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IMPACT OF AUTOMATION ON PROCESS CONTROL DECISION-MAKING

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This paper investigates changes in the process control of a vehicle assembly plant which had been modernized from a principally manual procedure to one that uses programmable automation extensively. Process control is defined as the information flow and decision-making required to perform basic process operations. We investigate the effects of implementing a computer-integrated production system on the amount and types of process control decision-making and on the distribution of process control decision-making between humans and machines. After automation, the emphasis on decisions regarding product quality specifications increased and the emphasis on decisions related to flexibility in handling a variety of product options decreased. Decisions concerning product quality specifications, as well as timing and synchronization of tasks, were usually performed by automated equipment, while decisions relating to the flexibility of the process remained, to a large extent, under manual control. Whereas humans made nearly 75% of the decisions required to assemble and weld a vehicle body in the principally manual system, humans made fewer than 10% of similar decisions in the automated system.

OVERVIEW

This paper compares the manual and computer-controlled forms of the same production process. The production process studied is in the body shop of a vehicle assembly plant, where sheet metal parts are assembled and welded together to form the outer structure of an automobile. The vehicle assembly plant underwent extensive modernization in 1984, when it was transformed from a principally manual 1960s vintage plant to one that uses programmable automation extensively through an integrated system of minicomputers, robots, programmable logic controllers and other shopfloor programmable devices.

In comparing the old and new production processes, we focus on changes in process control decision-making. We define process control as the information processing and decision-making involved in: (i) coordinating and sequencing the motions and operations of operators, tools and conveyors and (ii) selecting parameters for tool operations.

This definition of process control is particularly appropriate for discrete parts manufacturing, in which production principally entails a sequence of discrete events and where the principal purpose of process control is to sequence and coordinate these events. With asynchronous, independent control of equipment, control of one piece of equipment may depend on the state of other equipment. Another distinguishing feature of discrete parts manufacturing processes is that the properties of the output are often unique for each individual part produced (although the degree of variation between parts tends to decrease with increasing production volumes). Thus, another purpose of process control is to choose appropriate parameters to obtain the desired configuration of each product. For example, in vehicle assembly, process parameters such as weld parameters must be chosen for each weld spot on each workpiece.

A process control decision is a choice between alternatives. Some decisions involve the timing of a particular operation within a work station (such as when to fire a weld gun). Other decisions involve choosing a particular task or process parameter from several predetermined alternatives. The level of decision-making analyzed in this paper is at a "higher level" than basic machine control, since we do not consider details like how a robot controls its actuators to move its arm from one position to another. Similarly, we are not concerned with the details of how a human operator would control his arm motions once he has decided to execute a process control task. The level of decision-making analyzed is at a "lower level" than basic production control, since the sequence of operations and patterns of workpiece flow between work stations are predetermined at the level of detail examined here. Also, we do not consider "higher level" decisions such as alterations in the regular schedule of the amount of output per day. We refer to the level of decisions examined in this report as "process control" since the focus is on the types of decisions that the *system*-level controllers (be they human or machine) must make to coordinate the functioning of a manufacturing process consisting of tools, tool operators, parts and material handling devices for a known production process and schedule.

The manual and automated processes are compared in terms of:

- The amount of decision-making involved in performing the basic operations of parts loading, welding, piercing and workpiece transfers
- The types of decisions made to execute these four basic operations and the relative importance of each type of decision
- The division of process control decision-making responsibility between humans and machines.

The idea of comparing the old and new systems in terms of their needs for information processing and decision-making was motivated in part by the observation that the new system is not only more automated, but it is also controlled by more microprocessor-based devices. The control devices in the new process are essentially machines which collect information from other machines and which make decisions based on pre-programmed control logic. The use of a large number of computer-based control devices in the new system suggested that comparing and contrasting the old and new production processes in terms of the information processing used in production operations would yield a more basic understanding of how and why the modernized production process was more complex than the manual process it replaced.

A second motivation for this type of comparison was an awareness of the growing trend to conceptualize and analyze manufacturing systems in terms of information processing as well as material processing. Kutcher[3] discussed the importance of considering transfers and transformations of data as well as transfers and transformations of material when analyzing manufacturing operations. Skinner[6] described the importance of understanding the factory as a data processing operation rather than as an essentially physical operation. Comparing the complexity of two production processes in terms of transfers and transformations of data is consistent with this emerging "information processing" view of manufacturing systems.

