Volume 2, Number 1, 2005, pp. 81-104

Integrating Materials Flow, Production Control and Quality Control: a Proposal and Case Study

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Abstract

This paper presents a proposal for integrating materials flow, production control and quality control. The proposal is based on three principles: that materials flow must be as simple as possible, that a production control system must be compatible with the production system and that the production pace must take account of demand, capacity and quality. The paper examines the dependent relationship between Production Control (PC) and Quality Control (QC) since this relationship provides opportunities for improving manufacturing performance. A case study performed at the world's largest pencil factory suggests that the proposal contributes effectively to operations management at the shop floor level.

Keywords: shop floor level, Production Control, Quality Control, takt time, cycle time, rejection rate

Introduction

To be competitive, a production system has to meet concurrently the objectives of quality, cost and time (Sipper and Bulfin, 1997). Production Control (PC) determines and regulates (schedules, co-ordinates, commands and monitors) the material flows and activities in a production system in the short term (Burbidge, 1990). Quality Control (QC) is the management function which aims to measure, understand and improve the production

Volume 2, Number 1, 2005, pp. 81-104

process in order to produce products to specification. The methodology for QC can be represented by the Deming Control cycle, known as the PDCA (Plan-Do-Check-Act) cycle.

This paper proposes integrating materials flow, PC and QC at the shop floor level so as to achieve their associated manufacturing aims of improving productivity, time and quality. The proposal is the IME (Integrating the Manufacturing elements: materials flow, production control and quality control) strategy composed by three principles:

i) Materials flow must be as simple as possible Production flow is the backbone of any production system (Sipper and Bulfin, 1997). Materials flow simplification brings cost, time and quality benefits (Burbidge, 1975);

ii) The production control system (PCS) must be compatible with the production system. According to MacCarthy and Fernandes, 2000 some of the most used PC systems are kanban, PBC (Period Batch Control), CONWIP, MRP/MRPII, OPT and PERT/CPM. The choice of an adequate PCS is crucial in manufacturing management; this issue is treated in many references, e.g.: (Goddard, 1982), (Aggarwal, 1985), (Ramsay et al. 1990), (Ptak 1991), (Gstettner and Kuhn 1996), (Miltenburg, 1997), (Little et al., 2000); (MacCarthy and Fernandes, 2000); (Sale and Inman, 2003); (Olhager and Rudberg, 2002) and (Jonsson and Mattsson, 2002). The methodology proposed by (MacCarthy and Fernandes, 2000) has been used to choose a PCS according to production system characteristics; and

iii) The production pace must take account of demand, capacity and quality. This principle identifies a dependency between PC and QC that arises because the production pace (rate) influences the rejection rate. This relationship provides opportunities for improving manufacturing management. As (Rummler and Brache, 1990) state: "… the greatest management improvement opportunities are, nowadays, on the processes integration…". An algorithm that considers capacity and quality has been developed for production pace determination.

A review of 55 papers that deal with the PC and QC relationship showed that the majority of these papers use mathematical models that aim to optimise variables such as production batch size and inspection batch size. Examples of these papers are: (Ouyang et al., 2002); (Affisco et al., 2002); (Khouja, 2003); (Ioannidis et al., 2004); (Sheu and Chen, 2004); (Balkhi, 2004); (Rahim and Ohta, 2005). These models are complex and difficult to implement. Only six papers did not optimise variables. These relate: JIT and TQM (Total Quality Management) (Hohner (1988) and Kagemann (1990)), lot size and quality improvement (Inman (1994)), production management and quality management by means of a general model (Jokinen et al. (1995)), quality control and shop floor control (Arentsen et al. (1996) and the performance of production control and the performance of quality control (Van Der Bij and Van Ekert (1999)). None of these papers discuss the influence of the production rate on the rejection rate, a central issue of this paper.

Another important characteristic of this paper is that it identifies the situations where Six Sigma programs have more potential to bring benefits (see Table 2).

Integrating Materials Flow, Production Control and Quality Control

The paper examines the PC and QC processes and the dependency between them. The three principles shown in Figure 1 are now described in greater detail.

Principle I: Materials flow must be as simple as possible

An effective technique for materials flow simplification is to use group or cellular layout. This kind of layout divides components into families and groups machines into cells that may process all the components of a family. (Burbidge, 1975) suggested that the advantages of group layout include reduced throughput time, quality improvement, reduced preparation and handling costs, simplification of paper work, reduced indirect labour, improved human relations, reduced investment per unit of output, reduced set up time and others.

Many papers have been published in the last twenty years dealing with cellular layout formation e.g. 331 papers regarding group technology were found on the Compendex data bank including the papers of Escoto et al. (1998) and Li (2003). Wemmerlöv and Hyer (1986), Selin et al. (1998) and Venupogal (1999) review group technology formation. Selim et al. (1998) classify the papers regarding cell formation into five groups according to the method used for the problem solution. These groups are i) descriptive procedures, which include the well-known components classification and codification and production flow analysis (PFA) methods; ii) Cluster analysis, which includes the paper of Chan and Milner (1982); iii) Graph partitioning, which includes the papers of Rajagopalan (1975) and Mukhopadhyay et al. (2000). iv) Artificial intelligence, which includes the paper by Elmaghraby and Gu (1988); and v) Mathematical programming, which includes the papers by Kusiak (1987) and Shafers and Rogers (1991).

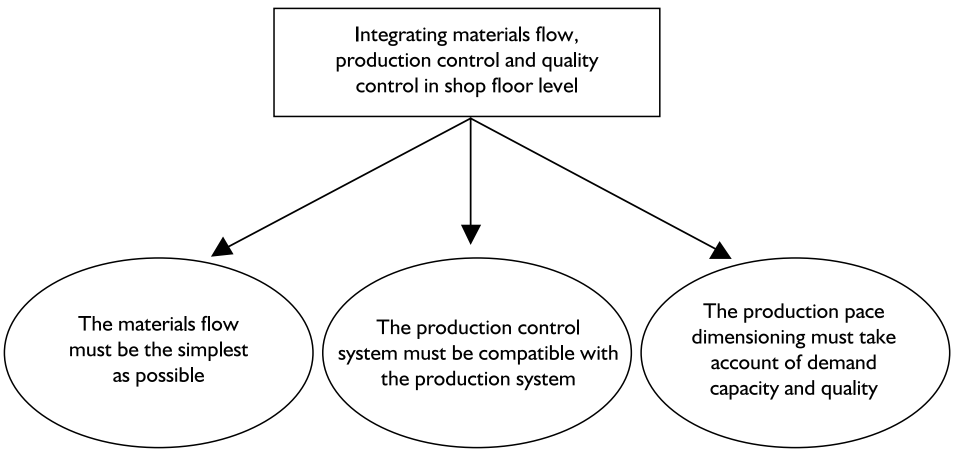

Figure 1 – Principles for integrating materials flow, production control and quality control.

