioning and de-commissioning of machine tool resources to suit the changed production environment poses a challenge for the inventory manager who must now store tools for the cycles they are decommissioned and bring them into production during the other cycles. Fortunately, companies such as Robotic Parking Inc. are developing equipment and systems to facilitate efficient and quick storage/retrieval of large equipment. Using mechanical lifts, pallets and carriers, large equipment are parked and retrieved from multi-level warehouses that are modular in structure. The National Science Foundation Engineering Research Center on Re-configurable Machines focuses on developing tools that can be readily customized to match a new production scenario, i.e., when there is a reasonable shift in product mix and volumes.

Clearly, some advances in processing technology favor enhancing capacity and functionality to a stationary tool on an as needed basis, thereby minimizing material handling and movement. Other advances favor use of rapidly re-configurable light weight machine tools that can process light weight parts. Both advances enable a manufacturing system to cost effectively adapt to frequent changes in the production environment. Heragu and Kochhar (1994) envisioned factories with wheel mounted, track guided, portable light weight equipment. In fact, the infrastructure itself is designed to support agility. "Plug points" for support services such as compressed gas, water or coolant lines must be made available at multiple locations. Interface devices for control systems must be designed to be interchangeable and open with "plug and play" features implemented in the machine tools. With such advances, one might reasonably argue that it is feasible to have multiple (as many as two dozen or more) layout changes per year.

3. Literature Review

The earliest research paper to focus on relocation of facilities dynamically can be found in Reimert and Gambrell (1966). Some other papers that advocate design of dynamic facilities include Rosenblatt and Lee (1987) and Urban (1998). Benjafaar et al. (2001) mention that the design of next generation factory layouts can be done using two approaches. The first is to develop layouts that are robust for multiple production periods or scenarios. The second approach is to develop flexible layouts that can be reconfigured with minimal effort to meet the changed production requirement. The underlying assumption of the first approach is that production data for multiple (future) planning periods is available at the initial design stage. In the event that we do not have this luxury, this approach assumes a robust layout with inherent features can be developed so that changes in production over the multiple periods can be accommodated with little material handling cost. Examples of papers that assume rich data is available at the initial design stage include Shore and Tompkins (1980), Rosenblatt and Lee (1987), Palekar et al. (1991) and Urban (1998). Calling the problem a dynamic layout problem, these papers use various strategies to find a layout that is robust over multiple periods. All these approaches assume production data for multiple periods is available in the initial design stage itself. Because such an assumption is questionable in next generation factories, it appears that the dynamic layout approach will be unsuitable in the new environment. There are papers that assume a layout with built-in features, for example, duplication of key resources in strategic locations, can be developed to handle production changes over future periods. These include Montreuil and Venkatadri (1991), Yang and Peters (1998) and Benjafaar and Sheikzadeh (2000), among others. Although elements of this approach could be applied to design next generation factory layouts, one disadvantage is that it calls for duplication of key resources in strategic locations. Not only are the key resources expensive, but identifying strategic locations for future production periods of which we do not have too many details is a difficult, if not impossible task.

In today's volatile manufacturing environment, it is common to see drastic production changes take place very frequently. It is also common to see old production resources being de-commissioned and new ones being commissioned rather frequently. What is challenging for designers is that very often, the changes that are to take place in a production cycle - whether it is change in products, routings, production volume or commissioning and de-commissioning of resources, are known only slightly ahead of the start of the new production cycle. Thus, it seems reasonable for a designer not to look beyond the next period and instead generate layouts that can be reconfigured quickly and without much cost to suit the upcoming period's production requirements. A genetic algorithm approach to solve such a re-configurable layout problem is presented in Kochhar and Heragu (1999).

Agarwal and Sarkis (1998) as well as Govil and Fu (1999) survey papers pertaining to the performance evaluation of a cellular manufacturing system (CMS). The former authors provide a taxonomy of the research papers according to the three commonly used research methodologies: simulation, empirical and analytical. The review is comprehensive in areas of simulation and empirical study, but in the analytical models area, only a few papers, those by Suresh (1991), Suresh (1992) and Agarwal et al. (1995), are mentioned. There are other papers in the analytical category. For example, Karmarkar et al. (1985) analyze the influence of the lot size on the lead time performance measure of a CMS. Benjaafar (1999) presents a formulation of layout design problem where the objective function is to minimize work-in-process.

Govil and Fu (1999) classify the literature according to types of the system whose performance being evaluated. Models for job shop, flexible manufacturing system (FMS), assembly/disassembly networks and flow lines are surveyed in the paper. For each type of system, exact and approximation queuing models are reviewed. Shambu and Suresh (2000) build a simulation model of a shop floor and study the performance measures of the system when the configuration gradually changes from functional layout to cellular. Many other simulation studies comparing the performance of cellular manufacturing and functional layouts are available in Flynn and Jacobs (1986), Morris and Tersine (1990), Suresh (1992) and Shafer and Charnes (1993). Farington and Nazametz (1998) conduct a comprehensive simulation experiment on five traditional performance measures and three managerial performance measures of a manufacturing system under two layout configurations: CM and job-shop. Researchers such as Suresh (1991 and 1992), Agarwal et al. (1995) conduct analytical studies on the performance of CM, and the performance measures they consider are flow time, work-in-process (WIP) inventory and machine utilization. Both use the M/M/c approximations to calculate performance measures under the possion arrival rate and exponential service time assumptions. Benjaafar (1999) considers the layout design problem with WIP minimization included in the objective function. An open queuing network with GI/G/c queues is used to model the problem.

4. Framework for Generating and Evaluating Re-configurable Layouts

The re-configurable layout system assumes that the product mix and volume are constantly in a state of flux. It is therefore important for a facility to be agile and able to adapt to a new set of conditions in the next planning period. In fact, the life span of a production planning period may be as short as one week or even a few shifts. The objective is to permit a high degree of adaptability and responsiveness for the entire system, along with the flexibility that is inherent in many current day facilities.