METHODOLOGY FOR COMPARING PROCESS CONTROL DECISION-MAKING

The purpose of the body shop in both processes is to join metal components to form the body of the vehicle. The types of operations used to make the vehicle body remain the same: loading and assembling metal parts, welding, piercing, polishing and finishing metal, applying sealer and transferring workpieces between conveyors. We focused on four *basic operations*: loading, welding, piercing and transferring the workpiece between conveyors. These operations account for nearly all of the processing activities involved in assembling and welding a vehicle body. Operations such as sealing and finishing account for only a small portion of the work done in the body shop, so they were not studied. We also did not study operations that were not performed in both production processes, such as soldering operations that were used in the old process but were designed out of the new process.

We describe each of the four basic operations as a sequence of decisions (Table 1). The process control decisions required to execute a basic operation remain fundamentally similar across technological alternatives. For example, the decision "when to fire a weld gun" must be made for all weld spots, whether the weld is done by a human operator in the old process, or by a robot or an automatic press welder in the new process. The details required to carry out this decision, such as squeezing a trigger, tripping a relay or pushing a button are dependent on the mechanism performing the weld. These types of details were not considered in this study.

For each process control decision, we identified a purpose and a type of decision-maker. Three decision purposes are identified: synchronization, flexibility and quality. Synchronization decisions concern the coordination and timing of operations and the positioning of tools (e.g. when to move a weld gun to the next position in a sequence or when to fire a weld gun). Flexibility decisions involve the choice of operations depending on product style options (for example, choices regarding which sequence of welds

Table 1. Process control decisions

- Loading:
    - When to move conveyor to next station
    - Whether to add parts
    - Which sequence of parts to add
    - When to load next part in sequence
    - Whether to adjust part
- Welding:
    - When to move conveyor to next station
    - Whether to execute weld
    - Which sequence to weld
    - When to move weld gun to next position in sequence
    - Which schedule of weld parameters to choose at a particular spot
    - When to squeeze weld gun
    - When to fire weld gun
    - When to quit squeezing weld gun
- Piercing/drilling:
    - When to move conveyor to next station
    - Whether to execute pierce/drill
    - Which sequence to pierce/drill
    - When to move to next position in sequence
    - When to pierce/drill
- Transferring between conveyors:
    - When to move shuttle to get new workpiece
    - When to lower shuttle onto workpiece
    - When to close shuttle arms over workpiece
    - When to pick up workpiece
    - When to move workpiece to destination
    - When to lower workpiece onto new destination
    - When to open shuttle arms
    - When to get shuttle out of way

to perform or which set of parts to load). Quality-related decisions are those whose motivation is quality-driven. In some cases, identifying quality-related decisions is straightforward, as in the decision to adjust the fit of a part that has been loaded. In other cases, quality decisions are difficult to distinguish from synchronization or flexibility decisions until their intention is understood. For example, the coordination of conveyor stops at each station was implemented to improve the positioning of each weld spot. Accurate weld positioning improves the appearance and structural integrity of the body. Thus a decision to stop the conveyor at each station is motivated by quality concerns, so these decisions are categorized as quality-related, though they may seem to be synchronization decisions at first. The decision-maker is the entity that collects the information required for the decision, makes the choice between alternatives and performs the appropriate control actions. The decision-maker can be either human (i.e. an operator) or machine (a robot, programmable logic controller or other programmable device).

The measures of change in process control after modernization are represented by the total number of decisions executed per vehicle body, categorized by decision-maker and decision purpose. Enumeration of the total number of decisions allows analysis of the differences in the amount of information processing in the manual and computer-controlled processes. Categorizing the results by decision purpose allows analysis of differences in the kinds of decisions being made. Categorizing the results by type of decision-maker provides for analysis of the division of process control responsibility between humans and machines. Breakdown by both decision-maker and decision purpose allows an assessment of the kinds of decisions that are automated as opposed to those that are still principally the responsibility of humans. Additional information on the calculation of these measures is given in Miller and Bereiter.[5]

RESULTS AND CONCLUSIONS

Changes in the amount of decision-making involved in production tasks

Table 2 shows the total number of decisions required to produce a vehicle body in the old and the new process. The decisions are categorized by basic operation. Decisions associated with conveyor stops have been categorized separately because they are particularly noted in the following discussion. (The decision "when to move the conveyor to the next station" affects three of the four basic operations analyzed: loading, welding and piercing.) The total number of process control decisions required to execute the four basic operations studied nearly tripled (from 6142 to 17,361). This increase results from the basic operations being executed more times, as well as from more decisions per basic operation.

