Balanced Automation in Flexible Manufacturing Systems

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Abstract: Partly due to the introduction of computers and intelligent machines in modern manufacturing, the role of the operator has changed with time. More and more of the work tasks have been automated, reducing the need for human interactions. One reason for this is the decrease in the relative cost of computers and machinery compared to the cost of having operators. Even though this statement may be true in industrialized countries it is not evident that it is valid in developing countries. However, a statement that is valid for both industrialized countries and developing countries is to obtain balanced automation systems. A balanced automation system is characterized by "the correct mix of automated activities and the human activities". The way of reaching this goal, however, might be different depending on the place of the manufacturing installation. Aspects, such as time, money, safety, flexibility and quality, govern the steps to take in order to reach a balanced automation system.
In this paper there are defined six steps of automation that identify areas of work activities in a modern manufacturing system, that might be performed by either an automatic system or a human. By combining these steps of automation in what is called levels of automation, a mix of automatic and manual activities is obtained. Through the analysis of these levels of automation, with respect to machine costs and product quality, it is demonstrated which the lowest possible automation level should be when striving for balanced automation systems in developing countries. The bottom line of the discussion is that product supervision should not be left to human operators solely, but rather be performed automatically by the system.

Keywords: Balanced automation systems, flexible manufacturing systems, quality control

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1 Introduction

The role of the operator in a manufacturing system has changed with time. In early days of manufacturing, the tasks of an operator were to manually load, operate and unload machines. Later on, more advanced machines were introduced that could work autonomously, although with no intercommunication. As progress had been made towards more intelligent machines and with the introduction of computers, the manufacturing system was expected to take over more and more of the operator's work and eventually became the ultimate, unmanned factory. This view has slightly been moderated slightly in recent years and the role of the operator in a manufacturing system has become more appreciated. The knowledge and experience of a skilled operator is very difficult and expensive to achieve and build into a system otherwise.

Various papers have been written on the role of the human operator in manufacturing systems, e.g:

- Operator control activities, Adlemo et al (1995a), Sheridan (1992).
- Operator roles and conflicts, Badham and Schallock (1991), Drury et al (1986), Stahre (1995).
- Operator interfaces, Geary et al (1992), Olsson and Lee (1994), Schneiderman (1987), Sylla (1992).
- Anthropocentrinc aspects, Kovács and Moniz (1995).

The tendency in modern manufacturing systems has been to reduce human interactions with systems to a minimum. One important reason for this, albeit not the only one, has been to reduce costs caused by increases in the salaries of human operators. At the same time, the cost of introducing intelligent machines and automatic control systems has decreased in relative terms as compared with operators' salaries. Reductions in human interactions with a manufacturing system, and thus indirect reduction in the number of human operators involved in production, are understandable adjustments made by chief executives. Humans are notoriously inconsistent, both inter-individually and over time. Humans tire easily. They often reject products they regard with suspicion more on account of fixed quotas than on actual defect levels. Computers and machines, on the other hand, are very patient supervisors, over long periods of time, neither complaining nor becoming bored. An important aspect, however, is how to obtain a balanced manufacturing system, meaning a system that has the proper mix of operators and machines to obtain the highest profit possible, taking into account the country in which the system is located, and without suffering any losses of product quality.

1.1 A Balanced Automation System

A balanced automation system (BAS) is defined as a system consisting of both automated and manual activities and machines.

A BAS is the result of a pre - study on designing a manufacturing system, a pre - study that is influenced by various aspects, e.g. production cost, level of required flexibility or desired product quality. Furthermore, a BAS is not an invariable construction as the manufacturing system environment may change, e.g. the cost of manual labour compared to the introduction of an automatic machine may change. In addition, when moving from one BAS to another, one is confined to the installed legacy manufacturing system. This movement should affect as little as possible the already installed equipment and programs.

One of the most important aspects when defining a BAS is product quality. To be able to obtain the required product quality, the quality verification should not be left to a human operator solely. Instead, the operator should be backed up by automatic supervision.