The approach being proposed to solve the re-configurable layout problem is an iterative, four phase approach (see figure 1). Whenever there is a reasonable change in the production mix and volume or the analyst would otherwise like to consider a layout change, the model is run to see whether the new manufacturing environment warrants a new layout. The first phase involves generating a layout design that may or may not specify the grouping of machines into corresponding departments. If a grouping is specified, obviously the layout of the departments and that of the machines must be specified as well. Otherwise, a layout of the machines alone is sufficient. If the machines are to be grouped into departments or cells, a group technology model can be used to determine a preliminary grouping of machine cells and corresponding part families. Because we are considering static design factors as well as dynamic performance related factors in assessing a layout, it is important that the grouping technique group machines in such a way that the resulting design performs well with respect to both static and dynamic factors. This could be accomplished for example by allocating machines to cells so as to minimize intercellular travel *and* process time variability.

It is well known that a high degree of process time variability on a machine induces higher levels of work in process inventory and cycle time (Hopp and Spearman, 2000). Similarly, given that some parts may have to travel to multiple cells to complete processing, if the grouping is done in such a way that the parts requiring intercellular travel induce relatively little variability in the materials handling time, such a grouping is likely to optimize operational performance measures. In fact, the grouping of machines into departments could be done so that a number of variability factors in addition to process time and transportation time, are minimized. This stems from the belief that is also supported by just-in-time proponents, that variability is the root of all evil (Hopp and Spearman, 2000). Clearly, some variability factors, for example, demand fluctuations, are beyond our direct control, but others such as travel time variability and process time variability can be controlled by a judicious formation of cells or departments and corresponding part families.

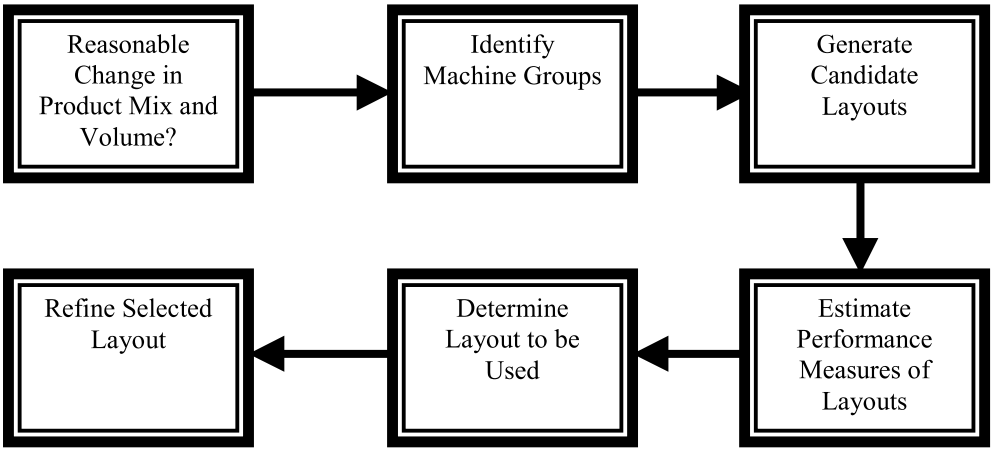

Figure 1. Four phase approach for design and analysis of re-configurable layouts

The second phase calls for generation of a number of candidate layouts so each can be evaluated with respect to operational performance measures in the third phase. An analyst may consider developing cellular, job-shop or any other type of layout. As noted before, each layout must be generated so that it is expected to perform well with respect to deterministic design factors (material handling and machine relocation costs) as well as stochastic performance related factors (cycle time, inventory and utilization). It must be observed that most existing grouping techniques only look at the routing and ignore process and travel times and do not explicitly consider variability reduction.

Since we cannot rule out the possibility of retaining the existing layout for the new production scenario, the current layout must also be analyzed with respect to material handling costs and operational performance factors. In addition, an analyst could consider a flow-line layout in addition to the group technology and job-shop layouts. However, in the dynamic manufacturing environment previously described, it is highly unlikely that a flow-line layout will be employed. This is primarily because of the widely held belief that manufacturing in the future will be primarily concerned with high variety, low volume production making it uneconomical to use a flow-line layout due to the difficulty in identifying dominant product lines or flow patterns. Although other types of layouts have been discussed in the literature, for example, virtual cellular layouts and holonic layouts, these are either inadequate from the material handling and queuing points of view or specific procedures to develop such layouts have not yet been developed. Moreover, the flow-line and job-shop layouts are two extreme types of layouts and the group technology layout is in between the two extremes. It can be modified to fit any part of the spectrum between the two extreme types of layouts. In any case, our method allows any layout type - with or without cells or departments, to be evaluated via the queuing network model.

Once the machine grouping and corresponding part family formation are determined, a detailed layout must be developed using an appropriate algorithm. The technique in Kochhar and Heragu (1999) is specifically designed for re-configurable layouts and could be used. There are a number of other techniques and these have been reviewed in Meller and Gau (1996). In addition, a detailed job shop layout must also be developed for the new production planning period. At the end of the second phase, we have several detailed layouts including the existing layout, cellular manufacturing layout and job shop layout.

The open queuing network model discussed in the next section can be used in the third phase to estimate the steady state operational performance measures for each of the three layouts. Then, in the fourth phase, a decision on which candidate layout to use is made for the upcoming production period. After a layout decision is made, the selected layout is refined so that it performs well with respect to material handling and machine relocation costs as well as operational performance metrics. This refinement is a manual process and is done as follows. An analysis of the performance measures may suggest minor changes to the design and layout. For example, the bottleneck identification (location as well as extent) might suggest changes to design (for example, addition of highly utilized resources), layout (re grouping of machines) or product routing that will improve system performance. These changes will be incorporated in a modified layout whose operational performance in turn will be estimated via the queuing network model. The above procedure of generating a layout, estimating its operational performance, making suitable changes to the design, re-developing the layout, estimating the new system performance measures will be repeated until a satisfactory design - one that is optimal or near optimal with respect to design and operational performance factors, is obtained.

5. Evaluating Layouts Via Open Queuing Network Models

The purpose of this section is to describe an open queuing network model that helps in determining the layout that would be preferable for the given data concerning product mix, volume, routing probabilities, machine service rate, capacity and capability information. The primary objective here is to identify the layout to use in order to minimize cycle time and work in process inventory. However, since we want a layout that is good with respect to operational performance *and* material handling/machine relocation considerations, the operational performance cost measures (e.g., work-in-process inventory costs) from the queuing network model can be combined with material handling/machine relocation cost factors, subject to cycle time, utilization and layout feasibility constraints to determine the specific type of layout to use for the new production period.