Within descriptive methods, the two main ways to find the product families and the groups for the development of group layout are by using:

i) Component classification and codification based on the components' sketches; and

ii) Production Flow Analysis (PFA).

PFA uses information from the process sheets, which show how the products are made. According to (Burbidge, 1996a), PFA is better than the component classification and codification methodology which finds the families but does not create the machine groups for these families. PFA on the other hand divides components into families and machines into groups simultaneously at a much lower cost. The case study described later uses the PFA method.

The PFA technique created by Burbidge in the 60's consists of a sequence of sub-techniques. In large companies it starts by simplifying the flow among factories or divisions using Company Flow Analysis (CFA). Next, Factory Flow Analysis (FFA) unites "closely associated processes into sets to form departments before considering the re-allocation of machines between the departments". After this, it divides departments into groups using Group Analysis (GA). The materials flow among the work centres within the group is then studied using Line Analysis (LA). Finally, Tooling Analysis (TA) is used to find the tooling families (groups of parts all of which can be made using the same set up using the same set of tools). The aim is to plan the operation sequencing and find feasible sets of parts for automation. In the case study, the FFA and GA stages were sufficient to obtain the materials flow simplification.

Principle II: The production control system and production systems must be compatible

For each processing unit of the company, this principle aims to choose a compatible production control system. It does this by basing the Production Control System (PCS) choice on the production systems classification methodology developed by (MacCarthy and Fernandes, 2000). They identified twelve variables, namely: repetitiveness level, enterprise size, response time, automation level, product structure, level of customisation, number of products, and the type of buffer, layout, flow, assembly and work organisation that affect the PCS complexity level. Table 1 shows how the choice of an adequate PC system is affected by the variables, the most important being the repetitiveness level. The last line of Table 1 indicates an appropriate PC system based on the repetitiveness level of the production system. A Kanban control system can be used for the repetitive manufacture of items. Period batch control (PBC), described in (Burbidge, 1996b), can be chosen for semi-repetitive production whereas MRP may be necessary for non-repetitive situations. For large projects, PERT/CPM can be the most appropriate choice.

While the repetitiveness level affects the basic PC system choice, the other variables affect the detailing and complexity of the system. Table 1 shows that the Response Time (R) depends on the state in which stock is held. If the system maintains finished product stock, then provided stock is available, R= DL where DL = Distribution Lead-time. If the system produces to order but maintains stock of raw materials, R=PL+DL where PL = the Production Lead-time. If the system produces to order and does not maintain raw material stock, R=SL+PL+DL where SL= Supply Lead-time. If the system assembles to order and maintains stocks of components R=AL+DL where AL= Assembly Lead-time and so on. The type of buffer (1= buffer before the first production stage; 2= buffers between intermediary stages and 3= buffer after the last production stage) and the type of flow (F1= mono-stage; ...; F12= multi-directional multi-stages with unequal machines in parallel) influence the scheduling of the work, and the type of assembly (A1= mixture of chemical ingredients; A2= assembly of a large project; ...; A9= unpaced assembly line) influences line sequencing and line balancing. A more detailed description of Table 1 is provided in (MacCarthy and Fernandes, 2000).

Table 1 – The variables and the choice of a PC system. Source: (MacCarthy and Fernandes, 2000).

Variables	**Description of Production control system**						
Production system repetitiveness	Pure continuous	Semi-continuous	Mass production	Repetitive	Semi-repetitive	Non-repetitive	Large Projects
Enterprise size	**For all levels of repetitiveness, the larger the enterprise, the greater the complexity of production planning and control (PC) activities**						
Response time	DL(a-P%)	DL(a-P%)	DL(a-P%)	DL(a-P%)	PL+DL	PL+DL or SL+PL+DL	SL+PL+DL
Automation Level	Rigid	Rigid	Rigid	Normal or Flexible	Normal or Flexible	Normal or Flexible	Normal
Product structure	**For all levels of repetitiveness, the PC activities for multi-level product structures are more complex than for single-level product structures**						
Level of Customisation	Standard products	Standard or mushroom	Standard or mushroom	Standard or mushroom	Mushroom or semi-customized	Semi-customized or customized	Customized
Number of products	**For all levels of repetitiveness, the PC activities for multi-products are much more complex than for single-products**						
Types of Layout	Product Layout	Product Layout	Product Layout	Group Layout	Group Layout	Functional Layout	Fixed position Layout
Types of buffer	(1) and (3)	(1), (2) and (3)	(1), (2) and (3)	(1), (2) and (3)	(1), (2) or (1)	(1), (2) or (2)	Without buffer
Types of flow	**The complexity of the PC activities increases from (F1) in direction of (F12)**						
Types of assembly	(A1) or disassembly	(A1) or disassembly	(A5) or (A6) or (A7) or no assembly	(A5) or (A6) or (A7) or no assembly	(A7) or (A8) or (A9) or no assembly	(A3) or (A4) or no assembly	(A2)
Types of work organization	**For assembly, work organization directly affects the way the work in the assembly is balanced**						
Appropriate production control system	Spreadsheet to control the rate of flow	Spreadsheet to schedule the work	Kanban	Kanban or PBC	PBC or OPT	MRP	PERT / CPM

Volume 2, Number 1, 2005, pp. 81-104

Principle III: The production pace (takt time) must take account of demand, capacity and quality

After simplifying the materials flow (first principle) and choosing the production control system (second principle), the third and main principle is that the production pace is determined by taking into account the demand, the capacity and the influence of the production pace on the rejection rate.