1.2 The Supervisor, the Dispatcher and the Monitor

For a manufacturing system to be able to produce, the operation lists have to be mapped on the resource model. An operation list describes the steps to be taken in order to produce a specific product on an imaginary production facility. The mapping is one of the main activities in obtaining a supervisor (Fabian, 1995). The basic research in this area was done by Ramadge and Wonham (1987). A supervisor is a discrete event process that is used by the dispatcher to execute the work on a manufacturing system that exhibits a pre - specified desired behaviour. During execution the work follows the closed loop system of the supervisor. A description of the automatic synthesis of a supervisor based on manually, a monitor can use the supervisor to check that correct steps are taken.

1.3 Levels of Control and Automation

This paper discusses the levels of control and automation in a manufacturing system appropriate to obtain a balanced system. This is achieved by studying a system and identifying conditions under which it is best to rely on an operator or on an automatic system. This adjustment is made considering various aspects, such as time (i.e. productivity), money (i.e. savings), safety (i.e. human safety), flexibility and quality. The objective of the research presented in this paper is to demonstrate situations in which an operator can perform a work task rather than have the system do it automatically. To illustrate this, a machining cell for the production of truck and bus axles is used. The machining cell is stripped in a number of steps, from a totally automatic system to a totally manual system. The main theme of the discussions in this paper is that, even when human operators perform activities in a manufacturing system that would normally be considered as appropriate for automatic control and automatic production, the supervisory portion of the control should not be left to the operators solely if the quality goals of production are to be met. One reason for this is that the equipment needed for supervision (computers, data network and sensors) is relatively cheap as compared with advanced machines, such as a computerized milling machine. To obtain 100% inspection using humans typically requires a considerable amount of redundancy, often as much as three re-inspections (Dreyfuss, 1989; Freeman, 1988). At the end of the paper another example of a balanced manufacturing system is given. Here, however, an assembly cell in a car manufacturing installation is used rather than a machining cell.

The work presented in this paper is the result of work by a cross departmental research group at Chalmers University of Technology, Göteborg, Sweden. The group consists of individuals from the Department of Computer Engineering, Department of Computing Science, Department of Production

Engineering and the Control Engineering Laboratory. Other work performed by the group relates to high level operational lists (Andréasson et al, 1995), the control system in a machining cell (Fabian et al, 1995) and generic resource models (Gullander et al, 1995). The research aims at demonstrating how a truly flexible manufacturing system can be achieved (see Adlemo et al, 1995b, for some preliminary results).

2 Case Study of A Machining Cell

A machining cell for rear - axles has recently been installed at one site at Saab Scania Trucks and Buses in Sweden. The cell serves as an example of a highly automatic manufacturing system and of how a balanced system can be achieved in a country in which salaries are comparatively high. However, the following sections demonstrate how this system can be stripped of different parts to obtain balance in a country in which salaries are comparatively low.

As one can observe in Figure 1, the cell consists of seven resources; a lathe and a multi operational milling device, together with a quality control (QC) station; two exit buffers and one entry buffer; and a gantry crane (GC) for loading and unloading the devices. A local- area network interconnects the resources with each other and with the cell controller. An initial premise was that all communication should take place by means of MMS messages (MMS, 1990). Finally, however, only the Read - and Write Variable messages were chosen to be implemented.

Rear axles are manually entered by the operator at the entry buffer. Here, the bar code reader registers the incoming axles by identifying their article number. The operator can manually enter re-work codes for those axles that have already been through the system but have been rejected by the QC. The normal flow through the system for each axle is first to visit the milling machine and then the lathe, and finally to exit through the main exit. However, the operator (or operators) can at any time request a specific axle to the QC station, where it will be tested for adherence to the tolerance specifications. This testing is done manually.