The performance analysis of any system including a CMS in which machines are grouped into a department or cell based on some criteria, follows a two-level hierarchical framework in which the cells are analyzed at a higher (aggregate) level first. Notice that each machine could be put in its own distinct cell, thereby allowing us to use the queuing network model to evaluate any type of layout – even one that does not have “cells” or departments. Also, how the machines are grouped is irrelevant to the open queuing network model. Based on the output of the aggregate analysis, each cell is analyzed to provide specific detailed information on estimates of performance measures at the cell level. In the higher level analysis, the material handling system (MHS) used to transfer parts between cells is modeled as another network of discrete material handling devices (MHDs). We assume we have a layout in which the following are known.

- number of cells;
- number and types of machines;
- number and types of discrete material handling devices;
- number, types, volume and routing of products to be manufactured in the specified production planning period;
- first two moments of external arrival rate for each product;
- first two moments of service time for each processing operation;
- set-up time as well as batch size for each operation and transfer, for each product;
- assignment of machines to cells;
- assignment of MHDs to cells;
- assignment of products to families; and
- assignment of products to cells.

Given the above information, the procedure to estimate operational performance measures is based on the Whitt (1983) method and is fairly simple. Before we discuss this procedure, it is necessary to introduce the following notation.

Notation

i	Product type index, $i=1,2,\ldots,p$
j, k	Machining cell index, $j,k=1,2,\ldots,n-1$
n	MHS cell index
o^i	Number of operations required by product i, $i=1,2,\ldots,p$
l	Operation index, $l=1,2,\ldots, o^i$
λ_{0k}^{i}	Arrival rate of product i from the external world into machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$

scv^i_{0k}	Squared coefficient of variation of inter-arrival time for product i from the external world into machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$
to^i_{kl}	Natural service time for l^{th} operation on product i at machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$
scv^i_{okl}	Squared coefficient of variation of natural service time for l^{th} operation on product i at machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$
ts^i_{kl}	Mean set-up time for l^{th} operation on product i at machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$
scv^i_{skl}	Set-up time squared coefficient of variation for l^{th} operation on product i at machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$
tr_{jk}	Travel time between machining cells j and k, $j, k=1,2,\ldots,n-1$
scv_{rjk}	Squared coefficient of variation of travel time between machining cells j and k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$
tp^i	Mean set-up time for loading product i on MHD in MHS cell n, $i=1,2,\ldots,p$
scv^i_p	Squared coefficient of variation of set-up time for loading product i on MHD in MHS cell, $i=1,2,\ldots,p$
b^i_{kl}	Batch-size of product i at machining cell k for l^{th} operation, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$
bt^i_{jk}	Batch-size for transferring product i between machining cells j and k, $i=1,2,\ldots,p$; $j, k=1,2,\ldots,n-1$
m_k	Number of machines in cell k, $k=1,2,\ldots,n$
Y^i_{kl}	1 if the l^{th} operation of product i is done at machining cell k, $i=1,2,\ldots,p$; $k=1,2,\ldots,n-1$; $l=1,2,\ldots,o^i$; 0 otherwise

5.1 Higher level analysis

Notice that it is assumed that the n^{th} cell is the MHS cell with identical servers (MHDs) in the above notation. It is convenient to obtain an indicator variable that tells us whether or not the two successive operations (say the l-1th and the l^{th}) on a product i are done at a pair of machining cells j and k. It is also necessary to determine the total external arrival rate for product i as follows.

$$Y^i_{jkl} = Y^i_{j,l-1} Y^i_{kl},\ i=1,2,\ldots,p;\ j,\ k=1,2,\ldots,n-1;\ l=2,3,\ldots,\ o^i \qquad (1)$$

$$\hat{\lambda}^i = \sum_{k=1}^{n-1} \lambda^i_{0k},\ i=1,2,\ldots,p \qquad (2)$$

Because we are assuming deterministic routing, for each product i, λ^i_{0k} is greater than zero for only one k. Based on the above, it is easy to get the total arrival rate of products into each machining cell from the external world as well as out of each cell to the external world. Notice that the material transfer from and to the external world is not included in our analysis. If necessary, however, this can be easily incorporated. Furthermore, it is assumed that the intra-cell material transfer is accomplished by a MHD residing in that cell and is treated like an ‘operation’ for modeling purposes. However, the inter-cell material transfer is completed by the MHS node consisting of one or more identical MHDs and is treated as a transfer. Thus, since all the inter cell transfers between machining cells must take place via the MHS cell *n*, the arrival rate from a machining cell *j* to machining cell *k* for $j \neq k$ will be zero. The total arrival rate from a machining cell to the MHS cell and vice-versa is not zero however and can be easily determined.

$$\hat{\lambda}_{0k} = \sum_{i=1}^{p} \lambda_{0k}^{i}, \quad k = 1,2,...,n-1 \tag{3}$$

$$\hat{\lambda}_{kk} = \sum_{i=1}^{p} \sum_{l=2}^{o^i} \frac{\hat{\lambda}^i Y_{kkl}^i}{b_{kl}^i}, k = 1,2,...,n-1 \tag{4}$$

$$\hat{\lambda}_{jk} = 0, \quad j,k = 1,2,...,n-1, j \neq k \tag{5}$$

$$\hat{\lambda}_{kn} = \sum_{i=1}^{p} \sum_{\substack{j=1 \\ j \neq k}}^{n-1} \sum_{l=2}^{o^i} \frac{\hat{\lambda}^i Y_{kjl}^i}{bt_{kj}^i}, \quad k = 1,2,...,n-1 \tag{6}$$

$$\hat{\lambda}_{nk} = \sum_{i=1}^{p} \sum_{\substack{j=1 \\ j \neq k}}^{n-1} \sum_{l=2}^{o^i} \frac{\hat{\lambda}^i Y_{jkl}^i}{bt_{jk}^i}, \quad k = 1,2,...,n-1 \tag{7}$$

$$\hat{\lambda}_{k0} = \sum_{i=1}^{p} \frac{\hat{\lambda}^i Y_{ko^i}^i}{b_{ko^i}^i}, \quad k = 1,2,...,n-1 \tag{8}$$

Observing that all inter cellular transfer takes place via the MHS cell and that the MHS cell never transfers parts to itself, the proportion of a batch of parts visiting cell *k* after cell *j* is easy to calculate.

