Activity-based cost estimation in a push/pull advanced manufacturing system

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Abstract

The objective of this paper is to estimate the manufacturing and product costs by using activity-based costing (ABC) method in an advanced manufacturing system that is run under either material requirements planning (MRP) or just in time (JIT) system. ABC is a method that can overcome many of the limitations of traditional costing systems. This paper reports and discusses the implementation of the ABC alongside a mathematical and simulation model to estimate the manufacturing and product cost in an automated manufacturing system. The potential effects of manufacturing planning and control strategies implemented on financial structure of the manufacturing system are initially analysed. ABC has been used to model the manufacturing and product costs. An extensive analysis has been carried out to calculate the product costs under the two strategies. The comparison of the two strategies in terms of effects on the manufacturing and product costs are carried out to highlight the difference between the two strategies. © 2003 Elsevier Science B.V. All rights reserved.

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1. Introduction

Increasing competitiveness worldwide has forced manufacturing organisations to seek to produce high-quality products more quickly and at a competitive cost. In order to reach these goals, today’s manufacturing organisations are required to become more flexible, integrated and highly automated. However, since the initial and operating costs are high, advanced manufacturing system users are concerned with achieving high system utilisation. Despite the advantages of having high levels of automation, and flexibility, and producing high quality products, without a realistic and more accurate cost calculation mechanism, these systems cannot be expected to sustain competitiveness.

Activity-based costing (ABC) was introduced by Kaplan and Cooper as an alternative to traditional accounting techniques (Cooper and Kaplan, 1988a,b). Since then, it has been increasingly used in multi-level, complex manufacturing organisations. ABC models the relationships between products and the resources used in their
production at all stages. ABC is preferable to classical cost calculations (CCC) because it provides a more accurate and consistent way of calculating manufacturing costs (Andrea et al., 1999). This results in a more accurate cost calculation (Kee and Schmidt, 2000). A number of sources are available on various implementations of ABC ranging from simply calculating a simple product manufacturing cost to modelling costing for multiple products in a multi-level, highly automated complex manufacturing system (Kee, 1995; Noreen, 1991; Malik and Sullivan, 1995; Spedding and Sun, 1999; Koltai et al., 2000).

It is impractical to create an ABC model without a proper design tool that clearly identifies all the individual activities that take place in a manufacturing system from beginning to end. Such a tool can greatly help to reduce time used for modelling and overcome the difficulties present in creating a cost model (Spedding and Sun, 1999). The model developed in this paper uses simulation as a modelling tool to observe the manufacturing cost behaviour under two manufacturing planning and control strategies, of the push and pull types, respectively.

In recent years, the remarkable success stories of Japanese understanding of production planning and control systems introduced a new paradigm to production research literature. The so-called just in time (JIT) system organizes the production such that materials arrive just as they are needed in relatively small batches through an attached ‘Kanban’ which identifies a standard quantity of transfer batch or size of a container. JIT has been widely accepted and gained remarkable attention among researchers as well as practitioners (Huang and Kusiak, 1998; Baykoc and Erol, 1998; Thesen, 1999; Koufteros, 1999). A distinction is frequently made between this relatively new system and classical material requirements planning (MRP) based production planning and control. JIT uses a ‘pull’ approach, where a work centre finishes its operations and then requests the next job from the preceding work centre. The preceding work centre can only start making the products when it gets its request, so that queues and work in progress (WIP) are greatly eliminated.

In contrast, an MRP-based ‘push’ system schedules the jobs in advance for a series of work centres, and each work centre pushes its completed jobs to the succeeding work centres. This approach pushes the partially completed jobs and ignores the workload of the next work centre so that WIP queues and stock levels increase and long delays often occur. Nevertheless, the two approaches aim at creating a better way of planning and controlling production and some researchers see no major difference between the two approaches in terms of several performance measures (Bonney et al., 1999). This paper is concerned with creating a model that calculates the manufacturing costs using ABC for each of the manufacturing planning and control strategies only. Although “mixed” systems combining elements of JIT and MRP are evident in some manufacturing systems they are not considered here.

The objective of this paper is to offer a simulation-based model that uses ABC to estimate the manufacturing and product costs in an advanced manufacturing organisation that is run under either a push or pull system. The paper first describes the cell hardware structure considered and the basic control system implemented. Manufacturing activities are then described alongside a mathematical model, which calculates the unit costs of manufactured products using ABC analysis. This provides the basic data for the simulation model. The simulation model identifies every single activity that either directly or indirectly affects the cost of an item, in a prototype manufacturing system under both push and pull control strategies and uses the ABC-based mathematical model to calculate the manufacturing and product costs. An experimental study has been conducted to demonstrate the calculation of the manufacturing as well as product costs under different manufacturing scenarios to gain an insight into the effects of different planning and control strategies on costs. The output of the each model is considered separately in order to distinguish and compare the effects of these two strategies on product costing. Finally, the conclusions highlight the advantages of the approach developed.
2. Modelling of manufacturing activities

In this study a flexible manufacturing system (FMS) with six cells, each containing one workstation, is considered. The system is capable of processing small and large prismatic and rotational components. Each machine has 3-, 5-, and 7-job input and an output buffers. Each cell may also have a queue holding a maximum of 7 jobs under push-based strategy. The cell has an inspection station, and an automated storage and retrieval system (AS/RS). There are also up to two-vehicle automated guided vehicle (AGV) transporter system to move parts to and from machines and a robotic material handling system that loads and unloads parts from the machines. The layout of the system modelled is shown in Fig. 1.

The system considered is a demand driven system where the next 6 months demand is known through contracts made between company and the customers, which are evident especially in the contract-based manufacturing industry such as automotive, avionics, electric appliances, and so on. Table 1 shows the next 6 months demand.