The GC is a special type equipped with twin grippers. Under normal operation, one of the grippers is always empty, while the other holds an axle. Loading a device with a new axle means first fetching the old axle with the empty gripper, rotating 180 degrees and then loading the device with the new axle. Thus, loading a device is actually an unload/load sequence under normal operation. When leaving an axle at one of the exit buffers, the GC becomes empty, and then always moves to the entry buffer to fetch a new axle Special work cycles must naturally exist for the starting up and emptying of the cell. The fact that the GC has twin grippers, with one always empty, is equivalent to having one global buffer place within the system. Thus, the system can never come to a deadlock. This fact significantly simplifies the implementation of the control functions.

With production times of about 10 minutes for each device, normal operation means that the GC will spend most of its time waiting for the axles to finish their work cycles. When the

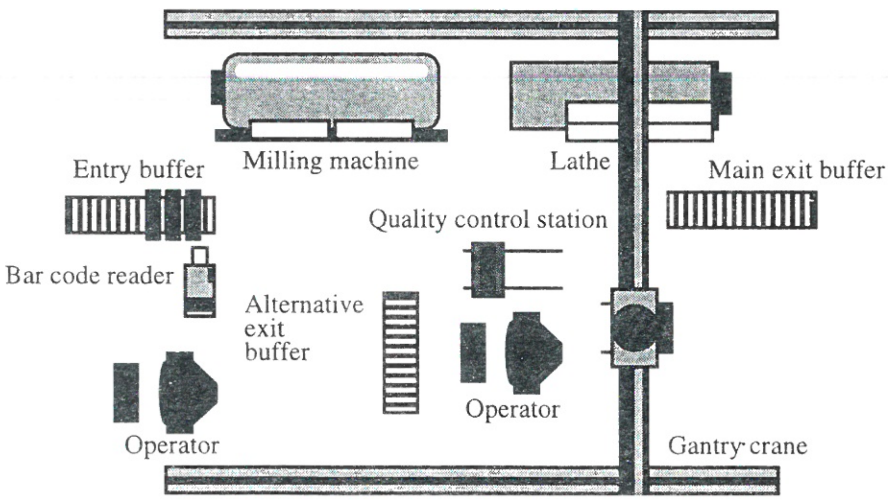

Figure 1. The Machining Cell in the Case Study

GC has fetched a new axle from the entry buffer, it will wait for the milling machine to finish its current task. When the milling machine has been served, the GC stands idle waiting for the lathe to finish its current job. Finally, when the lathe has been unloaded/ loaded, the processed axle will be left at the main exit, whereafter the GC fetches a new axle from the entry buffer.

The result of normal operation is that incoming axles push the outgoing material in front of them. Axles will only be unloaded when new axles are to be loaded. This has several important implications. For instance, if the input flow of axles stops, axles will remain in the devices until a new axle forces the other axles to exit the devices. When the system is not in the start - up or emptying phase, there will usually be an axle at the QC station waiting to be moved to some other unit, so that axles should wait a good deal of time to be moved from the QC station.

3 Control and Automation Concepts

The production in the machining cell described in Section 2 is designed to be more or less automatic, i.e. human interference with production should be at minimum. The only interference is that of the operator supervising the system. However, the machining cell, as presented in the case study, can be stripped of parts of the automatic resources, e.g. the gantry crane. The result of a totally stripped system is a completely manual system with manually operated machines and manual transportations.The place where the exact amount of automation should exist is governed by a number of concepts, e.g. time, money, safety, flexibility and quality. These concepts and their effect when making decisions are described below.

3.1 Time

The first concept, time, is normally associated with the level of automation such that higher automation leads to faster production and thus to time saving. However, in some special situations, this may not be true. Another aspect is that it is difficult to manually optimize production, which leads to a longer overall production time.

3.2. Money

In the second concept, money, it is not so easy to identify the relation between the degree of automation and the costs or savings. Normally, the replacement of an operator by an automatic equivalent renders some cost reductions, as the operator is one of the most expensive parts. However, in some countries, the cost of an operator is a relatively small expenditure. This leads to the situation in which it might be more favourable to use humans instead of unmanned, automatic machines.

