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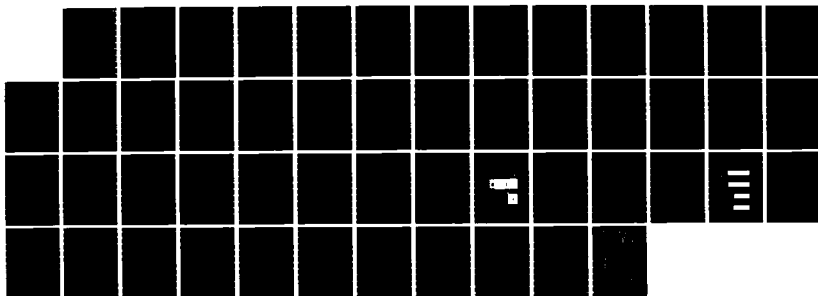
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A Comparison of a Manual and Computer-Integrated Production Process in Terms of Process Control Decision-making

Steven M. Miller*
Susan R. Bereiter**

CMU-RI-TR-86-6

**The Robotics Institute
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213**

March 1986

***Assistant Professor of Industrial Administration
Graduate School of Industrial Administration**

****Doctoral Candidate
Department of Engineering and Public Policy**

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Abstract

This paper is an investigation into the changes in process control that took place in the body shop of a vehicle assembly plant that was modernized from a principally manual process to one that extensively uses programmable automation. In this study, process control is defined as the information flow and decision-making required to perform basic process operations. We investigate affects of the implementation of a computer-integrated production system on the amount of process control decision-making, the types of process control decisions being made, and the distribution of process control decision-making between humans and machines. We found that as a result of the modernization, the amount of process control decision-making nearly tripled, the emphasis on decisions to meet product quality specifications increased, and the emphasis on decisions related to flexibility in handling a variety of product options decreased. Decisions relating to meeting product quality specifications and to timing and synchronization of tasks were mostly taken on 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 percent of the decisions required to assemble and weld a vehicle body in the principally manual system, humans made fewer than ten percent of the comparable decisions in the automated system. The framework used to produce these results provides a general approach for comparing levels of technological sophistication in manufacturing systems in terms of the amount and type of information processing.

Chapter 1

Overview

The purpose of this paper is to report the results of a comparison of a manual form and a computer-integrated form of the same production process. The motivation for the comparison was to develop an in-depth understanding of why a computer-integrated production system is more complex than its manual counterpart.

The production process studied is 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 an extensive modernization in 1984, in which it was transformed from a principally manual 1960's vintage plant to one that uses programmable automation extensively in an integrated system of minicomputers, robots, programmable logic controllers, and other shop floor programmable devices. To make this comparison, we focus on changes in process control decision-making. In this study, process control is defined as the information processing and decision-making involved in

1. coordinating the sequencing the motions and operations of operators, tools, and conveyors, and
2. selecting parameters for tool operations

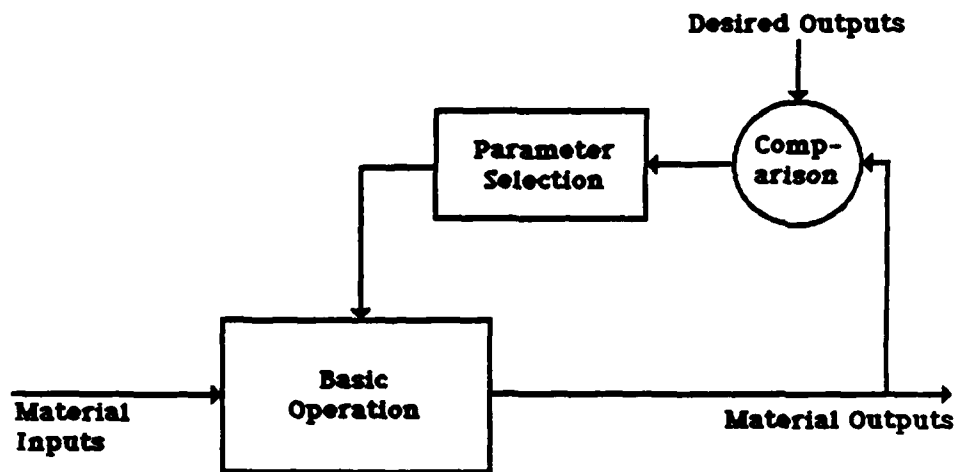
This definition of process control is particularly appropriate for discrete parts manufacturing, in which the production process is principally a sequence of discrete events and the principal purpose of process control is to sequence and coordinate these events. With asynchronous, independent control 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.

