## Appendix A1: Characteristics of Alternative Production Systems

<table>
<thead>
<tr>
<th>System / Process properties</th>
<th>Partially automated cellular layout (PACL)</th>
<th>Multipurpose production system with partial automation (MPPS)</th>
<th>Partially focused highly automated factory system (HAF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic focus</td>
<td>Broad purpose design to produce a wide range of batch production orders</td>
<td>Limited purpose design to produce large lot sizes of product sets</td>
<td>Partially dedicated production lines/factories to core products with considerable variations in product features, scheduling and order sizes.</td>
</tr>
<tr>
<td>Automation</td>
<td>Relatively low, labor intensive except within cells – numerical control machines (NCM) at some stations can form islands of automation, some substitution of capital for labor but relatively limited capital investment</td>
<td>Moderate, functions that can be easily programmed are automated, difficult activities are labor intensive, robots used only in special situations where task is simple, hazardous, or otherwise undesirable, considerable substitution of capital for labor</td>
<td>High level of computer numerical control (CNC) and other automation with little direct labor. Robots used in limited operations. Capital intensive since each work-station must be equipped in advance with tooling required to process the work</td>
</tr>
<tr>
<td>Transfer modes among positions/cells for tools/WIP</td>
<td>Mostly labor directed except automatic transfer within cells</td>
<td>Partly labor, partly automatic transfer modes</td>
<td>Automatic transfer among positions/cells, general purpose transfer devices</td>
</tr>
<tr>
<td>Automation of work flow among stages in the production system</td>
<td>Minimal from raw material storage to cell</td>
<td>Some in work cell as well as in storage</td>
<td>Extensive throughout work cells</td>
</tr>
<tr>
<td>Linkages among work stations/storage areas</td>
<td>Loosely defined linkage among cells, close linkage within cells</td>
<td>Mostly defined linkages with some variability</td>
<td>Programmmed, automated linkages with considerable variability possible</td>
</tr>
<tr>
<td>Assignment of equipment</td>
<td>Partially dedicated since cells are partly rationalized by group technology analysis</td>
<td>Partially dedicated</td>
<td>Dedicated to product family, variable within product family</td>
</tr>
<tr>
<td>Information system technology</td>
<td>Moderately low</td>
<td>Moderate tech</td>
<td>Moderately high</td>
</tr>
<tr>
<td>Degree of computer aided manufacturing (CAM), computer integrated manufacturing (CIM), and enterprise resource planning (ERP) to support integration of product design and manufacturing process</td>
<td>Limited integration and only available within cells, mostly sequentially developed with limited interaction of the two specialists</td>
<td>Some integration, mostly sequentially developed except considerable interaction to reduce complexity product at prototype stage to enable easier production process</td>
<td>High integration of CAM with MRP II, mostly sequential development with extensive interaction of product designer, production process designer and industrial engineers</td>
</tr>
<tr>
<td>Characteristics of indirect/supportive personnel, e.g. industrial engineers, process engineers, production schedulers, maintenance engineers</td>
<td>Moderate staff of product designers and industrial design engineers, some representation of other specialists</td>
<td>Small staff of industrial engineers other intensive knowledge base specialists</td>
<td>Large staff of intensive knowledge based specialists, specialists (e.g.) operations research (OR), information systems, programmers, engineers, statisticians, etc.</td>
</tr>
<tr>
<td>Specialization of equipment</td>
<td>Mostly general purpose equipment, some specialized equipment within cells</td>
<td>Partially specialized and partially general purpose equipment</td>
<td>Product family drives type of equipment; frequent use of machines that perform multiple operations at one station</td>
</tr>
</tbody>
</table>