At the beginning of the planning horizon, the system is assumed to be empty. It is also assumed that operation times, transportation times and the part routes are known either from experience or by calculation. Parts are either pushed or pulled and are sequenced and scheduled according to one of four scheduling rules, which are: shortest processing time (SPT), longest processing time (LPT), first come first served (FCFS), and SLACK, and are transferred on pallets of variable sizes that form the transferred batches. The cell is operated using generic common sense rules and each planning and control system implements its own rules to run the shop floor. These generic and shop floor operating rules for the two strategies are given in appendix. Since the lot sizes are variable, a variable quantity of parts is introduced into the system every day. In total, 35 different part types belonging to 10 products are manufactured in the system. Also six different pallet types are used to transfer parts. The average set-up time for each batch is deterministic and known a priory. Workstations and other equipment may breakdown due to several reasons and regular maintenance or repair with a probabilistic time value has been introduced whenever necessary. Despite every step taken to minimise the scrap or rework level, some parts have to be scrapped or reworked due to several causes of malfunction and these are also represented by probabilistic values. The simulation was coded in SIMAN IV (Pedgen et al., 1990). The simulation has been run for three shifts a day, 6 days a week and 6 months, altogether 207,360 minutes.

3. Manufacturing activities and costing

3.1. Activities and activity centres

In any manufacturing organisation, tens of activities are carried out during the process of getting raw materials, transforming them into
finished products and delivering them to customers. To model each of these activities based on ABC is technically very difficult. Therefore, depending on the level of resource consumption, some of the resource centres will be described as activity centres.

There are six workstations, an inspection station and an assembly line in the automated system as the major operations centres. The following activity centres are described based on these operations centres:

1. Six workstations are used to process all the parts.
2. An inspection station is used to inspect all components.
3. An assembly line is used to assemble all sub and major components.
4. All set-up activities take place before the operations.
5. Robot and AGV are used for material handling, loading and unloading operations and AS/RS is used to store the components temporarily.

It is assumed that these activity centres consume certain levels of resources. The resource consumption is calculated using these centres’ utilisation levels.

3.2. Resources

The major goal in ABC is to calculate the activity costs. The product cost calculation is a secondary operation. The aim is to manage the activities that contribute to the overall cost. In this context, the cost of a product is the summation of the costs of activities that take place to manufacture that product. Therefore, after determining the activities, one should calculate how much resource each activity consumes.

Two different resources are available in automated manufacturing systems. These are capital expenditures and current expenditures. Capital expenditures are made for building, machines, equipment, etc., and converted to a cost figure when they are used for the purpose of manufacturing throughout the years. Current expenditures are the converted values of daily, weekly, and monthly expenditures made to run the system. The following are the major cost items involved in resource consumption in automated manufacturing systems:

1. **Machines and cutting tool holders**: This cost item includes the money spent to buy machine tools, and cutting tool holders used in machining processes.
2. **Computer system**: This cost item includes the expenditures made for all kinds of computer hardware and software systems used in an organisation to keep the system alive.
3. **Robot and AGV system**: These are the major hardware systems used to transport all kinds of flowing entities such as raw materials, WIP, tools, pallets, fixtures, subassemblies, or assembled products and utilisation of these resources is calculated considering the relationships with other hardware elements such as machines, and so on, used in system so the cost calculations.
4. **AS/RS system**: This system is used to temporarily store all kinds of entities flowing in the manufacturing systems whenever necessary and AS/RS cost is calculated like other ancillary equipment such as the computer system and the materials handling mechanism.
5. **Fixed assets**: This is the physical place where the shop floor, material stores as well as the offices is located and the cost of this resource is common for all activities but it is not equally distributed.
6. **Externally provided resources**: These are physical inputs such as the fuel for heating, electricity for lighting, ventilating, telecommunication service for communications, etc., obtained from outside of the organisation to run the system and the cost is the summation of all the bills.
7. **Direct and indirect labour**: Since the automated system uses either very little direct human power or no human power at all, and one man can deal with many machines, determining direct labour contribution to product cost is very difficult and many times these contributions are negligible. All labour costs are pooled as indirect labour cost.
8. **Insurance and indirect material**: Insurance and all other related cost items depend on the value of the items. Indirect materials are used to run the system at different stages of manufacturing and almost impossible to determine how much of these
indirect materials are used for each part manufactured in the system.

9. Cutting tools and fixtures: Cutting tools are consumables and are used for processing and then disposed. Fixtures may be specific, which could be used, for specific components or universal or modular fixtures that can be used for many operations.

10. Direct energy consumptions: Since operation times are known through modelling it is easy to calculate the energy consumption of each piece of equipment in an automated system. The cost involved in the energy consumption related to machines and other equipment can be calculated for each part.

11. Direct material: The quantity and the cost of materials used can be calculated through the related product bill-of-materials (BOM).

12. Other services: These are necessary services for survival of the organisation and cover all non-manufacturing services. These are: maintenance, process planning, industrial engineering activities, accounting and finance, administration departments, and marketing.

3.3. Selection of activity centres

An activity cost is the summation of costs of resources that are used by that activity. Determination of which activity consumed which resource and how much of the resource is used by that activity is not easy, especially in complex automated systems. Sometimes a resource may be used by several activities. In that case, the level of resource utilisation by each activity could be determined through activity centres. The resource centres are also known as cost centres and give the input–output relationship between activity and activity cost pool. However, in order to avoid any distortion or miscalculation in costing, cost items should be distributed to activity centres directly. If it is not possible, the indirect forecasting can be used to estimate the costs.