$$p_{nn} = p_{jk} = 0, \quad j,k = 1,2,...,n-1, j \neq k \tag{9}$$

$$p_{jj} = \frac{\hat{\lambda}_{jj}}{\hat{\lambda}_{j0} + \hat{\lambda}_{jj} + \hat{\lambda}_{jn}}, \quad j = 1,2,...,n-1 \tag{10}$$

$$p_{jn} = \frac{\hat{\lambda}_{jn}}{\hat{\lambda}_{j0} + \hat{\lambda}_{jj} + \hat{\lambda}_{jn}}, \quad j = 1,2,...,n-1 \tag{11}$$

$$p_{nj} = \frac{\hat{\lambda}_{nj}}{\sum_{k=1}^{n-1} \hat{\lambda}_{nk}}, \quad j = 1,2,...,n-1 \tag{12}$$

The natural service time for a processing operation is the average time required for that operation and is usually readily available or can be obtained from the machine responsible for the processing operation. However, the natural service time for a transfer depends not only on the actual (loaded) travel from the originating station to the destination station, but also on the empty travel time from the station at which the material handling carrier is currently located to the flow originating station. While the empty travel time may be small and negligible for intra-cell transfers, it can have dramatic impact on inter cell transfers. We use the approach of Benjafaar (1999) to include the loaded and empty travel time for inter-cell material transfers. However, unlike Benjafaar (1999), we do not assume the loaded travel is deterministic; instead, it is characterized by two moments – mean and squared coefficient of variation, which are assumed to be known or can be calculated. Although it can be relaxed, we assume unloaded travel is negligible for intra-cell transfers. The probability that a material transfer takes place from cell *j* to cell *k* is given by:

$$q_{jk} = \frac{\sum_{i=1}^{p} \sum_{l=2}^{o^i} \left(\hat{\lambda}^i Y_{jkl}^i / bt_{jk}^i \right)}{\sum_{s=1}^{n-1} \sum_{t=1}^{n-1} \sum_{i=1}^{p} \sum_{l=2}^{o^i} \left(\hat{\lambda}^i Y_{stl}^i / bt_{st}^i \right)}, j,k = 1,2,...n-1 \tag{13}$$

Using the Benjafaar (1999) approach, the average transfer time per trip between two cells (including loaded and unloaded travel) can be calculated via expression (14). The per batch or trip travel time (loaded or unloaded) between two machining cells *j* and *k* can be determined as shown in expression (15) if the distance between the two cells d_{jk} and the velocity of the transfer device *v* are known.

$$\hat{tr}_{jk} = \sum_{r=1}^{n-1} tr_{rj} \sum_{s=1}^{n-1} q_{sr} + tr_{jk}, j,k = 1,2,...n-1 \tag{14}$$

$$tr_{jk} = \frac{d_{jk}}{v}, \; j,k=1,2,...n\text{-}1 \tag{15}$$

The first part of (14) recognizes the fact that the material handling carrier dispatched to serve an inter-cell transfer request can be at any one of the *n*-1 cells. It explicitly includes empty travel time from the cell it is currently at to the cell where the transfer originates as well as the loaded travel time to the destination cell. The squared coefficient of variation for the intra and inter-cell transfer times is the corresponding variance divided by the square of the mean. Variance terms can be can be determined as follows.

$$Var\left(\hat{tr}_{jk}\right) = E\left[\hat{tr}_{jk}^2\right] - E\left[\left(\hat{tr}_{jk}\right)\right]^2 \tag{16}$$

$$E\left[\left(\hat{tr}_{jk}\right)^2\right] = \left[\sum_{r=1}^{n} \left(tr_{rj}\right)^2 \sum_{s=1}^{n} q_{sr} + \left(tr_{jk}\right)^2 + 2tr_{jk} \sum_{r=1}^{n} \left(tr_{rj}\right) \sum_{s=1}^{n} q_{sr} \right] \tag{17}$$

Obviously, the effective service time for an operation depends upon the batch size of the product. In our model, batch size can vary from one operation to the next. Similarly, the transfer batch size for the same product can vary from one transfer to the next. The following discussion shows how batch size and set-up impact the two moments of the effective service time of processing and transfer operations. It assumes that for each operation or transfer, the natural process or transfer time is independent of the corresponding set-up time.

$$\hat{te}^i_{kl} = b^i_{kl} to^i_{kl} + ts^i_{kl},\ i=1,2,\ldots,p;\ j,\ k=1,2,\ldots,n\text{-}1;\ l=1,2,\ldots,\ o^i \qquad (18)$$

$$s\hat{c}v^i_{ekl} = \frac{\left(b^i_{kl}\right)^2 \left(to^i_{kl}\right)^2 scv^i_{okl} + \left(ts^i_{kl}\right)^2 scv^i_{skl}}{\left(\hat{te}^i_{kl}\right)^2},\ i=1,2,\ldots,p;\ j,k=1,2,\ldots,n\text{-}1;\ l=1,2,\ldots,o^i \qquad (19)$$

$$\hat{te}^i_{rjk} = \left(\hat{tr}_{jk} + tp^i bt^i_{jk}\right),\ i=1,2,\ldots,p;\ j,k=1,2,\ldots,n\text{-}1 \qquad (20)$$

$$s\hat{c}v^i_{erjk} = \frac{\left(\hat{tr}_{jk}\right)^2 scv^i_{rjk} + \left(bt^i_{jk}\right)^2 \left(tp^i\right)^2 scv^i_p}{\left(\hat{te}^i_{rjk}\right)^2},\ i=1,2,\ldots,p;\ j,k=1,2,\ldots,n\text{-}1;\ l=1,2,\ldots,o^i \qquad (21)$$

It should again be noted that in many applications, production engineers routinely maintain data on the total processing time per batch instead of processing time per unit in a batch. If so, this value must be substituted in the first part of the right hand side of expression (18) directly. The first and second moments for the service time distribution at each machining and MHS cell can be obtained as follows.