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| System responsiveness to varying demands (system absorbing, or customer absorbing) | Low – some systems adjustments and mostly queueing/rationing for customers | Moderate system absorbing-buffering by inventories and/or adding personnel/shifts for high demand periods. Some queueing in for high demand products | Considerable system absorbing scheduling is very flexible, and engineering changes can be readily incorporated, change production rates to deal with demand variations |
| Handle different product families | Moderate | Low | Moderately high |
| Handle variations within a product family | High but still low efficiency | Moderate with some degree of efficiency | High – flexible and efficient |
| Handle a range of order sizes – small to large scale, efficiency | Some – inefficient when handling large scale orders | Moderate – can handle intermediate size order relatively efficiently | High – computer programs and automation enable most set-up costs to be eliminated |
| Respond to variations in demand to JIT relationships with customers | Some – adaptation in variations in demand is mostly rationing/queuing | Moderate – some degree of adaptation by shifting personnel, storming overtime, rationing and queuing used when system is overloaded | High flexibility because of automation and integrated production information systems |
| System response to product engineering changes | Moderate – system is structured to deal with common patterns within cells, engineering changes may upset the existing structure | Low – changes are costly to make, efficiency drops off dramatically | Moderate – integration of CAM enables the production system to rapidly accommodate engineering changes |
| Move from R&D to full production stage expeditiously and efficiently | Low – group technology pattern constraints introducing new products easily | Very low – costly and time consuming | Moderate – CAM provides the vehicle for rapid transactions efficiently |
| Fixed cost/variable costs balance | Low FC/high VC | Moderate FC/moderate VC | High FC/low VC expected |
| Average cost per unit (AC) behavior as plant capacity is achieved | Moderately stable AC at varying capacity utilization (low TFC/medium VC) | Declining AC over the range of capacity | Declining AC until full capacity utilization (high TFC/low VC) |
| Average machine and direct labor utilization | Relatively low, difficult to effect balancing among cells | Moderate utilization of both labor and machines, substantial set-up times reduce efficiency | Very high machine and direct labor utilizations; little downtime for setups |
| Set-up times for changing from one product family to next, for changing within product family | Moderately low from one family to next; relatively high within product families | Considerable set-up time for each product family, moderate time for changes within product families | Extensive for different family of products, but very short for changes within family |
| Quality of product and scope of service | Variable but somewhat more consistent than job shop, simpler system enables consistent quality | Moderate but variable quality, depends on man-machine interaction | High sustained quality |

(Source: adapted from Melcher et al., 2002; page 8)
Appendix A2: The DEA Models

The Basic CCR Model

Charnes, et al., (1978) proposed the basic data envelopment analysis (DEA) model, referred to as the CCR model, for evaluating the relative efficiencies of a homogenous set of decision making units (DMUs). The CCR model incorporates multiple inputs and outputs in evaluating the relative efficiencies of alternative DMUs, where efficiency can be defined as the ratio of weighted output to input. In this paper each DMU will be a supplier from the selection set. The general efficiency ratio for a DMU is defined by expression (1).

\[ E_{ks} = \frac{\sum_{j} O_{sy}v_{ky}}{\sum_{x} I_{sx}u_{ks}} \]  

where:

- \((E_{ks})\) is the efficiency or productivity measure of supplier \(s\), using the weights of “test” supplier \(k\), where the test supplier is the DMU whose efficiency is to be evaluated;
- \((O_{sy})\) is the value of output \(y\) for supplier \(s\);
- \((I_{sx})\) is the value for input \(x\) of supplier \(s\);
- \((v_{ky})\) is the weight assigned to supplier \(k\) for output \(y\); and
- \((u_{ks})\) is the weight assigned to supplier \(k\) for input \(x\).