This definition of process control is contrasted to the way the term is typically used in the continuous process industries, such as chemical production and metal roll casting. In continuous processes, the objective is to keep the output constant, so the primary purpose of control is to maintain uniformity of the output. In these industries, process control primarily involves monitoring parameters (such as temperature, pressure, or flow rate) and adjusting actions to keep the parameters within specified tolerance limits. The primary role of process control in continuous processes is error detection and correction. Figure 1 shows one way of describing the differences between process control in continuous and discrete processes.

A process control decision in our analysis is a choice between alternatives. Some decisions involve choosing the timing of particular operation within a work station (such as when to fire a weld gun). Other decisions involve choosing a particular task or option 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

Continuous Processes



Discrete Event Processes

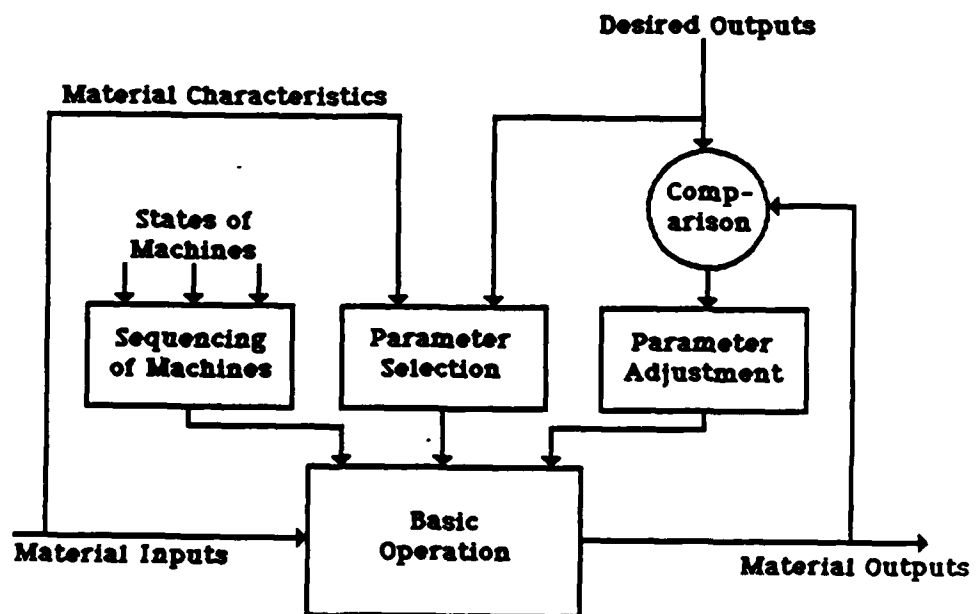


Figure 1

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 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. Based on the results of this study, we compare the manual and the highly automated process in terms of

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

To make these comparisons, we developed a framework to describe both the old and the new systems in terms of the information flow and decision-making required to set parameters and coordinate the timing of production tasks. The basis for the model is the assumption that each basic operation, such as welding two components together, can be described as a sequence of

decisions. Changes in process control are described in terms of changes in the kinds of decisions made and the ways the decisions are made.

A factory that is modernized as extensively as the one considered here changes in many ways. The changes in equipment were also accompanied by a major change in the design of the product produced. Management philosophies and practices changed in response to the international competitive pressure in the automotive industry. The number and mix of people required to operate the plant changed, as did the roles and responsibilities of employees throughout the entire workforce.¹ Changes in process control decision-making required to execute several key operations in one part of the plant constituted only one of many types of technological changes that occurred in this modernization to a computer-integrated system.

While the scope of changes considered here is relatively narrow, the advantage of our approach is that it clearly isolates and quantifies one of the ways in which a change in technology affected a manufacturing system. Since the types of basic operations performed in the body shop to assemble and weld a vehicle remained essentially unchanged, the execution of these operations could easily be compared in a "before and after" fashion. Also, the relative simplicity of the type of decision-making studied made the collection of data for the old and new process possible. We had to reconstruct the operation of the old system from available documentation and interviews with plant personnel. Collecting the data to do a "before and

1. See Miller and Bereiter (1985) for a discussion of the changes in the number and mix of people in this particular plant. See OTA (1984) for an overview of a broad range of impacts resulting from the transition to automated and computer-integrated manufacturing systems.

after" comparison of more complex and subtle decision-making such as production control and management practices would have been impossible.