$$te_k = \frac{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \lambda^i \hat{te}^i_{kl}\, Y^i_{kl} / b^i_{kl}}{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \lambda^i\, Y^i_{kl} / b^i_{kl}},\ k=1,2,\ldots,n\text{-}1 \qquad (22)$$

$$te^2_k (scv_k + 1) = \frac{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \hat{\lambda}^i \left(\hat{te}^i_{kl}\right)^2 \left(s\hat{c}v^i_{ekl} + 1\right) Y^i_{kl} / b^i_{kl}}{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \hat{\lambda}^i\, \hat{Y}^i_{kl} / b^i_{kl}},\ k=1,2,\ldots,n\text{-}1 \qquad (23)$$

$$te_n = \frac{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i \hat{te}^i_{rjk}\, Y^i_{jkl} / bt^i_{jk}}{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i\, Y^i_{jkl} / bt^i_{jk}} \qquad (24)$$

$$te^2_n (scv_n + 1) = \frac{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i \left(\hat{te}^i_{rjk}\right)^2 \left(s\hat{c}v^i_{erjk} + 1\right) Y^i_{jkl} / bt^i_{jk}}{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i\, Y^i_{jkl} / bt^i_{jk}} \qquad (25)$$

The fundamental traffic rate equations are obtained as shown below.

$$\hat{\lambda}_k = \hat{\lambda}_{0k} + \sum_{j=1}^{n} \hat{\lambda}_j \, p_{jk} \big/ b_j \,,\ k=1,2,\ldots,n \tag{26}$$

$$\text{where } b_j = \frac{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \hat{\lambda}^i Y^i_{jl}}{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \hat{\lambda}^i \, Y^i_{jl} \big/ b^i_{jl}},\ j=1,2,\ldots,n-1 \text{ and } b_n = \frac{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i Y^i_{jkl}}{\sum_{i=1}^{p}\sum_{\substack{j=1\\ j\neq k}}^{n-1}\sum_{k=1}^{n-1}\sum_{l=2}^{o^i} \hat{\lambda}^i \, Y^i_{jkl} \big/ bt^i_{jk}}$$

Observe that $p_{jk}=0$ for $j = 1,2,\ldots,n-1,\ j \neq k,\ \ \hat{\lambda}_{0n} = 0$ and b_j is cell j's average batch size in (26). The above set of linear equations can be solved to obtain the individual $\hat{\lambda}_k$. We can determine traffic intensities, the offered load (or expected number of busy servers), departure rate at each cell as well as the departure rate from the entire network.

$$\rho_k = \frac{\hat{\lambda}_k te_k}{m_k},\ k=1,2,\ldots,n \tag{27}$$

$$\alpha_k = \hat{\lambda}_k te_k,\ k=1,2,\ldots,n \tag{28}$$

$$D_k = \hat{\lambda}_k \left(1 - p_{kk} - p_{kn}\right),\ k=1,2,\ldots,n\text{-}1 \tag{29}$$

$$D = \sum_{k=1}^{n-1} D_k \tag{30}$$

We are now ready to calculate squared coefficient of variation for the arrival process at each cell k. The composite arrival process at each cell is determined using the hybrid approximation for superposition arrival processes as discussed in Whitt (1983).

$$s\hat{c}v_{ak} = a_k + \sum_{j=1}^{n} s\hat{c}v_{aj} c_{jk},\quad k = 1,2,\ldots,n \tag{31}$$

$$\text{where } a_k = 1 + w_k \left\{ \left(\left(\hat{\lambda}_{ok} / \hat{\lambda}_k\right)^2 scv_{ok} - 1 \right) + \sum_{j=1}^{n} \left(\hat{\lambda}_{jk} / \hat{\lambda}_k\right) \left[\left(1 - p_{jk}\right) + p_{jk} \rho_j^2 x_j \right] \right\},$$

$$c_{jk} = w_k p_{jk} (1 - \rho_j^2) \left(\frac{\hat{\lambda}_{jk}}{\hat{\lambda}_k} \right),\qquad w_k = \frac{1}{1 + 4(1-\rho_k)^2 (u_k - 1)},\ x_j = 1 + \frac{1}{\sqrt{m_j}} \left[\max\left\{ scv_j, 0.2 \right\} - 1 \right]$$

$$\text{and } u_k = \frac{1}{\sum_{j=0}^{n} \left(\hat{\lambda}_{jk} / \hat{\lambda}_k\right)^2}.$$

Recall again that $p_{jk} = \hat{\lambda}_{jk} = 0,\ j,k = 1,2,\ldots,n-1,\ j \neq k$. Also, $p_{nn} = \hat{\lambda}_{0n} = 0$. Now that we know the first and second moments of the effective arrival rates at each cell k, we can begin to analyze each in detail. Before doing that, we disaggregate the combined arrivals into each cell into product specific arrival rates, which will be used to calculate the routing probability in the cell. We then disaggregate these product specific arrival rates into a cell further into product and machine specific arrival rates into the cell. Finally we sum over machine to get machine specific arrival rates. Product based disaggregation of the combined arrival rates are done as follows.

$$\lambda_k^i = \hat{\lambda}_k \frac{\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i};\ i = 1,2,\ldots,p;\ k = 1,2,\ldots,n \tag{32}$$

$$scv_{ak}^i = \frac{\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i} s\hat{c}v_{ak} + 1 - \frac{\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i};\ i = 1,2,\ldots,p;\ k = 1,2,\ldots,n \tag{33}$$

Formula (33) is the standard approximation used when a departure stream is split into multiple ones and is based on the assumptions that the combined arrival process at each node is a renewal process and that the routing is Markovian.

5.2 Cell level analysis

The reader will observe that the structure of cell level analysis is very similar to that of the higher level analysis. Instead of focussing on the interactions between cells as we do in the higher level analysis, we focus on the interactions between machines in the cell under consideration. Each cell is assumed to have different types of machines. If all the machines in a cell are similar as is the case in job-shop environments or the MHD cell, calculation of the performance measures is rather easy and discussed in section 5.3. Unless otherwise noted, the index *k* in section 5.2 corresponds to a machine, rather than a cell. The cells considered include those with dissimilar machines and hence the discussion in this sub-section does not cover the MHD cell.