3.3 Safety

When it comes to safety, the advantages of an automatic system are more obvious. The removal of humans in a manufacturing system is almost always a way to reduce the risk of injuries during normal production. However, in terms of service, it is usually safer for an operator to work in a manually operated system.

3.4. Flexibility

As concerns flexibility the advantages of an automatic system over a human operator are not as tangible. When it comes to flexibility, who can beat man? For instance, if the space encountered in a manufacturing cell is very limited, it might be more flexible to rely on a human rather than on a big, bulky robot.

3.5. Quality

The upholding or improvement of production quality, finally, is more directly correlated to the automation of production. By introducing computers, data networks and intelligent machines into a manufacturing system, quality can be improved. As initially mentioned, humans tire easily and are notoriously inconsistent.

4 Steps of Automation in A Manufacturing System

The following Section describes a number of possible steps of automatic production in a manufacturing system, using the manufacturing cell in Section 2 as an example.

Four different steps of automation have been identified:

1. Cell control system

    dispatcher / monitor / not present

2. Mover

    asynchronous material transportation (i.e. transportation between machines)

    automatic /manual

    synchronous material transportation (i.e. transportation to an assembly machine)

    automatic / manual

3. Producer

    automatic / semi-automatic / manual

4. Data network

    present / not present

These four different automation alternatives can be combined in a number of possible combinations in what we call *automation levels*. However, if the product quality should be maintained, the monitor activities should be present (it is implicit that the cell computer is present) (Adlemo and Andréasson, 1995b).

4.1 Cell Control System

The control level can exist in three different forms, i.e. dispatcher, monitor or not present. Both the dispatcher and monitor work towards the supervisor with one big difference. The dispatcher, on the one hand, is actively initiating the production and movement of products while relying on the fact that the production and movement of products are carried out correctly. The monitor, on the other hand, is only monitoring the production and movement of products while relying on the fact that someone else carries out the actual production initiation and movement of products. We strongly suggest that at least the monitor with its activities should always be present while the rest of the automation alternatives can be chosen more freely.

4.2 Mover

The transportation of material between different machines in a machining cell is asynchronous, i.e.there are no requirements concerning synchronization with other flows of transportation.

In the case study, this automation alternative can be obtained by replacing the expensive gantry crane by a manually operated truck. Instead, here, printed truck orders are needed. If the quality of the products is to be maintained in this case, it is necessary to use sensors on the machines to verify that the correct product is delivered to the correct machine.

In an assembly cell, as compared with a pure machining cell, there is also a synchronous transportation of material between different stations. The synchronous transportation is special, as the arrival of a piece of material at a station should be co-ordinated with the arrival of other pieces of material.

4.3 Producer

Another method for reducing costs is to exchange automatically operated machines with semi-automatic or manually operated machines. This can be done for all of the machines or only for some of them.

In the case study, this automation alternative can be obtained by replacing the expensive milling machine and the expensive lathe by manually operated equivalents. Instead, here, printed working orders for the machines are needed. If the quality of the products is to be maintained at the same time when automatically operated machines are omitted, it is necessary to use sensors that verify the quality of the products.

4.4 Data Network

However another alternative to reducing costs is to remove the data network. This lets us with a system with stand-alone machines, where the instructions for the machines must be entered manually as no data network exists to transport these instructions.

In the case study, this level can be attained by removing the local - area network that interconnects the machines and the cell controller.

5 Appropriate Levels of Automation in A Manufacturing System

The six different steps of automation can be combined into different levels of automation. Table 1 describes some examples of possible levels of automation by combining the four steps of automation in different ways. For example, one level is the fully automated production, i.e.level I. Another level is to introduce manual asynchronous material transportation but to allow the rest to be automatic, i.e.level II. Still another level would be to have everything manually controlled and have no data network, i.e.level VI. A level that actually exists in many installations is automatically operated machines and no further automation, i.e.level III, although this level is inflexible as well as unpractical. Furthermore, verification of the quality of the products is very difficult.