In this study, the indirect resources are distributed to the main activity centres according to the utilisation levels obtained from the system simulation. Therefore, for each activity centre, two cost pools are formed as direct and indirect cost pools. The direct cost pool consists of raw materials, direct energy consumed, cutting tools, fixtures, etc. The indirect cost pool consists of externally provided service costs, indirect labour cost, indirect material cost, insurance cost, administration cost, etc. The resources, resource drivers, activities, activity centres, activity drivers, and cost objectives are displayed in Fig. 2.

3.4. Resource costs

The major production resources such as workstations, inspection station and assembly line and other auxiliary equipment such as AGV system, robot, AS/RS, and computer system cost a certain amount of capital. The cost of workstations is assumed as direct cost and the other equipment cost is assumed as indirect cost. The economic life of all major equipment in the system is assumed to be 15 years or 108,000 hours and the hourly depreciation cost of equipment can easily be calculated.

3.5. Unit cost calculation

The following notation is used to describe the model built to calculate the unit cost of the product manufactured based on ABC:

\[ j \] part level index, 0,1,2,…,\( J \), 0 shows the final product level, where the other increasing numbers show the part level used in a product.

\[ i_j \] 1,2,…,\( J \), part \( i \) at level \( j \)

\[ R(i_j) \] \( i_j \) part route, \( r = 1,2,\ldots,R(i_j) \)

\[ a(i_j,o) \] operation \( o \) of part \( i_j \) which is activity \( a \)

\[ B(i_j) \] batch size of \( i_j \) (pallet capacity)

\[ S(i_j,o) \] standard set-up time for operation \( o \) of batch \( B(i_j) \)

\[ t(i_j,o) \] process time for operation \( o \) of part \( i_j \)

\[ A(i_j,o) \] assembly time for operation \( o \) of part \( i_j \)

\[ DSCR(a) \] direct set-up cost rate for activity \( a \)

\[ DMCR(a) \] direct machining cost rate for activity \( a \)

\[ DACR(a) \] direct assembly cost rate for activity \( a \)

\[ MCR(a) \] machine tool cost rate for activity \( a \) ($/h)
OSCR(a) overall set-up cost rate for activity $a$ ($/h$)
ACR(a) assembly cost rate for activity $a$ ($/h$)
$M(i_j)$ unit material cost ($\$$)
$W(i_j)$ weight of materials used in part $i_j$
$HC(i_j)$ unit handling cost ($$/h$)
$d_{R(i_j)}$ distance route for part $(i_j)$
$StC(i_j)$ storage cost ($$/h$)
$w(i_j)$ average waiting time for part $i_j$ in AS/RS and in machine buffers
$s_{PAGV}$ speed of AGV vehicle
$n(i_{j+1}, i_j)$ necessary number of components $i_{j+1}$ for $i_j$
$SAC(i_j)$ standard additional cost for part $i_j$ ($\$$)
$SC(i_j)$ standard cost for part $i_j$ ($\$$)

Both the unit cost of each component and each product cost is calculated. This calculation also implies that the dynamic cost of components whenever they pass from one resource centre to another can be calculated. This also gives us the cost of WIP or finished component or product at any stage of the production process at any time. The technological order of the production processes is used so as the cost calculation follows the BOM structure of each product.

The following formulation is the modified and improved form of the formula developed by Kim et al. (1997) and has been used to calculate the unit cost of parts and products based on ABC in this work.

These formulations cover all components, sub-assemblies, assemblies, and final products. For example, the total cost of product $A$, Fig. 3, consists of costs of component $P_3$, subassembly $A_1$ (which consists of components $P_1$, and $P_2$) and the assembly of these parts to form product $A$. 
Standard cost covers the cost items that cannot be represented by a cost factor directly such as labour, fixed assets, computer systems, and so on.

\[
SC_{ij} = \sum_{o=1}^{R_i} \left\{ \frac{S(i_j, o)}{B(i_j)} \times \text{OSCR}[a(i_j, o)] + \text{DSCR}[a(i_j, o)] + \{t(i_j, o) \times \text{MCR}[a(i_j, o)] + \text{DMCR}[a(i_j, o)] + \{A(i_j, o)) \times \text{ACR}[a(i_j, o)] + \text{DACR}[a(i_j, o)] + \left\{ \left( \text{HC}(i_j) \times \frac{dR(i_j)}{SP_{AGV}} \right) + \text{StC}(i_j) \times w(i_j) \right\} + \{M(i_j) \times W(i_j)\} \right\}
\]

\[
\text{SAC}(i_j) = SC(i_j) + \sum_{\forall i_{j+1}} n(i_{j+1}, i_j)SC(i_{j+1}).
\]

4. An experimental study and discussion

To illustrate the concept presented in previous sections the production plan given in Table 1 is considered. The system was run in two separate modes as push and pull systems. Both production planning and control systems are aimed at meeting the demand placed for six months. However, each of the systems implemented has its own rules and strategies to run the organisation (see appendix) and the daily production plan with daily work contents being somewhat different. As a result of different planning approaches, the major manufacturing performance criteria such as production rate, finished product inventory, WIP, flow time, facilities utilisation, and so on are different and have different effects on product costs.

Four different material types at different levels are used for 10 products and weekly material requirements are calculated considering the production control system’s master production scheduling, and material consumption of individual part types.

The simulation ran 12 replications for each of the production planning and control systems, where each replication represents one production scenario. The system model was programmed to run and mimic the production recorded in the master production schedule. Since a vast amount of output is produced by each of the simulation-based scenarios, only runs with push- and pull-based FCFS with 3-pallet machine buffers are presented here. Simulation output data for ABC calculations was recorded according to the cost driver requirements.