All intra-cell material transfers are accomplished by the MHD residing in that cell. It is assumed that the transfer time is combined into the service time of next operation for modeling purposes. A primary reason is that the travel times are negligible and accomplished manually in a CMS due to the proximity of the machines in a cell. We are also assuming that no product visits the same machine for two consecutive operations, or that if it does, the two consecutive processing times could be combined. Thus, $\hat{\lambda}_{kk} = 0$ for k=1,2,…,n. However, if necessary, the travel time and consecutive operations can be modelled explicitly. Using expressions (1)-(12), noting that index k represents a machine, $p_{kk} = 0$ for all k, and that p_{jk}, need not necessarily be 0, the following expressions can be derived for the first two moments of the machine service times.

$$te_k = \frac{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \hat{\lambda}^i \hat{t}e^i_{kl} \, Y^i_{kl} / b^i_{kl}}{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \hat{\lambda}^i \, Y^i_{kl} / b^i_{kl}}, \; k=1,2,\ldots,n \tag{34}$$

$$te_k^2 (scv_k + 1) = \frac{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \hat{\lambda}^i \left(\hat{t}e^i_{kl}\right)^2 \left(s\hat{c}v^i_{ekl} + 1\right) Y^i_{kl} / b^i_{kl}}{\sum_{i=1}^{p} \sum_{l=1}^{o^i} \hat{\lambda}^i \, Y^i_{kl} / b^i_{kl}}, \; k=1,2,\ldots,n \tag{35}$$

Although not shown in (34)-(35), we have included the effect of machine failure and non pre-emptive machine set up on the first two moments of the service time, following the approach in Hopp and Spearman (2000). Disaggregation of the product specific arrival rates into a cell (as given by (32)) into machine and product specific arrival rates based on the number of visits to a machine is straightforward and shown below. Notice that $\lambda^i_{cell}, scv^i_{a,cell}$ in (36) refers to the λ^i_k, scv^i_{ak} value obtained in (32) for the cell under consideration.

$$\lambda^i_k = \lambda^i_{cell} \frac{\sum_{l=1}^{o^i} Y^i_{kl}}{\sum_{k=1}^{n} \sum_{l=1}^{o^i} Y^i_{kl}}; \; i = 1,2,\ldots,p; \, k = 1,2,\ldots,n \tag{36}$$

$$scv^i_{ak} = \frac{\sum_{l=1}^{o^i} Y^i_{kl}}{\sum_{k=1}^{n} \sum_{l=1}^{o^i} Y^i_{kl}} scv^i_{a,cell} + 1 - \frac{\sum_{l=1}^{o^i} Y^i_{kl}}{\sum_{k=1}^{n} \sum_{l=1}^{o^i} Y^i_{kl}}; \;\; i = 1,2,\ldots,p; \; k = 1,2,\ldots,n \tag{37}$$

To get combined arrival rates into each machine in the current cell, expressions (38) and (39) are used as in the higher level analysis.

$$\hat{\lambda}_k = \sum_{i=1}^{p} \lambda_k^i; \quad k = 1,2,...,n \tag{38}$$

$$scv_{ak} = w_k \sum_{i=1}^{p} \left(\frac{\lambda_k^i}{\sum_{i=1}^{p} \lambda_k^i} \right) s\hat{c}v_{ak} + 1\text{-}w_k \; ; k = 1,2,...,n \tag{39}$$

where $w_k = \dfrac{1}{1 + 4(1-\rho_k)^2 (u_k - 1)}$ and $u_k = \dfrac{1}{\sum_{j=0}^{n} \left(\hat{\lambda}_{jk} / \hat{\lambda}_k \right)^2}$.

With the first two moments of te_k (equations 34 and 35) and λ_k (equations 38 and 39), we can determine traffic intensities, the offered load (or expected number of busy servers), departure rate at each machine as well as the departure rate from the entire cell.

$\rho_k = \dfrac{\hat{\lambda}_k te_k}{m_k}$, k=1,2,…,n, m_k is the number of machines of type k, k=1,2,…,n (40)

$\alpha_k = \hat{\lambda}_k te_k$, k=1,2,…,n (41)

$D_k = \hat{\lambda}_k \left(1 - p_{kk}\right)$, k=1,2,…,n (42)

Now that we have the first two moments of the effective arrival rates at each machine k, we can compute the average waiting time in queue of a batch of a product. Depending upon the number of machines of type k, we analyze each node (machine type) as a GI/G/1 or GI/G/m queue using expression (43).

$$E(WQ_k) = \frac{(scv_{ak} + scv_k)}{2} E(WQ_k)^{M/M/m} \tag{43}$$

Since all products join the same queue to obtain service from node k, the average waiting time in queue for any product is given by (43). However, the overall expected average sojourn time (denoted as $E(W_k)$) depends upon the average waiting time and average processing time. The latter is known and thus the average sojourn time is obtained using formula (44).

$$E(W_k) = E(WQ_k) + te_k \tag{44}$$

The improvements in Kraemer and Langenbach-Belz (1976) and Whitt (1993) are used to further improve the waiting time estimates for the GI/G/1 and GI/G/m queues. Utilizing Little's law, the average number of products at node k as well as those waiting in queue can be readily determined.

$$L_k = \lambda_k E(W_k) \tag{45}$$

$$LQ_k = \lambda_k E(WQ_k) \tag{46}$$

To get the average number of parts of each type at each machine in the cell under consideration, the above results must be disaggregated as shown below.

$$L_k^i = L_k \frac{\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}, i = 1,2,\ldots,p; k = 1,2,\ldots,n \tag{47}$$

$$LQ_k^i = LQ_k \frac{\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i}{\sum_{i=1}^{p}\sum_{l=1}^{o^i} \lambda_{0k}^i Y_{kl}^i / b_{kl}^i},\ i = 1,2,\ldots,p; k = 1,2,\ldots,n \tag{48}$$

The average time spent in the system and queue per visit for a batch of each product type are calculated as shown in (49) and (50).

$$E(WQ_k^i) = E(WQ_k) \tag{49}$$

$$E(W_k^i) = E(WQ_k^i) + \frac{\sum_{l=1}^{o^i} te_{kl}^i Y_{kl}^i}{\sum_{l=1}^{o^i} Y_{kl}^i} \tag{50}$$

It is easy to get only the time spent at some of the nodes or a specific node, for example, the MHD node, from the above expressions. If we need additional measures, for example, the variance of the flow times or number in the system, these can also be obtained rather easily as shown in Whitt (1983). We now have estimates of three important performance measures – machine utilization (given by (40)) as well as work in process inventory and product flow time (given by (47) and (50)), for each cell.