(Sipper and Bulfin, 1997) suggest that production should be pulled using a production pace which establishes a constant production flow This production pace is determined, according to (Womack and Jones, 1996), by the takt time defined as the time that precisely matches the production rate to the customer demand. For (Ohno, 1988), the takt time is obtained by dividing the daily available production time by the quantity of products required in a day. For (Iwayama, 1997), the takt time is the production time allocated for the production of a part or product in a line or in a cell. Each connects the production pace with the demand. However, other factors that should be considered when calculating the production pace are the capacity and the influence of the production pace on the rejection rate. (Antunes, 2001) defines takt time as the necessary production pace to respond to the specific demand level, taking into account line or cell capacity restrictions. In other words, the necessary pace may not be possible due to capacity restrictions. Capacity then influences the production pace. This author distinguishes between takt time and the cycle time in order to clarify the relationship between them. Depending on this relationship, actions may be required to reduce the operation execution time. So (Antunes, 2001) defines line or cell cycle time as the operation execution time on the slowest machine or on the slowest point of the line, the "bottleneck" operation.. For example, if a line has a bottleneck with a minimum cycle time of 5 minutes and if the required production pace is 10/hour, the required takt time would be 6 minutes. On the other hand, to produce 15/hour, the required takt time would be 4 minutes whereas the bottleneck cycle time of 5 minutes would restrict production to 12/hour. The effective takt time is thus the calculated (or nominal) takt time if the capacity is greater than or equal to the demand but is the cycle time when the capacity is less than the demand. Thus:

Effective takt time = maximum (takt time, cycle time)

However, increasing the production pace (i.e. reducing the takt time) to fulfil a certain demand may, even if the capacity allows, increase the rejection rate and reduce the effective production pace and consequently the value flow. In other words Production Control and Quality Control are related. To determine the production pace taking into account this relationship between PC and QC requires knowledge of the takt time v rejection rate curve. This is likely to vary according to the products and the production process. The effective takt time (taking into consideration the demand and the capacity) of the line needs to be compared to this takt time v rejection rate curve for each machine which will be working with this takt time. This effective takt time can be then adjusted so as to reduce the rejection rate and to determine the effective takt time 2. An algorithm for defining effective takt time 2 that depends on the company strategy is now presented.

Algorithm for Defining Effective Takt Time 2

STEP 0: Classify the rejection levels for the machines or production line and for the products into 3 different groups:

- Zero i.e. rejection levels less than or equal to 3,4 parts per million (ppm), which is the aim of six sigma quality;
- Low i.e. rejection levels that are higher than zero but do not harm the production flow of the system; and
- High i.e. unacceptable rejection levels that can interrupt the materials flow.

The rejection level classification depends on the processes/machines/products involved

STEP 1: For a production line, find the line cycle time (balance the line if necessary using, for example, any of the techniques mentioned in (Erel and Sarin, 1998));

STEP 2: Analyse the calculated takt time and the cycle time, using Figure 2. The effective takt time can assume values between the calculated takt time and the cycle time. In this situation increasing the number of employees/improvement cycles could lead to a reduction of the cycle time, but not by enough to make the cycle time equal the calculated takt time. This intermediate value between the calculated takt time and the cycle time is called an improved cycle time.

STEP 3: Define the effective takt time. Figure 2 shows three cases:

i) Effective takt time equals the calculated one (demand is satisfied);
ii) Effective takt time equals the cycle time (some demand is unsatisfied); and
iii) Effective takt time equals an improved cycle time (unsatisfied demand is smaller than (ii)).

STEP 4: Build the rejection rate v takt time curves for all workstations on the production line, using historical data or empirical research.

STEP 5: Find on the rejection rate v takt time curve the rejection rate which is equivalent to the effective takt time found in step 3. Interpolate if necessary.

STEP 6: Use the rejection rate found in step 5 to classify the effective takt time as having: zero, low or high rejection levels (according to step 0). For a production line the line rejection level will be the worst of the machines rejection levels. For example: if the line has three machines one with zero defects, one with low and one with high rejection levels, then for that effective takt time the line rejection level will be high.

STEP 7: Effective takt time 2 definition: This step results in 9 cases that are a combination of the effective takt time definition (step 3) and the classification of rejection levels

Volume 2, Number 1, 2005, pp. 81-104

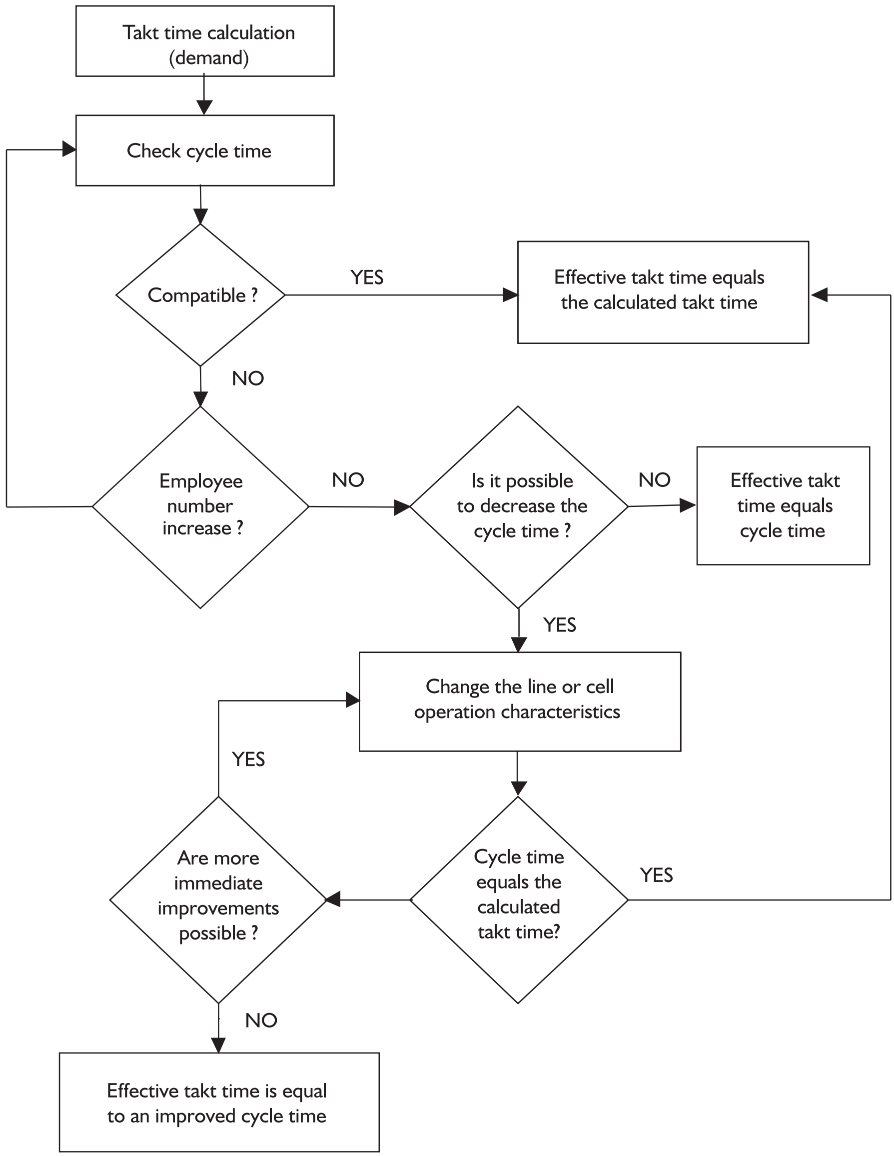

Figure 2 – Effective takt time calculation (taking demand and capacity into consideration).