For the basic CCR model, the objective is to maximize the efficiency value of a test supplier \(k\), from among a reference set of supplier \(s\), by selecting the optimal weights associated with the input and output measures. The maximum efficiencies are constrained to 1. The formulation is represented in expression (2).
maximize \quad E_{kk} = \frac{\sum O_{ky} v_{ky}}{\sum x I_{ks} u_{ks}} \tag{2}

subject to:

\[ E_{ks} \leq 1 \quad \forall \quad \text{Supplier } s \]

\[ u_{ks}, v_{ky} \geq 0 \]

This non-linear programming formulation (2) is equivalent to the following linear programming formulation (3):

maximize \quad E_{kk} = \sum y O_{ky} v_{ky} \tag{3}

subject to:

\[ E_{ks} \leq 1 \quad \forall \quad \text{Supplier } s \]

\[ \sum x I_{ks} u_{ks} = 1 \]

\[ u_{ks}, v_{ky} \geq 0 \]

The transformation is completed by constraining the efficiency ratio denominator from (2) to a value of 1. This is represented by the constraint:

\[ \sum x I_{ks} u_{ks} = 1. \]

The result of formulation (3) is an optimal “technical efficiency” value \( E_{kk}^* \) that is at most equal to 1. If \( E_{kk}^* = 1 \), then it means that no other supplier is more efficient than supplier \( k \) for its selected weights. That is, \( E_{kk}^* = 1 \) has supplier \( k \) on the optimal frontier and is not dominated by any other supplier. If \( E_{kk}^* < 1 \) then supplier \( k \) does not lie on the optimal frontier and there is at least one other supplier that is more efficient for
the optimal set of weights determined by (3). The formulation (3) is executed \( s \) times, once for each supplier. Since the CCR Model may provide a number of alternative suppliers that are efficient, it would be difficult for a decision-maker or organization to decide on a single supplier if there is more than one efficient supplier. To help discriminate among efficient suppliers and to help rank these suppliers, DEA ranking approaches may be used. One such approach is recommended here.

A Ranking DEA Model

A DEA approach that helps for ranking is a variation of the CCR model proposed by Anderson & Petersen (1993). In their model, they simply eliminate the test unit from the constraint set. The new formulation is represented by (4).

\[
\begin{align*}
\text{maximize} & \quad \sum_{s} O_{k} v_{k} \\
\text{subject to:} & \quad E_{s} \leq 1 \quad \forall \text{ Supplier } s \neq k \\
& \quad \sum_{s} I_{k} u_{k} = 1 \\
& \quad u_{k}, v_{k} \geq 0
\end{align*}
\]

Expression (4), which we will call the “reduced” CCR (RCCR) formulation, allows for technically efficient scores to be greater than 1. This result will allow for a more discriminating set of scores for technically efficient units and can thus be used for ranking purposes.
Integrating Managerial Preference into the DEA Ranking Approach

Constraining the “flexibility” or range of weights (u and v) provides an approach for integrating managerial preferences into the RCCR models. The use of assurance regions (AR) for restriction of weights is one approach to better map managerial preferences to DEA and to handle the problem of Zero multipliers (weights). The concept of AR is described in detail by Thompson, et al., (1990). The process of setting AR begins with defining upper and lower bounds for each input and output weight. The upper and lower bounds for each weight can help define constraints that relate the weight values of various factors. These LB and UB values may be ranges for preference weights for each of the factors as defined by the decision-makers. The AR constraints relate the weights and their bounds to each other while considering inputs/outputs of DEA model in pair. The generalized AR constraint sets that are derived from LB and UB data are:

\[ v_i \geq \frac{LB_i}{UB_j} v_j \quad \text{and} \quad v_i \leq \frac{UB_i}{LB_j} v_j \]  

(5)

These constraints can be added to expression (4) to form the RCCR with assurance regions (RCCR/AR) model. From a computational perspective, the number of additional constraints required to help define the AR is equal to \( \frac{I*(I-1)}{2} + \frac{O*(O-1)}{2} \), where I and O represent the number of inputs and outputs, respectively.
Appendix A3: LINDO Programs for DEA

Following is the LINDO program for CCR Model (DEA) for calculating the relative efficiency of DMU 1.