5.3 MHD Cell or Job-shop Department Analysis

The MHD cell is a cell with identical servers similar to a department in the case of a job-shop system. Cells with similar machines are rather easy to evaluate because each is a GI/G/m queue. Thus, to determine performance measures for the MHD cell, we use the first two moments of the inter-arrival and service times calculated via expressions (24)-(26) and (31) in the higher level analysis. We then use formulas similar to (27)-(30) and (47)-(50) to get department specific and product specific information, respectively. Job-shops can also be evaluated in a similar manner.

6. Experimental Results and Discussion

Four data sets were tested against the proposed analytical model and their results are compared with simulation results as well as with the FL-Q model developed by Benjafaar (1999). All the data sets have 4 cells including an MHD cell and 21 product types. There are 5 machines in cell 1, 4 machines in cell 2 and 3 respectively. Data set 1 has no inter-cellular trips, but data set 2 has 2 due to part #6. Data sets 3 and 4 have heavy inter-cellular traffic. In addition, data sets 2 and 4 have some heavily loaded machines. The part routings in data sets 1 and 2 as well as 3 and 4 are identical. The open queuing network model presented in this paper is called CMA for cellular manufacturing analyzer. Although CMA captures numerous parameters such as machine failure, set up, process and transfer batch size that could affect the variability of the network, these parameters are ignored in the four data sets in order to allow our model to be compared with FL-Q model which does not consider these. Because the performance of FL-Q and CMA are similar, only results from data set 4 are shown in this section (see table 1). The columns labelled C and M refer to cell and machine, respectively. The results show that CMA and FL-Q produce results comparable to simulation. However, an advantage of CMA is that it considers several factors such as set-up time, failure rate, batch size, etc., and can provide cell specific information. Such measures for all four data sets are provided in tables 2-5. Cell 4 refers to the material handling cell.

Table 1. Comparison of CMA and FL-Q with simulation

C	M	ρ			***WIP***			***Wq***		
		FL-Q	**CMA**	**Simu.**	**FL-Q**	**CMA**	**Simu.**	**FL-Q**	**CMA**	**Simu.**
1	1	0.635	0.860	0.858	1.90	7.58	7.38	1.01	4.48	4.38
1	2	0.876	0.876	0.886	10.18	11.07	11.41	2.82	3.09	3.22
1	3	0.724	0.724	0.704	2.95	3.32	3.36	1.27	1.48	1.56
1	4	0.953	0.953	0.935	27.88	32.18	30.68	8.83	10.24	9.85
1	5	0.990	0.990	0.981	181.79	215.13	134.44	45.20	53.53	33.55
2	1	0.988	0.763	0.749	92.72	3.99	3.83	55.60	2.31	2.21
2	2	0.950	0.950	0.944	21.77	22.61	22.04	11.90	12.38	12.07
2	3	0.895	0.895	0.877	13.49	14.80	13.28	5.35	5.92	5.32
2	4	0.795	0.796	0.784	7.23	7.72	6.86	2.39	2.57	2.27
3	1	0.931	0.931	0.929	15.47	18.54	19.04	4.93	5.97	6.14
3	2	0.967	0.967	0.945	38.31	44.56	21.36	16.24	18.95	9.05
3	3	0.800	0.800	0.807	4.11	4.63	4.23	2.65	3.07	2.70
3	4	0.978	0.978	0.964	72.99	83.89	39.33	19.73	22.72	10.60

Table 2. Cell specific performance measures for data set 1

C	RHO	L	LQ	W	WQ
1	0.444	9.43	7.21	19.30	14.85
2	0.522	9.86	7.78	34.81	27.61
3	0.455	28.57	26.75	45.30	42.13
4	0	0	0	0	0

Table 3. Cell specific performance measures for data set 2

C	RHO	L	LQ	W	WQ
1	0.797	40.33	31.42	70.10	61.27
2	0.847	44.58	37.28	110.98	101.12
3	0.819	30.34	43.53	68.45	63.78
4	0.175	2.10	4.83E-7	1.50	3.45E-7

Table 4. Cell specific performance measures for data set 3

C	RHO	L	LQ	W	WQ
1	0.405	6.84	4.82	19.92	14.82
2	0.583	10.52	8.19	31.02	24.38
3	0.443	4.4	2.67	8.52	4.84
4	0.838	12.43	2.38	1.32	0.25

Table 5. Cell specific performance measures for data set 4

C	RHO	L	LQ	W	WQ
1	0.880	269.76	265.36	669.66	657.11
2	0.851	49.58	46.17	143.93	134.49
3	0.919	151.87	148.19	297.91	290.23
4	0.838	12.43	2.38	1.32	0.25

7. Conclusions

Our approach to designing agile layout systems assumes production data are available at best for the upcoming production period since it is unreasonable to assume we would know this data at the initial design stage for multiple production periods in the future. Two delphi surveys - the millennium project panel consisting of 200 futurists, scholars and policymakers from 50 countries Cook (1999) and the National Research Council's Panel for Visionary Manufacturing Challenges in 2020 (National Research Council, 1998) have also suggested that it will be increasingly difficult to make forecasts too far into the future. In fact, the latter also mentions that facility configurations will be continually changing and must therefore be easily adaptable and re-configurable to survive in the competitive environment of next generation manufacturing systems. We believe that the time is ripe to consider adaptive manufacturing systems that can be easily reconfigured and that future research incorporate deterministic material flow based measures as well as stochastic queuing effects in analysis of re-configurable layouts. This paper presents a framework and methodology to aid in this effort.

The two level analysis technique presented in this paper using an open queuing network approach appears to provide reasonable estimates of performance measures even when the service times and inter arrival times follow a general distribution. Initial results are promising and further refinements will enhance its performance.

8. Acknowledgement

Research presented in this paper is funded in part by a National Science Foundation grant #DMI-9908437.