Increases due to the execution of more basic operations are driven primarily by changes in the design of the vehicle. For example, the number of weld spots applied to the vehicle body increased from 1300 to over 3000, the number of parts loaded increased from 166 to 247 and the number of pierces increased from 10 to 25. These increases were due to

Table 2. Changes in process control decision-making categorized by basic operation

Basic operation	Old process	New process
Weld	5529	16,221
Load	472	565
Conveyor transfer	103	402
Pierce	38	72
Conveyor stop†	0	111
Total	6142	17,361

†Conveyor stops are considered a part of each basic operation, but they are categorized separately here for explanatory purposes.

changes in both the size and design of the vehicle produced. Since the vehicle produced in the new system was larger, it required more parts to be loaded and more weld spots to join parts.† Increases due to the execution of more decisions per basic operation result from changes inherent in process automation.

In distinguishing the fraction of increase due to the change in vehicle design from the fraction due to the change in the nature of the process, we consider the number of decisions which would have been required to execute the basic operation for the *new* vehicle using the *old* process technology. For this hypothetical situation, the total number of decisions would have been 14,282. The difference between this total and the total number of decisions in the old process (6142) is that portion of the change accounted for by increases in the number of basic operations. This difference accounts for 73% of the total change. Thus, about three quarters of the increase results from the greater number of operations performed in the new system, and about one-quarter of the increase is due to a change in the nature of the process.

Increases in the number of transfers of the vehicle body from one conveyor to another in the new system resulted in a four-fold increase in decisions related to conveyor transfers (from 103 to 402). Although this increase accounts for only a negligible fraction of the total increase, this capability has very important implications. The very long, continuously moving conveyors of the old system were replaced by a set of more segmented conveyors with storage accumulators in the new system. Transfers between conveyors and movements in and out of accumulators are controlled automatically. This change modularizes the body shop so that the movement of parts through each section may be controlled independently. The primary advantage of this change is that each major conveyor line can run independently of the others. Thus a breakdown of one conveyor line does not necessarily halt the movement of parts on the other lines. The control of workpiece transfer between modularized conveyors is required in order to replace the sequential flow of products by parallel flows and variable routing according to both demand patterns and to the availability of parts and machines.

The remaining 27% of the increase in the number of decisions results from changes in the nature of the process. The use of programmable control is most responsible for this change. Decisions that were not technically or economically feasible in the old system became practical in the new system. For example, the ability to stop the conveyor at each station was implemented in the new system. This eliminated the need for operators (human or machine) to follow the moving vehicles performing the part-loading and welding operations. While decision-making for conveyor stops accounts for only 111 decisions in the new process, the ability to have stationary processing allows more precise positioning of parts and of spot welds, and contributes to improving the quality of the vehicle.

Programmable control in the new computer-integrated system made it possible to make some decisions frequently which occurred only rarely in the old system. This in turn contributed to an increase in the number of decisions made per basic operation. An example of this is the selection of weld parameters, such as the voltage applied and the weld "slope" (the ramp up of the voltage application over time). In the manual system, a set of weld parameters was associated with each weld gun, and the operator defined weld parameters for each sequence of welds by choosing the appropriate weld gun. Once the operator chose a gun, he used the same gun for the entire sequence of weld spots he performed. Since it was time consuming and cumbersome to switch guns, design engineers made efforts to minimize the number of situations where it was necessary to work with multiple weld guns. In the computer-integrated system, the weld parameters for each individual weld spot are controlled by a programmable weld timer. Therefore, it is quick and easy to adjust the parameters for each separate weld according to the characteristics of the material being welded at that spot (galvanized vs. nongalvanized metal, metal thickness, etc.). The overall result is improved weld quality. This also contributes to improving the quality of the vehicle.

Changes in the types of decisions being made

Figure 1 shows the change in the number of process control decisions, expressed in order to show changes in the types of decisions being made. As a result of the modernization, the number of syn-

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† Also, in the old process, some components of the vehicle body arrived at the plant already welded together, whereas in the new plant, all parts of the body were welded together on site. In addition, design philosophies changed, and as a result of increased emphasis on structural integrity for the new product, more weld spots were applied per area than in the old product.