The conclusion drawn from observing the different levels of automation is that the lowest acceptable level of automation for a manufacturer is the case in which production supervision is left to the automatic system. This would be a system described by level IV. If the automatic supervision is removed, i.e.level V, the quality of the products would be affected.

1. Cell control system:	**D** Dispatcher	**M** Monitor	**MC** Manual
2. Mover:			
a) Synchronous Transportation:		**SA** Automatic	**SM** Manual
b) Asynchronous Transportation:		**AA** Automatic	**AM** Manual
3. Producer	**PA** Automatic	**PS** Semi-automatic	**PM** Manual
4. Data network	**P** Present	**ND** No Data Network	

Table 1. Steps of Automation Combined To Achieve Different Levels of Automation

		Steps of automation				
No.	*Examples of levels of automation*	*1.*	*2a.*	*2b.*	*3.*	*4.*
I	Fully automated manufacturing cell	D	SA	AA	PA	P
II	Manual asynchronous material transportation	D	SA	AM	PA	P
III	Automatically operated machines only	MC	SM	AM	PA	ND
IV	Lowest acceptable level of automation	M	SM	AM	PS	P
V	Not acceptable level of automation	MC	SM	AM	PS	ND
VI	Non automatic production	MC	SM	AM	PM	ND
VII	The machining cell in the case study (Section 2)	D	–	AA	PA	P
VIII	The assembly cell in the example (Section 6)	D	SM	AM	PA	P

To achieve a balanced manufacturing system, one should omit expensive automatic parts in behalf of manual counterparts if the manual counterparts are cheaper in the long run and if the product quality can be maintained.

Taking into consideration the aspects of safety, quality ,etc., we believe that the following steps should be taken in the following order to achieve a balanced manufacturing system:

- Omit automatic asynchronous material transportation
- Omit automatically operated machines
- Omit automatic synchronous material transportation.

We believe that it is most cost- effective to have manual material transportation, as described before, and then, if a greater reduction in automation is required, to continue by omitting manually operated machines. The reason for this is that it is easier to maintain a certain level of product quality using manual transportation than it is to introduce manually operated machines, where there is a greater risk of reduced product quality. The next step toward reducing costs is to remove the automatic supervision of production. However, we strongly believe that this is an unwise step, as the verification of the quality of the products is left to a human inspector who is more liable to commit errors than a correctly installed automatic supervision system. Furthermore, the cost of automatic supervision with computers and sensors is far less expensive than highly complex machines and automatic transporting systems. In order to have automatic supervision, it is necessary to have a data network and, hence, this component should not be omitted in a balanced manufacturing system.

Johansson (1990). The cell is also illustrated in Figure 2.

This cell produces kits, which are plastic bags containing small size parts (e.g. screws, nuts, and plugs) to be used in the assembly department of a company. Each kit contains the small parts needed for a specific portion of the assembly of one specific product. There is a large variety of kits (several hundreds), each containing between two and 20 different parts, i.e. parts with different part numbers, and between 10 to 40 single parts. A typical value is 8 part numbers corresponding to 25 single parts. The production of kits is divided into two major activities corresponding to physical areas in the system: automatic counting and packaging (consisting of bagging and printing). Counting is done in sectioned trays, where each tray has 18 sections.