(step 6). Table 2 shows the 9 possibilities for effective takt time 2 and suggests the action that should be taken for each possibility.

Case Study – An Application of the Proposal

This section applies the three principles to the printing department of the world' largest pencil factory which is situated in Brazil.

Stage 1: Simplify the materials flow as much as possible

The FFA (Factory Flow Analysis) and GA (Group Analysis) stages of the PFA methodology (Burbidge, 1996a) were used to simplify the materials flow. These stages group the items into product families and the machines into groups (group or cell layout). Both stages consist of several steps. Most of these stages are well known and understood and so only the basic results achieved with FFA and GA implementation are shown.

Table 2 – Demand characteristics, rejection characteristics and actions to be taken for each possible effective takt time 2.

Effective takt time 2 equals	Rejection level classification	Demand characteristic	Actions to be taken
Calculated takt time	Zero rejection level	Fulfilled demand	Keep quality standards
Calculated takt time	Rejection which does not harm the flow, but is over the six sigma limits (3,4 ppm)	Fulfilled demand	The rejection rate can be reduced by means of efforts on six sigma/ TQM
An increased calculated takt time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the calculated takt time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2)
Cycle time	Zero rejection level	Demand not fulfilled due to lack of capacity	Keep quality standards; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Cycle time	Rejection which does not harm the flow, but is over the six sigma limits (3,4 ppm)	Demand not fulfilled due to lack of capacity	The rejection rate can be reduced by means of efforts on six sigma/TQM; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
An increased cycle time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to lack of capacity and quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the cycle time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2); Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Improved cycle time	Zero rejection level	Demand not fulfilled due to lack of capacity	Keep quality standards; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
Improved cycle time	Rejection which does not harm the flow, but is over six sigma limit (3,4 ppm)	Demand not fulfilled due to lack of capacity	The rejection rate can be reduced by means of efforts on six sigma/TQM; Seek improvements to reduce cycle time (capacity increase – see Figure 2)
An increased improved cycle time due to quality reasons	Rejection which is harmful to the flow (high)	Demand not fulfilled due to lack of capacity and quality problems	Urgent action to reduce the rejection rate. While this improvement is not possible, increase the improved cycle time until it reaches the boundary between high and low rejection levels (this will be the effective takt time 2); Seek improvements to reduce cycle time (capacity increase – see Figure 2)

Volume 2, Number 1, 2005, pp. 81-104

Factory flow analysis (FFA)

FFA codifies the processes (Table 3) and studies the routing of the items along the processes in order to simplify the production flow. The initial materials flow (before FFA implementation) is shown in Figure 3 whereas Figure 4 shows the equivalent materials flow simplified using the FFA technique.

Group analysis

Group analysis allocates machines into manufacturing cells or groups according to similarities in the production routings. The groups and the available machines allocated in each group are shown in Table 4. Figure 5 shows the net encompassing all groups and machines.

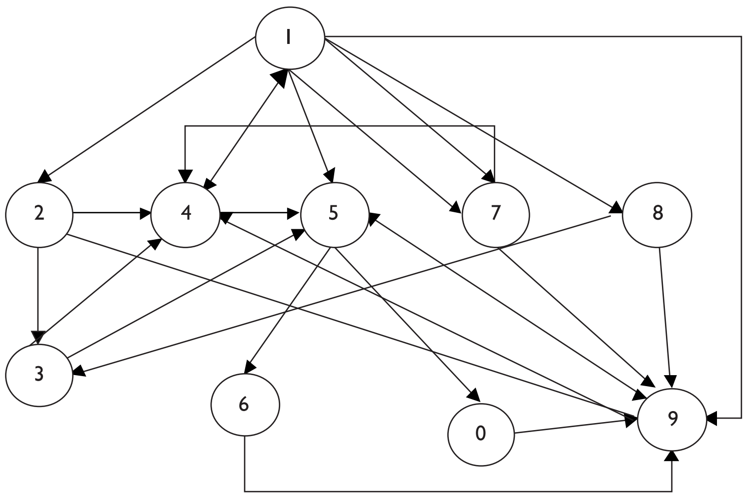

Figure 3 – Initial materials flow net.

Table 3 – Processes code assignment.

Code	Process
1	Cutting – Guillotine
2	Printing 1 – Solna
3	Varnishing
4	Cutting and Creasing
5	Highlighting
6	Pasting 1 – for pasting supermarket items
7	Printing 2 – Roland
8	Printing 3 - Planeta
9	Subcontracted
0	Pasting 2 – for pasting cartridges

Table 4 – Available machines allocated to each group.

Machines	**Roland Group**	**Planeta Group**	**Solna Group**	**Not Printed Group**
Guillotine	X	X	X	
Roland printer	X			
Planeta printer		X		
Solna printer			X	
Varnisher		X	X	
Cutting and creasing	**Service centre***	**Service centre ***	**Service centre***	**Service centre***
Highlighting	X	X	X	X
Hooker paster	X		X	X
Cartridge paster		X		

* a service centre serves any group which needs its services.

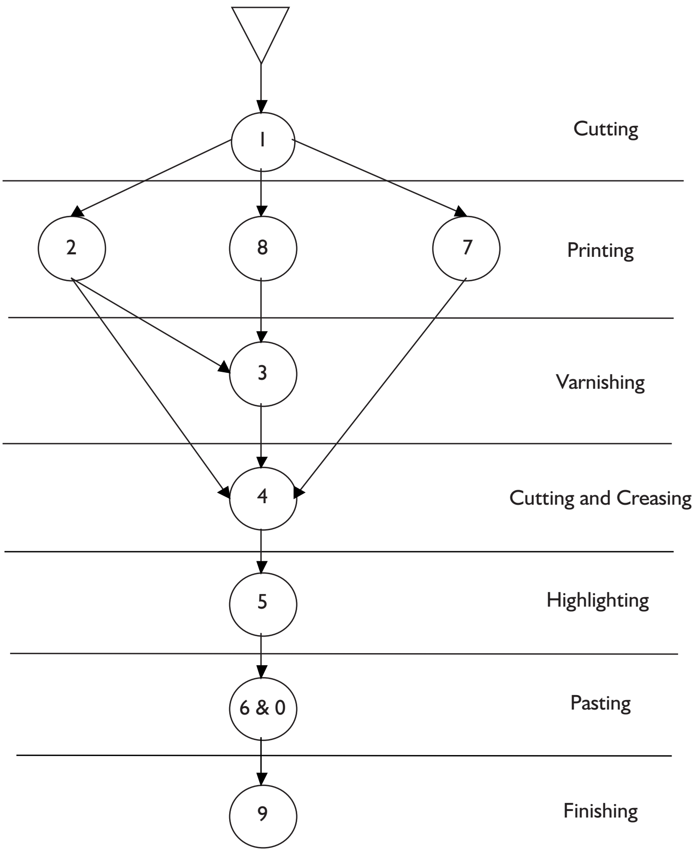

Figure 4 – Simplified materials flow net.