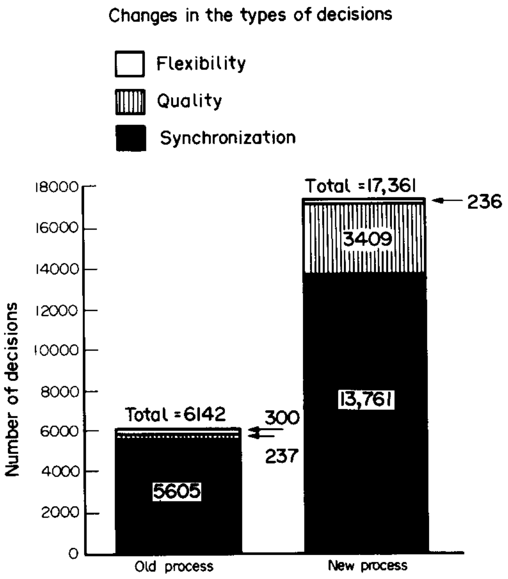

Fig. 1. Changes in the types of decisions.

chronization decisions more than doubled from 5605 to 13,716. However, the relative proportion dropped from 92% to 79%. Almost all of the synchronization decisions in the new process (89%) relate to synchronizating the machinery used in robot and automatic welding. Only 1% of the decisions are for transfers between conveyors, but these decisions are important because they modularize the body shop to allow individual sections to operate independently.

The number of quality-related decisions increased by a factor of 14, from 237 to 3409. The relative proportion of quality-related decisions increased from 4% of the total in the old process to 20% in the new process. Almost all of the quality related decisions (89%) concern selecting weld parameter schedules for individual welds. Only 3% of the decisions control the stopping and starting of the conveyors within a station.

The total number of flexibility-related decisions decreased from 300 to 236. Flexibility decisions which previously accounted for 5% of the total number of decisions now account for only 1%. The decrease in flexibility related decisions is a result of the reduction in the number of body style configurations produced in the new body shop. Whereas the old process produced a set of vehicles with a variety of fundamental body configuration differences, the new process produced a much more uniform set of vehicles with fewer major configuration differences.

Why are there fewer flexibility related decisions in the body shop of the new system? Is it because vehicle designers desired fewer variations in the new product, and hence the system required less flexibility decision-making? Or is it caused by the difficulties of building automated systems to produce a variety of product options? While we do not know the answer, we point out that building automated systems that can produce variations in product mix present technological difficulties which are well recognized by researchers of factory automation.[7]

Much of the current discussion of computerized process control focuses on increasing flexibility and its economic implications.[1,2] Yet here we see that the conversion to a computer-controlled process resulted in a decrease in flexibility-related decisions. While this might seem puzzling at first, it highlights a common misunderstanding that *programmable* automation always results in increased flexibility in any application (hence terms appear such as *flexible* manufacturing systems and *flexible* assembly). Programmable automation can be flexible when compared to "hard-automated" systems. This is not necessarily so when compared to principally manual systems, since human sensing and information processing capabilities make people the most flexible "production technology" available. Since the change here was from a principally manual system to a highly automated one, it is not surprising that the number of flexibility decisions decreased.

Changes in the division of process control decision-making responsibility betwen humans and machines

Figure 2 shows the increase in number of process control decisions expressed to highlight changes in the division of process control decision-making responsibility between human operators and machines.

Overall, the proportion of process control decisions per vehicle made by humans dropped from

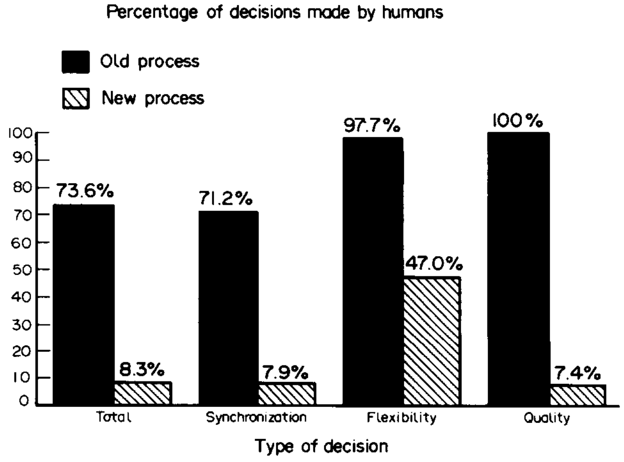

Fig. 2. Percentage of decisions made by humans.