Automatic counting is done by four identical

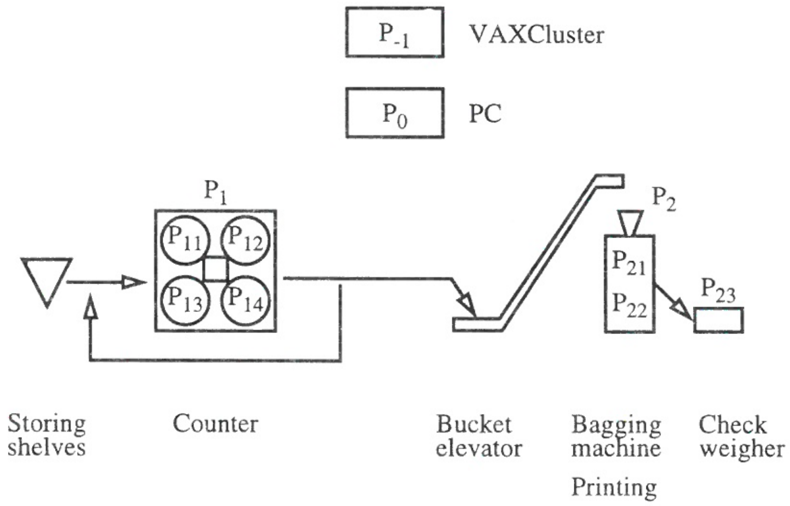

Figure 2. Layout of the Assembly Cell

6 Example of A Balanced Assembly Cell

As another example we will here describe a non - traditional assembly cell. Two of the primary differences, as compared with traditional cells, are the number of parallel assembly teams resulting in very long cycle times and the material feeding system, which is a pure kitting system. The cell has been studied extensively and the layout and function of the cell is described in Johansson and

vibratory bowl feeders that work in a so- called counter - group, P_1. The feeder can handle only one part number at a time, which means that four part numbers per kit is the maximum number that can be counted at one time. For this reason, many of the kits must pass the counter - group more than once. Bagging is done by a bagging machine, P_{21}. In a special machine, the tray is turned and the kits are placed into a bucket elevator that leads to the bagging machine. A printer that is attached to the bagging machine prints the internal part number of the kit on the bag, P_{22}. The quality of the kits with regard to part numbers and quantities of each part number is controlled by a check weigher connected to the bagging machine, P_{23}. The downloading of production information is retrieved from the VAXCluster, P_{-1}, via the personal computer, P_0.

The assembly cell is balanced in the sense that, when the cell was planned, it was decided that the asynchronous material transportation be performed manually, e.g. the transportation between P_1 and P_2, while the synchronous material transportation be performed automatically, e.g. the positioning of the tray in the P_1 area. This measurement was taken in a car producing facility in an industrialized country, i.e. Sweden, even though the salaries were high. The reason for this was simply that the asynchronous material transportation was too expensive to perform automatically. The cell control system is automatic and performed by the personal computer P_0. The machines, i.e. counting, P_1, bagging,P_{21}, printing, P_{22} and weighing, P_{23}, are automatically operated. Most of the supervision is done automatically but an operator manually enters the identification of the tray into the packaging system. Finally, a data network is connected to all the machines in the cell.

The weak part of the assembly cell is the manual supervision. There is an obvious risk for the operator to enter an erroneous identification. We therefore suggest that bar code readers are introduced, both at the counter, P_1, and at the packaging system, P_2. At P_1, the identification of the tray is read and saved in a database where it can be retrieved by P_2 afterwards. This way, the quality of the products is not endangered, as it is the case of manual supervision.

7 Conclusions

A number of levels of automatic control and automatic production has been presented in order to identify activities that may be performed by a human operator rather than an automatic system to achieve a balanced automation system with respect to such relevant aspects as cost, flexibility and quality. To do so it is essential for a manufacturing system that the supervisory portion exists and is performed automatically by the system. It is not possible to leave this task to a human operator solely, as it is common for humans to commit errors that might reduce the quality of the products. In addition, the cost of the equipment to perform the automatic supervision is now relatively low, compared with certain highly specialized machines. Nonetheless, certain parts of an automatic system can be omitted to reduce costs without reducing the production quality.

Thus, by removing expensive machines, such as the gantry crane described in Section 2, in exchange for humans and simple, cheap machines, it is possible to reduce costs, maintain the quality of the final product and uphold a higher degree of employment in countries in which salaries are low. However, it is essential in such situations that the manufacturing system should be able to rely on some kind of automatic supervision to check the product quality. We believe that the cost of having a reasonable amount of computer power together with a data network that connects computers with the sensors placed on the machines is reasonable and affordable. Even more important, this equipment is necessary if a manufacturer is to be able to provide products of good quality.

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