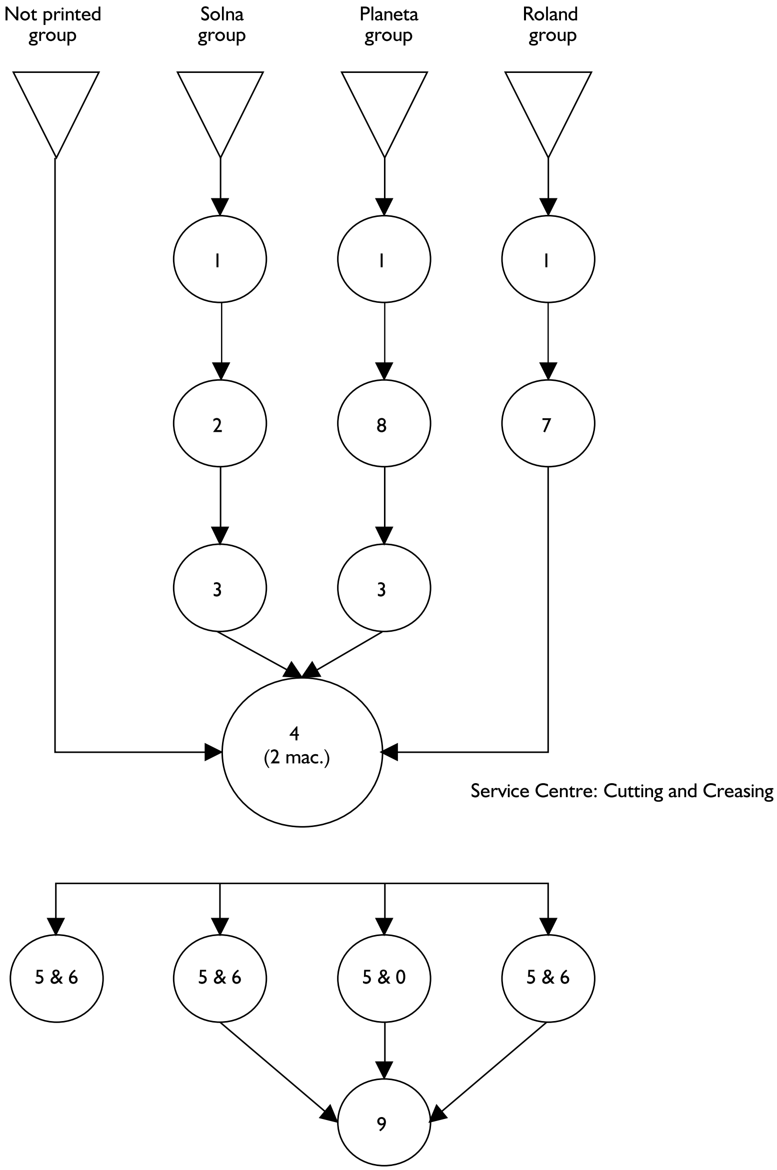

Figure 5 – Net encompassing all groups and machines (including service centre).

Stage 2: Choose the Production Control system (PCS) to match the production system

The multidimensional classification proposed by (MacCarthy and Fernandes, 2000), was used to classify the processing units and to choose a suitable PCS for each one. The four production groups found in the flow simplification performed in stage 1 (Roland, Planeta, Solna and Not printed groups) were classified. The results are shown below. The symbol (/) => (slash) is used to separate dimensions and (_) => (underline) is used to separate variables.

Characterisation
Group General Product Process

Roland: L/PL+DL/NR/N/ML_2_M/G_1-2-3_F4

Planeta: L/PL+DL/NR/N/ML_2_M/G_1-2-3_F4

Solna : L/PL+DL/SR/N/ML_2_M/G_1-2-3_F5

Not printed: L/PL+DL/RP/N/ML_2_M/G_1-2-3_F5

In the classification, L means a large enterprise (more than 500 employees). As there are inventories of raw materials but not of components or final products, the response time is equal to the Production Lead-time (PL) plus Distribution Lead-time (DL). The production systems are respectively non-repetitive (NR), non-repetitive (NR), semi-repetitive (SR) and repetitive production (RP). The automation level is Normal (N); the product structure is multi-level (ML), the level of customisation is 2 (semi-customised) and there are multi-products (M). There is group layout (G) with buffers before the first production stage (1), between intermediary stages (2) and after the last production stage (3) and the types of flow are uni-directional multi-stages (F4) and variable uni-directional multi-stages (F5).

From this classification the most adequate production control system (PCS) for each case is chosen using Table 1. For the Roland and Planeta groups, both non-repetitive systems, the most adequate PCS is MRP. For the Solna group, a semi-repetitive system, the most adequate PCS is PBC or OPT. Finally, for the Not printed group, a repetitive system, the most adequate PCS is Kanban or PBC.

In practice, the company uses MRP for all items. It is the easiest solution, even though it is not necessarily the best. This raises the important but difficult question whether it is better to operate with a single PCS for each processing unit of a production system, or whether is it better to operate with the most appropriate PCS for each processing unit? If a single system is chosen, it would need to be MRP, since it is the only one, which can properly deal with the non-repetitive case. However, it could be less effective than PBC or OPT in the semi-repetitive production unit (Solna group) and worse than Kanban in the repetitive case (Not printed group). On the other hand, operating with a single system may also bring real advantages, for example by avoiding the need to co-ordinate different systems.

Stage 3: Calculate the takt time taking account of the demand, capacity and takt time influence on quality

The takt time is calculated by considering the demand, the capacity, and the takt time influence on the rejection rate. The takt time is the pace at which each item will be produced, pulled by the customers' requirements from the final process of a continuous flow production line. The four groups (Roland, Planeta, Solna and Not printed) were arranged using principle 1 and classified by principle 2. This section deals only with the Not printed group (repetitive system) asit is difficult to use continuous flow for the other groups, which are semi-repetitive and non-repetitive systems.

The Not printed group uses 3 available processes: cutting and creasing, highlighting and pasting. One of them (cutting and creasing) is a service centre. Some characteristics of the three main products (products 1, 2 and 3) of the Not printed group are shown in Table 5 and are used to calculate the production pace.