4.1. Activity pools and cost drivers

ABC calculations are made according to the four-step ABC system. The first requirement of the calculations is that the cost drivers for each activity pool are determined. This process is described and discussed in detail using activity pools as an example.

Activity pool: Operation of machining/grinding parts
Operation of replacing machining/grinding tools

The cost drivers that need to be determined for these activities are the numbers of each part type operated upon and the total time spent per part in the operations. The total time spent over the 26-week simulated period in each specific operation is determined as the sum of the total time taken in each operation per week.

Activity pool indicates the basis on which costs from activities can be traced to parts. For example, in the case of allocating costs associated with small
It is realised that since Product A has the highest rate of consumption it should be given an appropriately high cost weighting. The easiest method of determining the true cost weighting is through percentage utilisation. The percentage utilisation of each product against activities is shown in Table 2.

It can be seen from Table 2 that the cost of small machining operations and the cost of replacing tools should be allocated to Product A in the proportion of 48%, to Product E in the proportion of 28.6% and to Product G in the proportion of 23.2% in an push-based scenario.

The cost for all other machining/grinding and tool-replacing activities is allocated in the same manner, where cost is allocated to parts and products on the basis of their utilisation of the resource.

Activity pool: Operation of replacing assembly tools
Activity pool: Operation of assembling products

The cost driver that will determine the allocation of activity cost to products is the number of products of each type assembled and the total time spent at assembly operations by each product type. The information for these two drivers is recorded in Table 3 as the total time spent by each product type in assembly operations over the 26-week production period. Table 3 also shows the time spent as a percentage value of total time.

Activity pool: Operation of transporting parts

The activity of transporting parts around the cell refers to the use of the AGV by parts as they are transported from machining to grinding, inspection station, AS/RS, and assembly line. Rather than consider the percentage time utilisation as with the allocation of station activity costs and tool activity costs, the allocation of the cost of transporting parts is driven by the total unit distance travelled by the AGV per part type. The percentage utilisation driver is calculated as the total number of parts transported multiplied by the unit distance per part route.

Activity pool: Automated storage and retrieval system operations

The AS/RS in the simulated model is split into three sections (store, part AS/RS and the assembly queue of product AS/RS). For the purpose of calculations all of these sections are considered in the AS/RS operations cost. Hence, the allocation

<table>
<thead>
<tr>
<th>Product</th>
<th>Push</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>0.48</td>
<td>0.475</td>
</tr>
<tr>
<td>Product B</td>
<td>0.604</td>
<td>0.599</td>
</tr>
<tr>
<td>Product C</td>
<td>0.442</td>
<td>0.23</td>
</tr>
<tr>
<td>Product D</td>
<td>0.286</td>
<td>0.553</td>
</tr>
<tr>
<td>Product E</td>
<td>0.142</td>
<td>0.144</td>
</tr>
<tr>
<td>Product F</td>
<td>0.232</td>
<td>0.236</td>
</tr>
<tr>
<td>Product G</td>
<td>0.396</td>
<td>0.4</td>
</tr>
<tr>
<td>Product H</td>
<td>0.416</td>
<td>0.417</td>
</tr>
<tr>
<td>Product I</td>
<td>0.44</td>
<td>0.446</td>
</tr>
<tr>
<td>Product J</td>
<td>0.215</td>
<td>0.224</td>
</tr>
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</table>

Push % use of Pull % use of
<table>
<thead>
<tr>
<th>MC1</th>
<th>MC2</th>
<th>TC1</th>
<th>TC2</th>
<th>GRP</th>
<th>GRS</th>
<th>MC1</th>
<th>MC2</th>
<th>TC1</th>
<th>TC2</th>
<th>GRP</th>
<th>GRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48</td>
<td>0.604</td>
<td>0.166</td>
<td>0.412</td>
<td>0.475</td>
<td>0.162</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.442</td>
<td>0.56</td>
<td>0.23</td>
<td>0.303</td>
<td>0.438</td>
<td>0.234</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.286</td>
<td>0.087</td>
<td>0.072</td>
<td>0.288</td>
<td>0.553</td>
<td>0.281</td>
<td></td>
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</tr>
<tr>
<td>0.142</td>
<td>0.092</td>
<td>0.236</td>
<td>0.4</td>
<td>0.144</td>
<td>0.089</td>
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<tr>
<td>0.396</td>
<td>0.243</td>
<td>0.417</td>
<td>0.0182</td>
<td>0.245</td>
<td>0.0182</td>
<td></td>
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</tr>
</tbody>
</table>

MC1 = small prismatic machine; MC2 = large prismatic machine; TC1 = small turning centre, TC2 = large turning centre; GRP = grinding machine for prismatic parts; GRS = grinding machine for rotational parts.
drivers for the AS/RS operations relate to the utilisation by each part and product of each storage area. In terms of simulation output, these drivers are the total time spent in stores per part type, the total time spent in part AS/RS per part type and the total time spent in the product AS/RS per product type.

Activity pool: Facility administration operations

Facility administration operations involve those non-manufacturing activities driven by the number of products required to meet customer demands. Such activities could include the number of purchase orders raised. The cost driver for facility administration operations is the number of products of each type manufactured by the system in the 26-week period under study.

Activity pool: Unit operations

Unit operations refer to engineering tasks not related to the quantity of products made but the production unit; for example, the design of products. The cost driver for allocating unit operations costs is the number of product types in manufacture.

4.2. Assigning cost from resources to activities

An important proportion of the total cost is the working cost of the manufacturing system. This includes the initial investment of machinery, the cost of tools, electricity and gas costs and labour expenses. These expenses must be allocated through a hierarchical chain of events downward to the products. The first stage of this process is to assign costs from resources to activities. This information is given in Tables 4a and b.