For RCCR model, erase the corresponding line of objective function from constraints

MAX \ V1 + V2 + 1.74 V3

ST

V1 > 0
V2 > 0
V3 > 0
U1 > 0
U2 > 0

V1 + V2 + 1.74 V3 - 1.03 U1 - 1.25 U2 <= 0
0.99 V1 + 0.99 V2 + 1.42 V3 - 1.02 U1 - 1.25 U2 <= 0
0.97 V1 + 1.01 V2 + 1.52 V3 - 1.01 U1 - 1.67 U2 <= 0
1.01 V1 + 0.99 V2 + 1.09 V3 - U1 - 1.25 U2 <= 0
V1 + 1.01 V2 + 1.08 V3 - 0.99 U1 - 1.25 U2 <= 0
0.97 V1 + 0.97 V2 + 1.09 V3 - 1.01 U1 - 0.83 U2 <= 0
1.02 V1 + 1.01 V2 + 0.38 V3 - 0.97 U1 - 0.83 U2 <= 0
1.01 V1 + 0.98 V2 + 0.35 V3 - 0.98 U1 - 0.42 U2 <= 0
1.01 V1 + V2 + 0.33 V3 - 0.98 U1 - 0.42 U2 <= 0

1.03 U1 + 1.25 U2 = 1

END
Following is the LINDO program for RCCR/AR Model (DEA) for calculating the relative efficiency of DMU 1.

MAX V1 + V2 + 1.74 V3

ST

V1 > 0
V2 > 0
V3 > 0
U1 > 0
U2 > 0

! V1 + V2 + 1.74 V3 - 1.03 U1 - 1.25 U2 <= 0
0.99 V1 + 0.99 V2 + 1.42 V3 - 1.02 U1 - 1.25 U2 <= 0
0.97 V1 + 1.01 V2 + 1.52 V3 - 1.01 U1 - 1.67 U2 <= 0
1.01 V1 + 0.99 V2 + 1.09 V3 - U1 - 1.25 U2 <= 0
V1 + 1.01 V2 + 1.08 V3 - 0.99 U1 - 1.25 U2 <= 0
0.97 V1 + 0.97 V2 + 1.09 V3 - 1.01 U1 - 0.83 U2 <= 0
1.02 V1 + 1.01 V2 + 0.38 V3 - 0.97 U1 - 0.83 U2 <= 0
1.01 V1 + 0.98 V2 + 0.35 V3 - 0.98 U1 - 0.42 U2 <= 0
1.01 V1 + V2 + 0.33 V3 - 0.98 U1 - 0.42 U2 <= 0

1.03 U1 + 1.25 U2 = 1

0.8 U1 - 0.2 U2 >= 0
0.333 U1 - 0.667 U2 <= 0
0.286 V1 - 0.111 V2 >= 0
0.222 V1 - 0.571 V2 <= 0
0.667 V1 - 0.111 V3 >= 0
0.143 V1 - 0.571 V3 <= 0
0.667 V2 - 0.222 V3 >= 0
0.143 V2 - 0.286 V3 <= 0