9. Reference

1. Agarwal, A., Huq, F. and Sarkis, J., 1995, “Performance of manufacturing cells for GT: a parametric analysis”, in H. Parsaei, A. K. Kamrani and D. Liles (Eds.), *Planning Design and Analysis of Cellular Manufacturing Systems*, Elsevier, London, pp.167-180.
2. Agarwal, A. and Sarkis, J., 1998, “A review and analysis of comparative performance studies on functional and cellular manufacturing layouts”, *Computers and Industrial Engineering*, vol. 34, no. 1, pp.77-89.
3. Akright, W.T. and Kroll, D.E., 1998, “Cell formation performance measures: determining when to change an existing layout”, *Computers and Industrial Engineering*, vol. 34, no. 1, pp159-171.
4. Arimond, J. and Ayles, W.R., 1993, "Phenolics Creep Up on Engine Applications", *Advanced Materials and Processes*, Vol. 143, No. 6, pp. 20.
5. Asari, M., 1993, "Electron Beam Hardening System", *Advanced Materials and Processes*, Vol. 143, No. 6, pp. 30-31.
6. Benjaafar, S., 1999, “Queuing Effects in Design of Factory Layouts”, Working Paper, Department of Mechanical Engineering, University of Minnesota, Minnesota, MN.
7. Benjaafar, S, Heragu, S.S. and Irani, S.A., 2000, “Next Generation Factory Layouts: Research Challenges and Recent Progress,” DSES Technical Report No. 38-00-482, Rensselaer Polytechnic Institute, Troy, NY.
8. Benjaafar, S. and Sheikhzadeh, M., 2000, “Design of Flexible Plant Layouts,” *IIE Transactions*, 32, 309-322.
9. Cook, R., 1999, “Facilities Management and Design for the 21st Century,” March, *Site Selection*.
10. Editor, 1996, “Norstart Custom Telephones Rely on Flexible Conveyor Systems,” *Assembly Magazine Online*.
11. Editor, 1993, "Technology Trends: Concepts for Work and Toolholding", *American Machinist*, Vol. 137, pp. 10.
12. Farrington, P.A. and Nazemetz, J.W., 1998, “Evaluation of the performance domain of cellular and functional layouts”, *Computers and Industrial Engineering*, vol. 34, no. 1, pp. 91-101.
13. Flynn, B.B. and Jacobs, F.R., 1986, “A simulation comparison of group technology with traditional job shop manufacturing”, *International Journal of Production Research*, vol. 24, pp.1171-1192.
14. Govil, M. K. and Fu, M. C., 1999, “ Queueing theory in manufacturing: a survey”, *Journal of Manufacturing Systems*, vol. 18, no. 3, pp. 214-240.
15. Fujine, M., Kaneko, T. and Okijima, J., 1993, "Aluminum Composite Replace Cast Iron", *Advanced Materials and Processes*, Vol. 143, No. 6, pp. 34-36.
16. Heragu, S.S. and Kochhar, J.S., 1994, “Material Handling Issues in Adaptive Manufacturing Systems”, *The Materials Handling Engineering Division 75th Anniversary Commemorative Volume*, ASME, New York, NY.
17. Hopp, W. E. and Spearman, M.L., 2000, *Factory Physics*, Irwin/Mc-Graw Hill, New York, NY.

18. Ikegaya, A., 2000, "Highly Productive And Reconfigurable Manufacturing System," Technical Project Report, Intelligent Manufacturing Systems Initiative, www.ims.org.
19. Karmarkar, U.S., Kekre, S., Kekre S. and Freeman, S., 1985, "Lot-sizing and lead time performance in a manufacturing cell". *Interfaces*, vol.15, no. 2, pp1-9.
20. Kochhar, J.S. and Heragu, S.S., 1999, "Facility Layout Design in a Changing Environment", *International Journal of Production Research*, 37(11), 2429-2446.
21. Kraemer, W. and Langenbach-Belz, M., 1976, "Approximate Formulae for the Delay in the Queuing System GI/G/1", *Proceedings of the Eighth International Teletraffic Congress*, Melbourne, 235, pp. 1-8.
22. Meller, R. and Gau, K.Y., 1996, "The Facility Layout Problem: Recent and Emerging Trends and Perspectives," *Journal of Manufacturing Systems*, 15(5), 351-366.
23. Montreuil, B. and Venkatadri, U., 1991, "Strategic Interpolative Design of Dynamic Manufacturing Systems Layout," *Management Science*, 37(6), 682-694.
24. Morris, S. J. and Tersine, R. J., 1990, "A simulation analysis of factors influencing the attractiveness of group technology cellular layouts", *Management Science*, vol. 36, no. 12, pp.1567-1578.
25. National Research Council, *Visionary Manufacturing Challenges for 2020*, 1998, National Academy Press, Washington, D.C.
26. Palekar, U.S., Batta, R., Bosch, R.M. and Elhence, S., 1992, "Modeling Uncertainties in Plant Layout Problems," *European Journal of Operational Research*, 63, 347-359.
27. Reimert, R.P. and Gambrell, C.C., 1966, "Minimizing materials handling with a flexible plant layout", *International Journal of Production Research*, 5, 23-28.
28. Rosenblatt, M. J. and Lee, H.L., 1987, "A Robustness Approach to Facilities Design," *International Journal on Production Research*, 25(4), 479-486.
29. Shafer, S.M. and Charnes, J.M., 1993, "Cellular versus functional layouts under a variety of shop operating conditions", *Decision Sciences*, vol. 24, no. 3, pp. 665-682.
30. Shambu, G. and Suresh, N.C., 2000, "Performance of hybrid cellular manufacturing systems: A computer simulation investigation", *European Journal of Operational Research*, Vol. 120, pp. 436-458.
31. Shore, R. H. and Tompkins, J. A., 1980, "Flexible Facilities Design," *AIIE Transactions*, 12(2), 200-205.
32. Suresh, N.C., 1991, "Partitioning work centers for group technology: insights from an analytical model", *Decision Sciences*, vol. 22, no. 4, pp. 772-791.
33. Suresh, N.C., 1992, "Partitioning work centers for Group Technology: analytical extension and shop-level simulation investigation", *Decision Sciences*, vol. 23, no. 2, pp. 267-290.
34. Urban, T.L., 1998, "Solution Procedures for the Dynamic Facility Layout Problem," *Annals of Operations Research*, 76, 323 – 342.
35. Whitt, W., 1993, "Approximations for the GI/G/m queue", *Production and Operations Management*, Vol. 2, No., 2, pp. 114-161.
36. Whitt, W., 1983, "The Queuing Network Analyzer", *The Bell Technical Systems Journal*, Vol. 62, No., 9, pp. 2779-2815.
37. Yang, T. and Peters, B.A., 1998, "Flexible Machine Layout Design for Dynamic and Uncertain Production Environments," European Journal of Operational Research, 108, 49-64.