Factory costs are allocated to simulated system resources on a direct and ‘traced’ basis. For example, the machining and grinding centres have a direct cost such as the depreciated value of their initial investment and traced costs such as the estimated requirement of direct labour.

Depreciation is calculated according to the initial investment and the service life of the machine taking into account the 26-week working period. No account has been taken of the scrap or resale price of the machines at this stage. The depreciation charge for buildings is apportioned according to the floor space taken by the machine or office area.

Electricity is charged to all resources according to their consumption. Gas is required to heat the buildings for the comfort of the employees and is therefore charged taking a view of the manpower required in the unit and facility operations, and hence the size of offices required for accommodating staff.

Labour costs are split into two categories: manufacturing related and non-manufacturing related labour. Examples of manufacturing related operations include the cost of operating processes

<table>
<thead>
<tr>
<th></th>
<th>Push Total time at assembly</th>
<th>% utilisation of assembly</th>
<th>Pull Total time at assembly</th>
<th>% utilisation of assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product A</td>
<td>4800</td>
<td>0.053</td>
<td>4480</td>
<td>0.053</td>
</tr>
<tr>
<td>Product B</td>
<td>15,312</td>
<td>0.171</td>
<td>14,784</td>
<td>0.174</td>
</tr>
<tr>
<td>Product C</td>
<td>7752</td>
<td>0.086</td>
<td>7296</td>
<td>0.086</td>
</tr>
<tr>
<td>Product D</td>
<td>8432</td>
<td>0.094</td>
<td>7936</td>
<td>0.093</td>
</tr>
<tr>
<td>Product E</td>
<td>4200</td>
<td>0.047</td>
<td>3780</td>
<td>0.044</td>
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<tr>
<td>Product F</td>
<td>6360</td>
<td>0.071</td>
<td>5830</td>
<td>0.068</td>
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<tr>
<td>Product G</td>
<td>7350</td>
<td>0.082</td>
<td>7000</td>
<td>0.082</td>
</tr>
<tr>
<td>Product H</td>
<td>10,880</td>
<td>0.122</td>
<td>10,540</td>
<td>0.124</td>
</tr>
<tr>
<td>Product I</td>
<td>10,032</td>
<td>0.112</td>
<td>9474</td>
<td>0.111</td>
</tr>
<tr>
<td>Product J</td>
<td>14,202</td>
<td>0.160</td>
<td>13,770</td>
<td>0.162</td>
</tr>
</tbody>
</table>

Table 3
Total time and percentage time spent by each product type at assembly operations for MRP and JIT
on several activity centres and relate directly to the simulated resources. Non-manufacturing related operations directly relate to the unit (engineering) and facility (non-engineering) operations.

The cost of tools is allocated directly, according to the number of tools consumed in machining, grinding and assembly operations. The total time spent in operations by each station is taken from the simulation output data and the cost of tools calculated according to this time, assuming that each tool has an average cutting life of 60 minutes.

4.3. Activity-based cost calculations

Using the cost information given in Table 2 and the activity pool cost drivers developed for cost allocation by percentage utilisation, part and product costs can be calculated. This calculation method follows the mathematical model developed in Section 3. This equation states that the total cost of a part is the sum of the allocated costs for each operation the part undergoes in its production process plus the raw material required.

Production can be considered in two stages, machining and grinding operations (MC/TC, GRP/GRS) and other operations. Tables 5a and b show the allocated cost to parts from activity centre machining operations and tool replacing operations. Since these operations share the same activity drivers, the table shows the combined cost of these operations. The cost for every cost pool has now been allocated. The next stage of calculation is combining these part and product costs, Table 6. Once the allocated cost of each activity pool is allocated as a percentage utilisation to each part and product, the ABC calculation may be made as described above.

Using the information compiled in Tables 5 and 6, the total cost of production for the part and product types may be made. The unit cost per part and product is calculated by dividing the total production cost by the number of elements (individual components, or batch).

The production costs of product types are calculated as the sum of the unit cost per part and product as allocated from the activity cost drivers.

### Table 4

(a) Tracing unit manufacturing costs to the system resources

<table>
<thead>
<tr>
<th>Cost item ($)</th>
<th>MC1 operations</th>
<th>MC2 operations</th>
<th>TC1 operations</th>
<th>TC2 operations</th>
<th>GRP operations</th>
<th>GRS operations</th>
<th>Inspection operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation (equipment)</td>
<td>9200</td>
<td>9200</td>
<td>6133.3</td>
<td>6133.3</td>
<td>4600</td>
<td>4600</td>
<td>3066.66</td>
</tr>
<tr>
<td>Depreciation (buildings)</td>
<td>15,058.97</td>
<td>16,438.42</td>
<td>15,518.79</td>
<td>16,093.56</td>
<td>15,403.83</td>
<td>16,668.33</td>
<td>10,920.63</td>
</tr>
<tr>
<td>Electricity</td>
<td>7472</td>
<td>5698.8</td>
<td>5504.6</td>
<td>5472</td>
<td>4377.2</td>
<td>4730</td>
<td>2514.6</td>
</tr>
<tr>
<td>Gas</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
</tr>
<tr>
<td>Direct labour</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tools/Fixture</td>
<td>68,137.5</td>
<td>74,175</td>
<td>70,293.2</td>
<td>72,881.2</td>
<td>69,431.2</td>
<td>75,272.5</td>
<td>0</td>
</tr>
</tbody>
</table>