END
### Appendix A4: Zero-One Integer Goal Program

<table>
<thead>
<tr>
<th>Zero-One Integer Goal Program</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINIMIZE(d^-_5 + d^-_1 + d^-_2 + d^-_3 + d^-_4)</td>
<td>Satisfy all Goals</td>
</tr>
<tr>
<td>SUBJECT TO</td>
<td>Select a combination of VCCs with lowest NET PRICE</td>
</tr>
<tr>
<td>(0.413x_{11} + 0.398x_{12} + 0.434x_{13} + 0.496x_{21} + 0.487x_{22} + 0.478x_{23} + 0.139x_{31} + 0.147x_{32} + 0.124x_{33} - d^-_1 = 1)</td>
<td>Select a combination of VCCs with highest QUALITY</td>
</tr>
<tr>
<td>(0.331x_{11} + 0.324x_{12} + 0.331x_{13} + 0.324x_{21} + 0.331x_{22} + 0.338x_{23} + 0.331x_{31} + 0.324x_{32} + 0.331x_{33} + d^-_2 = 1)</td>
<td>Select a combination of VCCs with highest SERVICE</td>
</tr>
<tr>
<td>(0.325x_{11} + 0.332x_{12} + 0.322x_{13} + 0.329x_{21} + 0.329x_{22} + 0.311x_{23} + 0.339x_{31} + 0.324x_{32} + 0.329x_{33} + d^-_3 = 1)</td>
<td>Select a combination of VCCs with lowest LEAD TIME</td>
</tr>
<tr>
<td>(0.698x_{11} + 0.581x_{12} + 0.465x_{13} + 0.465x_{21} + 0.558x_{22} + 0.512x_{23} + 0.093x_{31} + 0.070x_{32} + 0.093x_{33} - d^-_4 = 1)</td>
<td>Select a combination of VCCs with highest QUALITATIVE BENEFITS</td>
</tr>
<tr>
<td>(x_{11} + x_{12} + x_{13} = 1)</td>
<td>Select only one Designer Process VCC</td>
</tr>
<tr>
<td>(x_{21} + x_{22} + x_{23} = 1)</td>
<td>Select only one Manufacturing Process VCC</td>
</tr>
<tr>
<td>(x_{31} + x_{32} + x_{33} = 1)</td>
<td>Select only one Distributor (Logistics) Process VCC</td>
</tr>
<tr>
<td>(x_{11} + x_{21} = 1)</td>
<td>VCC 1 of Process 1 (Designer) is not compatible with VCC 1 of Process 2 (Manufacturing)</td>
</tr>
<tr>
<td>(x_{22} + x_{32} = 1)</td>
<td>VCC 2 of Process 2 (Manufacturing) is not compatible with VCC 2 of Process 3 (Logistics)</td>
</tr>
<tr>
<td>(10x_{21} + 15x_{22} + 20x_{23} \geq 12)</td>
<td>Select a Manufacturing process VCC that has the capacity of simultaneously manufacturing 12 or more machines (mfg. process VCCs 1, 2, &amp; 3 have the capacity of simultaneously mfg. 10, 15, &amp; 20 machines respectively)</td>
</tr>
<tr>
<td>END</td>
<td></td>
</tr>
<tr>
<td>INT (x_{11}, x_{12}, x_{13}, x_{21}, x_{22}, x_{23}, x_{31}, x_{32}, x_{33})</td>
<td></td>
</tr>
</tbody>
</table>

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Appendix A5: Papers Published / Communicated from this Research

(1) A paper titled "Supplier Selection in an Agile Manufacturing Environment using DEA and ANP" has been accepted for publication in the "International Journal of Logistics Systems and Management".

(2) A paper titled "A Study of Barriers to Agile Manufacturing" has been accepted for publication in the "International Journal of Agile Systems and Management".

(3) A paper titled "Virtual company formation for agile manufacturing using ANP & Goal Programming" has been accepted for publication in the "International Journal of Operational Research" and forthcoming in Vol. 4, No. 6, 2009.

(4) A paper titled "Production system selection for the agile manufacturing of modularly designed products" has been accepted for publication in the "International Journal of Manufacturing Technology and Management".

(5) A paper titled "A Study of Enablers of Agile Manufacturing" has been communicated for publication consideration in the "International Journal of Industrial and Systems Engineering (IJISE)".
Appendix A6: Biographical Profile of Researcher

(As on August, 2007)

Academics

2007: Currently pursuing for the degree of Doctor of Philosophy as a teacher candidate at Aligarh Muslim University (AMU), Aligarh, India (supervisor from AMU and co-supervisor from Indian Institute of Technology, Delhi, India).

1996: Post-Graduated from Zakir Hussain College of Engineering & Technology (Z.H.C.O.E.T.), AMU, Aligarh, India, with a Master’s degree in Mechanical Engineering (specialization in Industrial Engineering).

1992: Graduated from Z.H.C.O.E.T., AMU, India, with a Bachelor’s degree in Mechanical Engineering.

Experience

Working as a faculty of Mechanical Engineering at University Polytechnic, AMU, India, since 1997.