Chapter 2

Motivation

This study was motivated by a basic conceptual problem initially encountered when we tried to describe the differences in the level of complexity in the manual and highly automated systems used in the plant. Plant and corporate personnel repeatedly claimed that the new system was substantially "more complex" than the old system. They justified this claim by comparing the old and new systems in terms of *units of hardware*, as shown in Figure 2. The new system had more robots, more automatic press welders, more microprocessor-controlled weld timers, and more programmable logic controllers. While this comparison clearly emphasized that the new system used substantially more computer-controlled equipment, it did not provide a basic understanding of *how* the new system was different and *why* it was more complex.

The idea of comparing the old and new systems in terms of requirements for information processing and decision-making was partly motivated 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 that collect information from other machines and 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 to carry out production operations would

Comparison of the Amount of Process Equipment in the Body Shop

		Pre- Modernization	Post- Modernization
Welding Tools	Manual Weld Guns	300	80
	Robot Welders (One weld gun per robot)	2	46
	Automatic Welders (multiple weld guns per machine)	2	52
Control Devices	Electro-mechanical Relay Control Panels	16	1
	Solid-State Programmable Logic Controllers	4	250
	Programmable Weld Timers	0	325

Figure 2

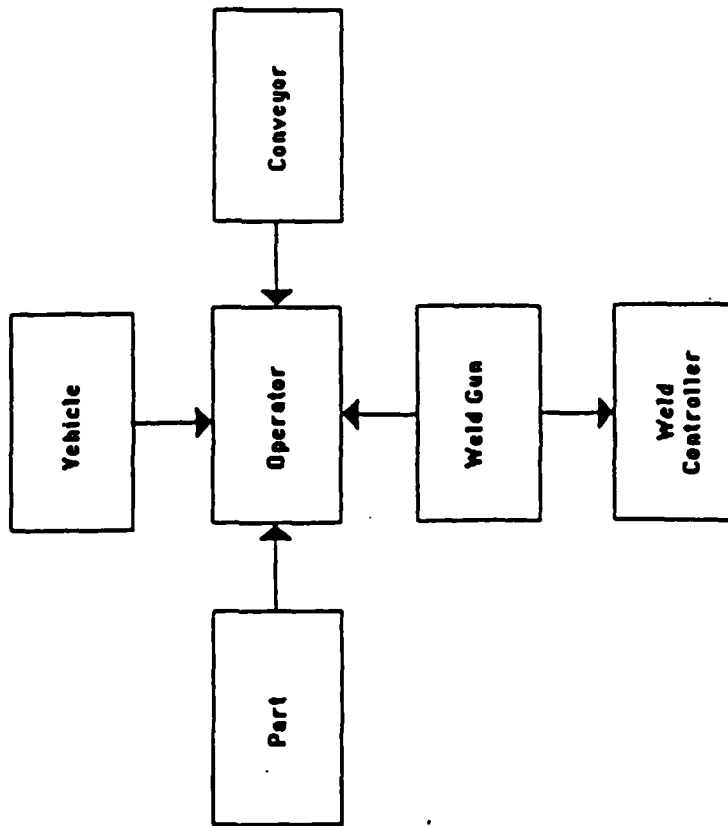
yield a more basic understanding of how and why the modernized production process was more complex than the manual process it replaced.

A second motivation for this type of comparison was an awareness of the growing trend in the manufacturing engineering and management literatures to conceptualize and analyze manufacturing systems in terms of information processing as well as material processing. Kutcher (1983) discussed the importance of considering transfers and transformations of data as well as transfers and transformations of material when analyzing manufacturing operations. The Manufacturing Studies Board (1984) discussed the challenge of "broadening from the historic interest in handling and processing materials to include the management of information that controls these processes." Skinner (1984) described the importance of understanding the factory as a data processing operation rather than an essentially physically operation. The U. S. Air Force ICAM program (1984) takes the view that "manufacturing in the ultimate analysis is a series of information processing steps." 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.