(b) Tracing unit non-manufacturing costs to the system resources

<table>
<thead>
<tr>
<th>Cost item ($)</th>
<th>Assembly operations</th>
<th>AGV operations</th>
<th>AS/RS operations</th>
<th>Facility admin. operations</th>
<th>Unit admin. operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depreciation (equipment)</td>
<td>10,732</td>
<td>36,800</td>
<td>76,666.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Depreciation (buildings)</td>
<td>8506.5</td>
<td>9196.3</td>
<td>13,794.48</td>
<td>24,140.4</td>
<td>10,345.8</td>
</tr>
<tr>
<td>Electricity</td>
<td>1610.4</td>
<td>771.82</td>
<td>5299.2</td>
<td>1656.2</td>
<td>1104</td>
</tr>
<tr>
<td>Gas</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10,907.5</td>
<td>5873.23</td>
</tr>
<tr>
<td>Manufacturing-labour</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Non-manufacturing-labour</td>
<td>69,000</td>
<td>69,000</td>
<td>69,000</td>
<td>1,350,000</td>
<td>600,000</td>
</tr>
</tbody>
</table>
According to the mathematical model, the final cost consideration is the cost per product of materials.

The total cost of one unit of each product type is the sum of unit production cost and raw material cost per product type. Hence, the push and
pull-based costs for each product types are shown in Table 7.

This improved understanding of the relationships between products, activities and costs leads to more efficient management of the manufacturing process, even down to the level of product design and plant layout design.

The complete cost figures of the products under push- and pull-based production planning and control systems as well as different scenarios are given in Table 8.

5. Concluding discussion and conclusions

This work has investigated the effects of production planning and control systems on the estimation of the manufacturing cost with ABC calculation in an advanced manufacturing system.

The hypothetical manufacturing system developed for the purpose of this study considered a number of different cost items that would be expected to feature in any ‘real-life’ manufacturing system. The costs were classified as manufacturing or non-manufacturing related. The category selection was chosen to reflect items that can be described in different ways depending on the accounting method used. For the purpose of this study the costs were traced to unit-level, batch-level and facility-level cost items within the simulation model.

Under the ABC methodology, all costs have been assigned to activities. If the cost items cannot be justifiably assigned to activities, the existence of that facility must be questioned. ABC methods have a variety of advantages over traditional cost accounting methods. These advantages relate to the way the costing process is assessed and the improved “visibility” of cost items.

The improved visibility of cost items traditionally considered as an inconsequential overhead, is one advantage of ABC. Fig. 4 shows the allocation of cost to product A from all the resource areas associated with its production. The allocation has been shown as a percentage of the total cost for clarity.

The process of allocating cost from resources to activities to products is the second benefit of ABC. By understanding the hierarchy of costs and the way products consume the lower cost items, the visibility of ‘overheads’ is improved. Under traditional cost accounting systems, the attention of management would be drawn only to the higher cost items, which in this case, are the transport system and the AS and RS.

Under ABC all the model costs are assigned to activities in the system. Thus, by comparing the model cost items to the allocation of costs under ABC, it can be seen that the greatest cost item within the system is the small machining system, and hence it is this item that management should focus their attention on reducing.

The greatest benefits of ABC can be seen in conjunction with the simulation model. Simulation provides a powerful visualisation tool for the analysis of system performance thus improving the qualitative understanding of how cost is incurred in products. The ABC results provide quantitative figures to determine the cost effectiveness of the system and to justify strategic decision making. Such a system could provide a firm basis for establishing the selling cost for products not yet manufactured, provide guidance for the purposes of concurrent engineering, justify capital investment in equipment, evaluate new technology and assist in exploring “what-if” scenarios.

The main concern of this paper is to investigate the manufacturing cost implications; whereas the discussions on cell performance measures are the
subject of a separate paper (Ozbayrak et al., 2002, 2003). The system’s reactions under different planning and control strategies or scenarios according to several cell performance criteria such as mean flow times, average queue times, etc. are therefore not discussed here.

Table 8
Product costs under different policies and scenarios

<table>
<thead>
<tr>
<th>Products</th>
<th>Buffer Size under SPT</th>
<th>Buffer Size under LPT</th>
<th>Buffer Size under SLACK</th>
<th>Buffer Size under FCFS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Push</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product A</td>
<td>738</td>
<td>744</td>
<td>741</td>
<td>747</td>
</tr>
<tr>
<td>Product B</td>
<td>576</td>
<td>581</td>
<td>581</td>
<td>593</td>
</tr>
<tr>
<td>Product C</td>
<td>649</td>
<td>655</td>
<td>659</td>
<td>658</td>
</tr>
<tr>
<td>Product D</td>
<td>828</td>
<td>833</td>
<td>837</td>
<td>837</td>
</tr>
<tr>
<td>Product E</td>
<td>431</td>
<td>433</td>
<td>444</td>
<td>443</td>
</tr>
<tr>
<td>Product F</td>
<td>352</td>
<td>353</td>
<td>363</td>
<td>366</td>
</tr>
<tr>
<td>Product G</td>
<td>486</td>
<td>486</td>
<td>495</td>
<td>494</td>
</tr>
<tr>
<td>Product H</td>
<td>724</td>
<td>727</td>
<td>728</td>
<td>729</td>
</tr>
<tr>
<td>Product I</td>
<td>551</td>
<td>554</td>
<td>554</td>
<td>556</td>
</tr>
<tr>
<td>Product J</td>
<td>847</td>
<td>855</td>
<td>858</td>
<td>861</td>
</tr>
<tr>
<td>Pull</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product A</td>
<td>711</td>
<td>712</td>
<td>718</td>
<td>718</td>
</tr>
<tr>
<td>Product B</td>
<td>538</td>
<td>541</td>
<td>547</td>
<td>543</td>
</tr>
<tr>
<td>Product C</td>
<td>589</td>
<td>603</td>
<td>611</td>
<td>605</td>
</tr>
<tr>
<td>Product D</td>
<td>803</td>
<td>808</td>
<td>816</td>
<td>810</td>
</tr>
<tr>
<td>Product E</td>
<td>424</td>
<td>429</td>
<td>439</td>
<td>435</td>
</tr>
<tr>
<td>Product F</td>
<td>351</td>
<td>357</td>
<td>365</td>
<td>359</td>
</tr>
<tr>
<td>Product G</td>
<td>460</td>
<td>465</td>
<td>471</td>
<td>471</td>
</tr>
<tr>
<td>Product H</td>
<td>633</td>
<td>638</td>
<td>646</td>
<td>640</td>
</tr>
<tr>
<td>Product I</td>
<td>545</td>
<td>554</td>
<td>560</td>
<td>559</td>
</tr>
<tr>
<td>Product J</td>
<td>781</td>
<td>791</td>
<td>793</td>
<td>794</td>
</tr>
</tbody>
</table>