First, the three processes are checked to see whether they can be connected in any way to obtain a continuous flow among them. However, the cutting and creasing process is a service centre that fits the four groups and so cannot be connected to the highlighting and pasting in a continuous form. Also this process could not be linked in a continuous flow to the highlighting and pasting because of the great difference in the production pace of this process (0.18) compared to the paster pace (1.0; 1.2; 1.8) and the highlighting pace (1.64; 1.16; 1.64).

The highlighting and pasting process times for the three products are similar and so that they can be connected using a continuous flow provided another person is allocated to highlighting for product 1. The cutting and creasing operations can be connected using Kanbans. The highlighting – paster set is used to illustrate the application of our algorithm to determine, by product, the effective takt time 2 taking into consideration demand, capacity and the influence of pace on quality.

Algorithm Application

STEP 0: Table 6 was developed using historical data of interruptions and stoppages to the materials flow. This illustrates, by product and work station, the rejection levels considered low and high.

Table 5 – Demand, production and capacity characteristics for the three studied products in the Not printed group.

Characteristics	Product 1	Product 2	Product 3
Demand (parts/day)	40,000	28,000	12,000
Working hours (per day)	7	7	7
Calculated Takt time	0.63	0.9	2.1
Cutting and creasing production pace (parts/hour)	20,000	20,000	20,000
Cutting and creasing cycle time (seconds)	0.18	0.18	0.18
Highlighting production pace (parts/hour) – 1 person	2,200	3,100	2,200
Highlighting cycle time (seconds)	1.64	1.16	1.64
Paster production pace (parts/hour)	3,600	3,000	2,000
Paster cycle time (seconds)	1.0	1.2	1.8

Table 6 – Rejection levels classification.

Product	Work station	Low rejection level (%)	High rejection level
1	Highlighting	0 - 2	Starting on 2 %
1	Paster	0 – 1.5	Starting on 1,5 %
2	Highlighting	0 – 2	Starting on 2 %
2	Paster	0 – 2	Starting on 2 %
3	Highlighting	0 – 2	Starting on 2 %
3	Paster	0 - 3	Starting on 3 %

STEP 1: Find the cycle time for the production line by product. If necessary, balance the line. Based on Table 5: for product 1, using two employees to work on the highlighting reduces the highlighting cycle time from 1.64 seconds to 0.82 seconds. The line cycle time will then be 1.0 second, the bottleneck time of the paster; the product 2 line is already balanced with a cycle time of 1.2 seconds (paster); the product 3 line is also balanced with a cycle time of 1.8 seconds (paster).

STEP 2: Analyse the calculated takt time and the cycle time for each product according to Figure 2:

- For product 1, the cycle time (1 second) is not compatible with the desired takt time (0.63 seconds). In other words, there is not enough capacity to respond to the desired demand because the cycle time is not compatible with the desired takt time. Then it is checked whether, it is possible to improve the cycle time by using more employees.
  In this case, this is not possible because the bottleneck is the paster, an automated operation. Next an attempt is made to decrease the cycle time is by searching for improvements on the line. Fortunately, some improvements on this specific product's design had already been studied. These were introduced and this reduced the paster's (bottleneck) cycle time to 0.82, the same cycle time as for highlighting. Hence 0.82 seconds became the new line cycle time and the effective takt time;
- For product 2 the line cycle time (1.2 seconds) is greater than, and hence is not compatible with, the calculated takt time (0.9 seconds). Using more employees would not change the line cycle time, as the bottleneck is the paster. The next attempt to decrease the cycle time mentioned in Figure 2 is to search for improvements on the line. For this specific product, immediate improvements seem impossible and so the effective takt time is equal to the cycle time of 1.2 seconds; and
- For Product 3, the calculated takt time of 2.1 seconds is compatible with the line cycle time of 1.8 seconds. In this case the effective takt time is equal to the calculated takt time of 2.1 seconds.

STEP 3: Define the effective takt time for the three products: For Product 1 the effective takt time equals the improved cycle time of 0.82 seconds. Some demand is not satisfied but less than it would be without changes in the cycle time. For Product 2 the effective takt time equals the cycle time of 1.2 seconds and there is some demand loss. For Product

Volume 2, Number 1, 2005, pp. 81-104

3 the effective takt time equals the calculated takt time (2.1 seconds) and the demand is easily fulfilled.

STEP 4: Create the takt time v rejection rate curves using historical data. The takt time *vs.* rejection rate curves for the three products on the two workstations are shown in Figures 6 to 11.

STEP 5: Use the curves above to design Table 7. This shows for each work station and product the rejection rates that correspond to the effective takt time calculated in step 3:

STEP 6: Based on step 0, Table 8 classifies the rejection levels for the effective takt time, using the rejection rates found in step 5.
In the production line case, a high rejection level is assigned for that takt time if at least one of the work stations present a high rejection level. This was the case on product 2, which although showing a low rejection rate on the highlighting, displayed a high rejection rate on the paster. Therefore there will be a high rejection level if the 1.2 seconds takt time is introduced.

STEP 7: The effective takt time 2 is defined according to the relationship between effective takt time definition (step 3) and the rejection level (defined in step 6). Thus:

- **Product 1:** The work will be done on a line and the effective takt time 2 of the line will be the highest effective takt time of the work stations. The effective takt time is equal to an improved cycle time (0.82 seconds) and from Table 7 it will be seen that the corresponding rejection level is 6.02% i.e. greater than 2% and therefore high according

Table 7 – Rejection rates that correspond to the effective takt time.

Product	Work station	Effective Takt time	Rejection rate
1	Highlighting	0.82 seconds	6.02 %
1	Paster	0.82 seconds	6.80 %
2	Highlighting	1.2 seconds	1.9 %
2	Paster	1.2 seconds	2.7 %
3	Highlighting	2.1 seconds	1.8 %
3	Paster	2.1 seconds	1.7 %

Table 8 – Rejection level determination for the effective takt time.

Product	Work station	Rejection rate	Takt time	Classification
1	Highlighting	6.02 %	0.82 seconds	High rejection level
1	Paster	6.80 %		
2	Highlighting	1.9 %	1.2 seconds	High rejection level
2	Paster	2.7 %		
3	Highlighting	1.8 %	2.1 seconds	Low rejection level
3	Paster	1.7 %		

to Table 6. This is unacceptable. However, if we choose a takt time that corresponds to the boundary of the high and low rejection rates (2% for the highlighting workstation and 1.5% for the paster workstation), the effective takt time 2 for highlighting and paster are 1.57 seconds and 1.68 seconds respectively based on interpolation of data from Figures 6 and 7. The effective takt time 2 for the line will then be 1.68 seconds (the larger of the two). This takt time is much greater than 0.63, the original calculated takt time. In order to reach a takt time of 0.63 an improvement in cycle time (capacity) will be needed. Even more important is that a drastic improvement in the process (aiming to reduce the rejection rate) will be needed.