73.6% of the total to only 8.3%. This indicates a shift from primarily manual to automatic process control. The proportion of synchronization decisions made by humans dropped from 71.2% to 7.9%. Apparently, significant portions of synchronization decision-making can be automated. The proportion of quality-related decisions made by humans fell from virtually all to only 7.4%. Evidently, significant portions of decision-making related to parameter selection and positioning precision can be automated. The distribution of flexibility decisions shifted from nearly all human to roughly half-human, half-machine split. Since this is a relatively small shift compared with shifts in the other types of decisions studied, it appears that decisions related to flexibility in the choice of product options are not as easily automated as the other types of decisions studied.

Conclusions

The motivation for this paper is to develop a more basic understanding of how and why a new, highly automated computer-controlled manufacturing process is more complex than the older, principally manual, and electro-mechanically controlled process it replaced. By identifying the type and number of process control decisions required to load parts, spot weld, pierce holes and transfer the workpiece from conveyor to conveyor, we were able to compare the functions of the old and new processes in a common framework, despite the differences in technologies used to execute the basic operations.

From the comparison, it is evident that the new system is controlled more extensively than the old one. Weld parameters are "individualized" for each separate spot weld. Conveyors are segmented into separate modules, and the movement of each part into and out of a work station within the module is separately controlled.

While a process with similar capabilities could, in principal, have been built with the old electro-mechanically based relay technology, the cabinets housing the control mechanisms would have been very large and the system very difficult to debug, maintain and modify. As a result, the system would have been too complicated to achieve the same capabilities. Thus, the new form of programmable control, in conjunction with automation, has made it possible to perform more operations with increased complexity in a facility of given size.

The comparison of the types of process control decisions made reveals that the new process allows tighter control over product quality. In the new system, many more decisions are made for the purpose of improving product quality (i.e. adjusting parameters for different welds or stopping the conveyor at a weld station to more precisely position the weld) than in the old system. Quality related decisions increased by the largest relative proportion, from 4% of the total number of process control decisions in the old system to nearly 20% in the new. Management claimed that one of the major motivations for modernizing to programmable automation and control in the body shop (and the plant in general) was to achieve a higher level of quality. This analysis gives an insight into why programmable automation would realize higher levels of quality for welded vehicle bodies.

A surprising result was the decrease in the number of process control decisions related to selecting options based on alternative product configurations (flexibility). It is not known whether this occurred because of a reduction in the need for flexibility in body styles due to the changed product mix or because of the limited technology for dealing with an increase in product alternatives (especially in a process such as vehicle body welding where much special tooling and fixturing is required to achieve very precise dimensional tolerances).† In the one plant studied, computerized control is not used to increase flexibility in the body shop as extensively as one might expect. The equipment is primarily being used to time and synchronize the basic operations at each station independently. The computerized equipment is also used to tightly control the quality of the products, as shown by the increase in quality-related decision-making.

While an increase in flexibility was not achieved in this particular manufacturing system, the increased ability to automate decisions controlling synchronization and quality demonstrated here is necessary for the future development of high volume continuous flow systems which can produce a diverse set of products (i.e. flexible mass production). The independent control of modularized conveyors, individual stations and process parameters for each individual unit operation within a station are all important steps toward the development of high volume, continuous flow systems with variable pro-

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†In a vehicle paint shop, where the process tools do not have to physically touch the work piece, and the setting of physical dimensions is not an issue, one might expect programmable control to result in an increase in flexibility.

cess routing across stations and variable processing alternatives within stations. The analysis of the process control of the new body shop in this vehicle assembly plant shows that its building block capabilities have the potential to realize high volume, continued flow flexible systems.

It is interesting that even without an increase in decisions related to product flexibility, there was nearly a three-fold increase in the number of process control decisions made. This should point out just how difficult it would have been in terms of process control requirements to make the new process capable of producing a wider range of body styles. Some of the capabilities demonstrated by this example show that we are, in fact, moving closer to the reality of processes than can produce a range of product configurations at high speeds (i.e. flexible mass production). The example also suggests, however, that such a system would be even more complex than the one studied here. Given that this system took nearly a year to initiate[4] a complicated system requiring even more extensive process control decision-making would pose a formidable technical and managerial challenge.

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