Fig. 4. Division of the contributing costs of Product A based on MRP FCFC run.
While simulation models the stochastic nature inherent in a manufacturing system, thus recording the variable and dynamic nature, ABC reflects the complexity of cause and effect among production levels of different items. Even in the small manufacturing cell modelled in this study, 9 time-based drivers and 12 occurrence-based cost drivers were used for every part and product type to assist with tracing costs. In a larger system the number of interactions among the vast quantity of drivers would make ABC a highly complex and demanding (if not impossible) task without the use of a suitable model.

In a real-life manufacturing organisation, once the ABC system has been developed, the ABC process can be conducted on a weekly basis to provide a ‘rolling’ assessment of production expenditure and to identify potential sources of cost problems. By implementing dynamic modelling techniques, the laborious calculation stages of ABC can be performed automatically and eliminate the chance of calculation errors.

The level of detail and activity types used in the ABC system will have important implications for the quality of information output. In the case used in this study, mainly unit- and batch-level activities were considered in reasonable detail. Cost information referred mainly to unit- and batch-level activities (raw materials, tools), although some costs at facility- and corporate-level (buildings, non-manufacturing labour) were used as well. The level of detail used in determining these costs also varied considerably. For example, unit-level and facility-level labour activities were assigned to products purely according to the quantities made, whereas the machining activity costs were assigned according to a number of detailed criteria. In using simulation, some activities will, by the nature of simulation, be more readily modelled than others. Obviously, modelling activities without the correct level of detail has the potential of distorting product cost and the analyst must be aware of these effects when deciding what to include in the ABC system. In the case of assessing the performance of a production facility, it would be most beneficial to consider only unit- and batch-level activities and ignore any other corporate costs (provision for these costs could be made in separate facility- and corporate-level ABC simulated systems).

5.1. Conclusions

ABC is seen as a valuable tool in providing accurate cost information for strategic decision-making procedures. ABC has been developed considering current manufacturing practices, and therefore is a more credible costing system, since it traces cost from resources according to the way they are consumed by products, rather than by some arbitrary basis.

ABC provides more than a product pricing system. It improves the visibility of costs and shows how costs are passed down to products by activities. As a result, ABC is a valuable information tool that provides management with an unrivalled insight into the workings of the manufacturing system.

Using simulation modelling, the effects of manufacturing planning and control strategies, namely push and pull; on the manufacturing costs are examined. Randomness, buffer capacity, and lead time are found to be important cost drivers in terms of their effect on WIP and throughput in both push- and pull-based production environments. An increase in variation and buffer capacity can result in a build up of WIP inventory and a slight increase of throughput volume with the expense of considerable increase in manufacturing cost.

It is important to understand the effects of these cost drivers and to manage their effects in the context of a product value chain. Any action that takes place in cycle time that either contributes to the product manufacturing or not, is associated with one of the cost drivers. By applying a planning and control strategy these actions are transformed into a direct or indirect positive contribution towards the production or into a total waste through waiting or WIP. Therefore, if the planning and control strategy does not have the ability to create a balanced work load and streamlined manufacturing, which would lead to minimisation of any form of waste, all the wasted actions will be translated into cost.
The results of the experimentation reveal that the manufacturing planning and control strategies play an important role on the level of manufacturing costs of a product. The reliance of push system on larger batch sizes and relatively high level of inventory to provide the relative independence among the work centres automatically creates a considerable amount of WIP between machines and results in longer average waiting, flow, and completion time which leads to a higher manufacturing cost.

One interesting outcome of this study is that the pull-based planning and control strategy has consistently given lower manufacturing costs in each scenario. The major cost differences come from lead times differences. The pull-based batching policy is to issue smaller batches in comparison to push-based batching policy. Therefore, the time spent for a batch in either set-up operations or in machine buffers is consistently less in pull-based planning and control and conversion of these time-based activities to costs has resulted in lower cost figures.

When buffer size increased, the product cost also increased remarkably. This is valid for both push and pull-based strategies and for all scenarios with a few exceptions that may be a result of the random nature of part scheduling. The major explanation of this cost increase is that when the buffer size is increased the average waiting times as well as job queue times increase. This is the driving factor for average flow time and radically affects the average waiting time in the machine buffer. Yet again, the average number of components waiting in either machine buffers or flowing in the system or waiting in AS/RS to be processed is always greater in the push-based scenarios because of the batching and job release policies implemented. The cost implication of large batch size policies is always higher in push-based scenarios in comparison to pull-based scenarios.