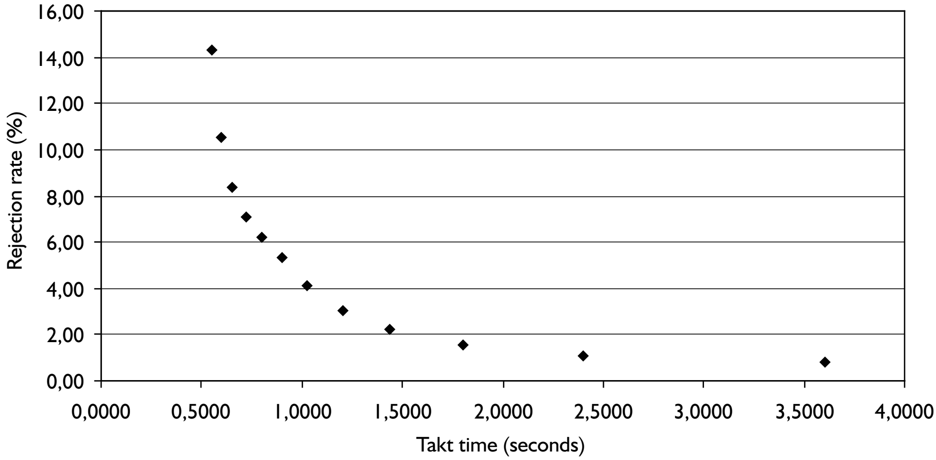

Figure 6 – Takt time *vs.* rejection rate for product 1 on the highlighting work station.

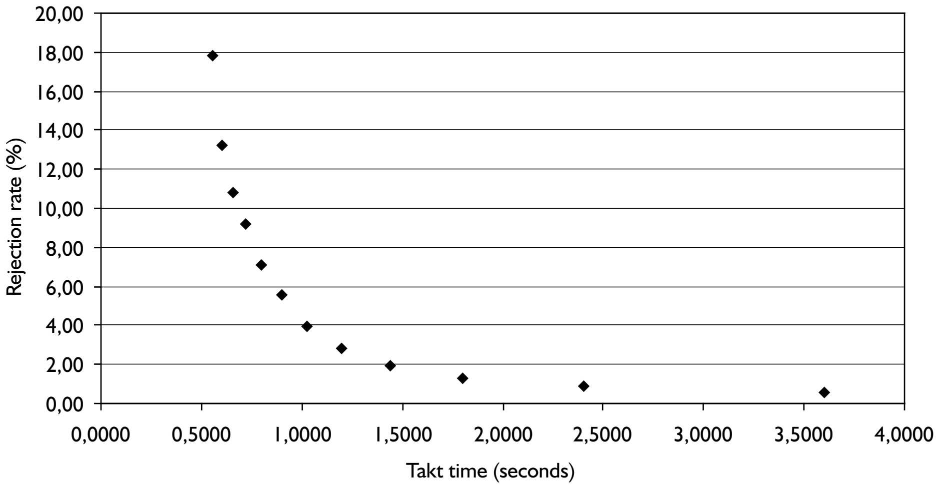

Figure 7 – Takt time *vs.* rejection rate for product 1 on the paster work station.

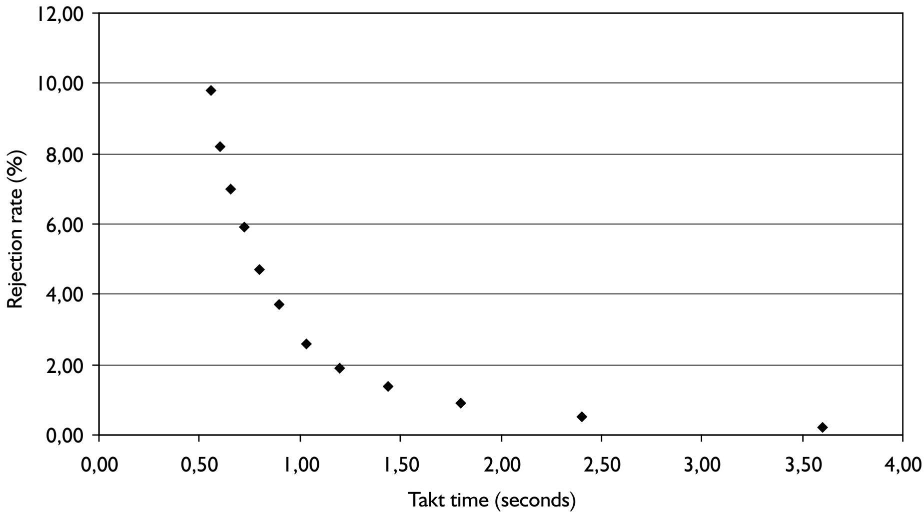

Figure 8 – Takt time *vs.* rejection rate for product 2 on the highlighting work station.

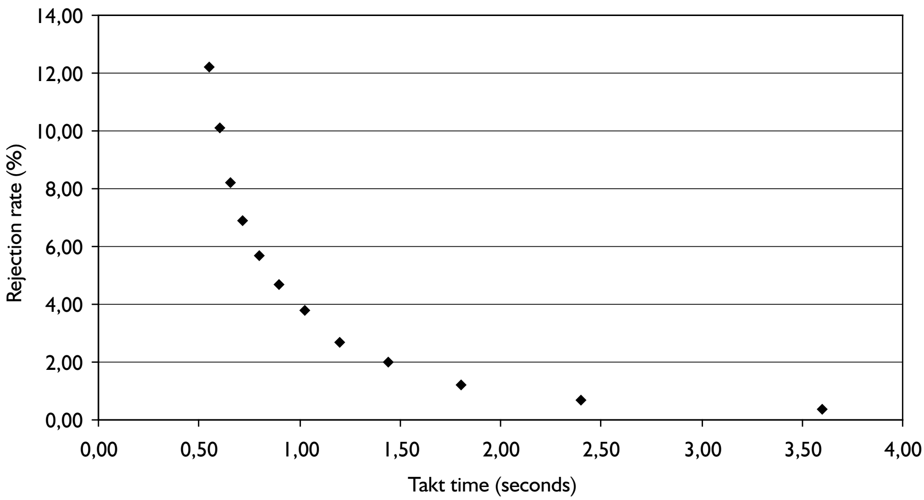

Figure 9 – Takt time *vs.* rejection rate for product 2 on the paster work station.

- **Product 2:** The effective takt time is equal to the cycle time (1.2 seconds) and the rejection level is high. As the work will be done in a line, the line effective takt time 2 will be the highest effective takt time of the work stations. Arguing as above, the effective takt time 2 of the highlighting work station will be the takt time equivalent to the 2% rejection rate, and the effective takt time 2 of the paster work station will be also the takt time equivalent to the 2% rejection rate. Therefore, based on interpolation of data from Figures 8 and 9, the effective takt time 2

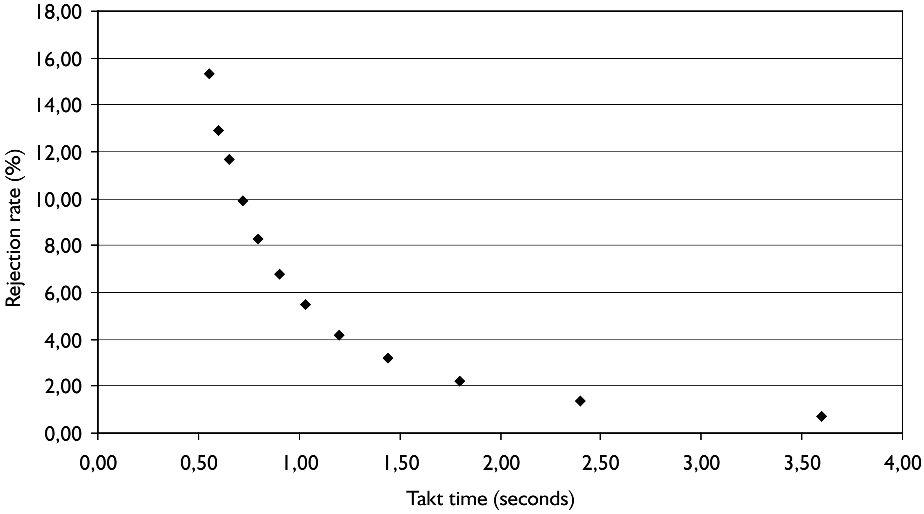

Figure 10 – Takt time *vs.* rejection rate for product 3 on the highlighting work station.

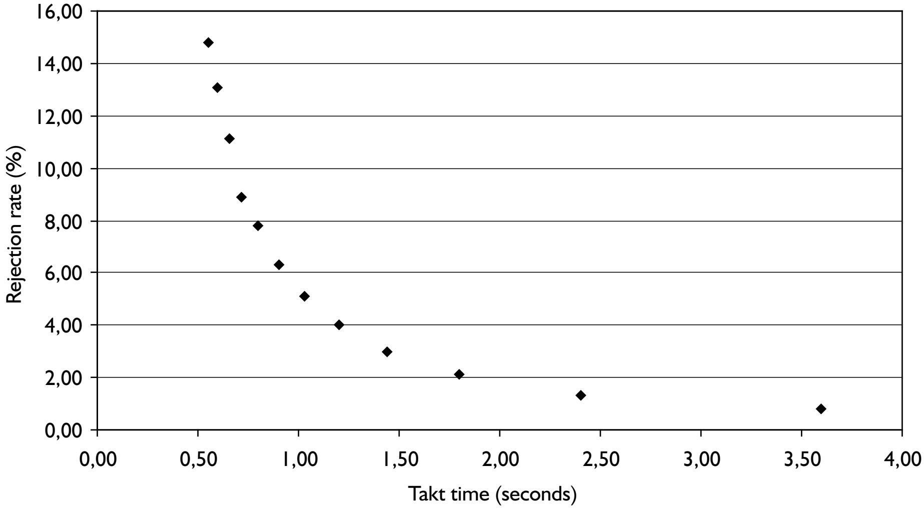

Figure 11 – Takt time *vs.* rejection rate for product 3 on the paster work station.

for highlighting and paster are respectively 1.18 seconds and 1.44 seconds. The effective takt time 2 for the line will be then 1.44 seconds (the highest one between them). This takt time is much greater than 0.9, which was the calculated takt time. In order to reach this takt time, an improvement in cycle time (capacity) and a drastic improvement in the process (aiming to reduce the rejection rate) will be needed.

- **Product 3:** The effective takt time is equal to the calculated takt time (2.1 seconds) and the rejection level is low (row 2 of Table 2). The effective takt time 2 for this product will be equal to the effective takt time of 2.1 seconds. In this case the demand will be fulfilled and the rejection rate can be reduced by means of six sigma/TQM efforts.

Conclusions

This paper has presented and applied a proposal for integrating materials flow, production control and quality control at the shop floor level. The proposal focuses on two important management functions: PC (choosing an adequate production control system and work flow that improves productivity and time) and QC (understanding that the reduction in rejection rate with subsequent efforts to improve quality is essential to the flow maintenance).

Many strategies have been proposed in the literature for improving manufacturing management. These strategies, which are based on principles, were not reviewed because they have different proposals in relation to the strategy proposed in this paper, the IME. However, we would like to mention the tenth (and last) principle of the responsive manufacturing strategy named QRM (Quick Response Manufacturing) proposed by (Suri, 1998): "The biggest obstacle to QRM is not technology, but "mind-set". Combat this through training. Next, engage in low-cost or no-cost lead time reductions. Leave big-ticket technological solutions for a later stage." This principle points out that some difficulties will always appear in implementing any strategy for improving manufacturing management: people do not want to change the way they do things but, on the other hand, human commitment is essential for reaching true improvements. Besides, the following message is universal: expensive technological changes must be postponed until cheaper priorities have already been implemented.

Focusing on the three principles of our proposal , the IME, it can be said that simplification of the materials flow is derived from Group Technology. So, this is not a new principle. Ashby's cybernetics law - "Only variety can destroy variety" - is the inspiration for our second principle, which is related to Production Control while Ashby's is a general law for the area of control by means of communication. Our third principle is the most original in terms of literature and it is based on a Brazilian proverb ("Haste makes waste"); i.e., things must be done rapidly, since this helps the reduction of leadtimes, which is prescribed in the strategy proposed by (Suri, 1998). However, he does not add an essential component: we must be fast only as far as velocity does not disrupt quality (our third principle).

The algorithm proposed in this paper contains an original numerical measure, "effective takt time 2". This measure is more complete than the definition of "effective takt time" that is present in the literature; it is worth to point out that it is exactly the effective takt time 2 concept that makes it possible to formally relate Production Control decisions (production pace) and the important Quality Control variable (rejection rate)..

The case study illustrates the application of the IME's three principles in the case of repetitive production systems. The widening of the IME's scope for semi-repetitive and non-repetitive systems will be a task for future research. Also, further study is required to determine whether it is better to have each processing unit controlled by the ideal PC system, or to have all processing units controlled by the same PC system.

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Volume 2, Number 1, 2005, pp. 81-104

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