For most of the time, SPT sequencing rule has given relatively lower cost figures in both push- and pull-based strategies regardless of the buffer size applied. The reason, understandably, is that the average flow time is relatively shorter than for other scheduling rules.

Although it is not the main subject of this paper, the limited machine breakdown has also been introduced in this experimentation and a full study can be found in Ozbayrak et al. (2002, 2003). The machine breakdown problem in the pull-based strategy has created serious interruptions and blocked the entire system until the broken machine is repaired and the system is returned to normal. Since no machine bids for a job during the blockage, depending on the length of repair time some machines have starved and caused lengthy lead times and a very poor throughput volume. Push-based strategy has responded better to machine breakdown and random interruptions. Since the system continued to feed the machines through buffers and queue of jobs, even during the lengthy repair times, push-based strategy continued to call the jobs for processing for the running machines. This strategy has led to a better cell performance but created the worst WIP record. However, the lead time and the throughput time performance is better than pull-based strategy and is more successful in meeting the demands on time in a relatively unreliable manufacturing environment.

It is worth noting that despite of the poor performance of push systems in terms of WIP, lead time, and throughput, it has been discovered with a limited study that average flow times in push system are shorter than the average flow times in pull system when possible delays such as equipment failure, interruptions in work feeding, missing cutting tools, operator absence, and so on are considered. Work buffers indeed act as an insurance system during unintended interruptions and continue feeding the work centres so that the jobs move around the shop floor more quickly. This results in shorter work flow times and lower production costs. However, in this study the underlying assumption is that the system has reliable hardware, constant job orders, predictable job processing and handling times, reliable raw material feeding, so that the requirements for buffer stocks are minimised. Consequently this has led to another conclusion, which in fact is hidden in the results, that if the push system is controlled through limited buffer capacity and tightly controlled part entry it results in relatively smaller size.
of WIP and can give better cell performance measures and better cost. It would certainly be interesting to conduct further full-scale research to investigate the behaviour of push and pull systems and the resulting cost implications in a non-automated and less sterile environment.

Appendix A

A.1. Cell operational rules

The following rules are general manufacturing system operational rules and are adopted to run the cell regardless of the planning and control system used:

Rule 0: If the required materials to produce all the planned products in a week exist, and if the pallets flowing within the system (in queues, buffers, AS/RS and on AGVs) are less than the planned daily schedule, a batch of components is released to the system with pallets according to one of the four sequencing rules used.

Rule 1: The transfer batch size is determined by the capacity of the pallet used for that product.

Rule 2: In order to transfer these batches, an AGV is called. The nearest idle AGV is directed to the load/unload station. The components, which are fixed on pallets, are loaded on to the AGV by a robot arm and launched to the shop floor.

Rule 3: Pallets are taken to the first machine specified in the part route. The operation priority is determined as workstation input buffer, workstation queue, AS/RS, and AGV car.

Rule 4: The cutting tools are loaded into the machine magazine at the beginning of production period and the worn tools are exchanged according to the adopted tool management system strategy.

Rule 5: The finished parts are unloaded to the machine output buffer to be picked up by an AGV. These parts are pushed towards the next machine in the route. Step 5 is repeated for every job.

Rule 6: After finishing the final operation on the inspection station, parts are defixtured, pallets and fixtures are sent to the pallet store and parts are sent to the assembly line.

Rule 7: Product assembly is undertaken according to a technological sequence, and after inspection the product is sent to the finished product store.

A.2. Push system rules

The push system converts the demands into master production scheduling considering the system’s production capacity. The following rules that are based on the push system are adopted on the shop floor to run the system.

Rule 0: Average materials required by size and weight for each of the individual 35 components and for the whole of the products are known beforehand. The required overall materials are calculated, considering the monthly demands for each product and product bill of materials.

Rule 1: The lot size policy adopted is fixed-period ordering. It is assumed that the first delivery is made just before the system is run. The other materials are ordered according to a two-week delivery policy. It is assumed that materials may be delivered to the system later than the planned time with a certain probabilistic chance. Lateness is represented by a normal distribution with certain average and standard deviation values.

Rule 2: The weekly production volume for each product type is equal to the weekly demand of each product and the manufactured products are delivered to the customer on a weekly basis and the delivery date is the last day of the related week.

A.3. Pull system rules

In this system, some of the part production times are more than one day and therefore two-day periods are used to balance the production level. For this purpose, the weekly based production planning implemented in the push system is converted into a two-day basis bucketless production planning system by considering customer demands. The material purchase policy has also been altered to suit the production plan implemented by pull the system. The information and material flow are controlled through Kanban. The pulling of raw materials on to the shop floor and
control of production as well as WIP is made through signal Kanban.

The following operational rules have been developed based on the pull system:

**Rule 0**: Production is planned according to assembly line requirements dictated by the last production stage in route.

**Rule 1**: The assembly line obtains the related finished components, which are planned to use in assemblies during the two-day planning periods from the inspection station by sending a signal Kanban.

**Rule 2**: In order to respond to the requirements of the assembly line, the signal (Kanban) follows the route of AS/RS, machine output buffer, parts in operation, machine input buffer, machine queue as WIP or in previous stations in route, which are searched in the same order.

**Rule 3**: The last point searched in route is the raw material store. If the materials used to manufacture the products are less than one-week production requirement, a material purchase signal is sent to vendor to pull the next bulk of material of the required kind.

**Rule 4**: No part is transferred without getting a signal Kanban from a previous station in route.

**Rule 5**: No part is produced on any station without getting a production Kanban from the previous station in the route.

**Rule 6**: The assembled products are delivered to the customers directly.

**References**