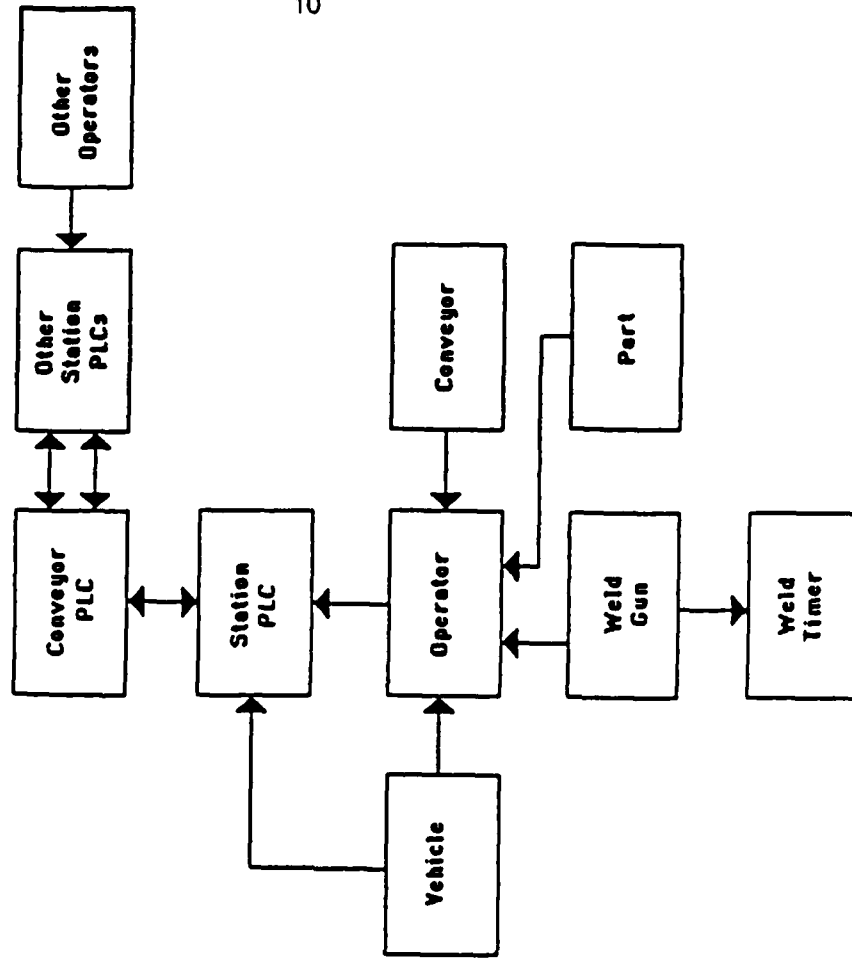
We started our analysis by trying to document the flow of information between processors by modeling each processor as a box and each information path as a directed arrow. It is clear from these figures, such as those shown in Figures 3, 4, and 5, that the information flow structure in the automated system is more complex in that there are more processors and more paths of information flow. In terms of documenting changes in *how* the information is processed, we found the diagrams to be of no more use than the comparisons of amount of equipment. We recognized a need to distinguish kinds of information and the timing of information flow, since each information flow path could

Paths of Information Flow Required to Execute Welding Operations Manually

Old Process



New Process

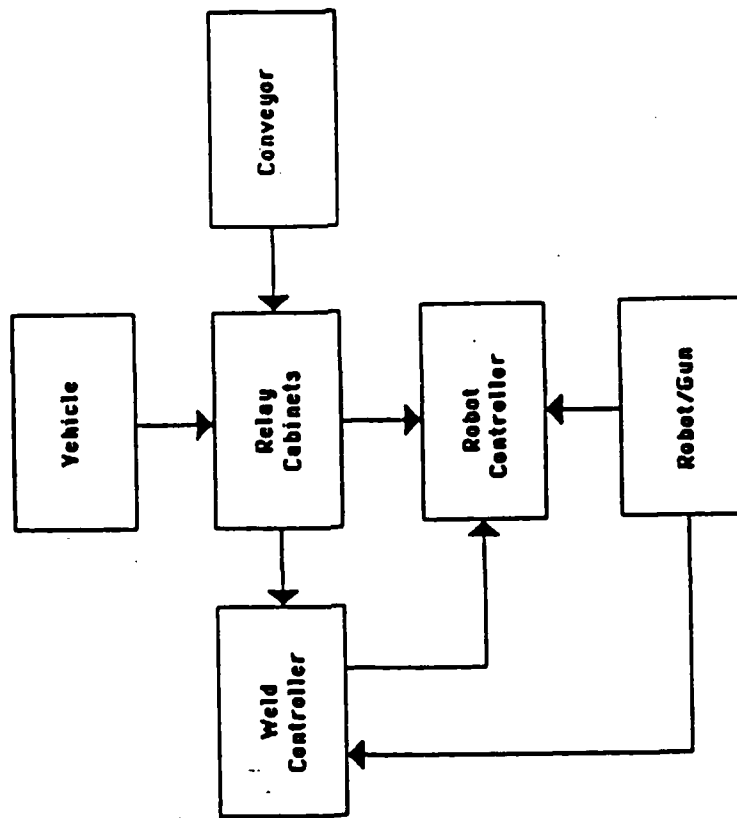


See Appendix I for explanation.

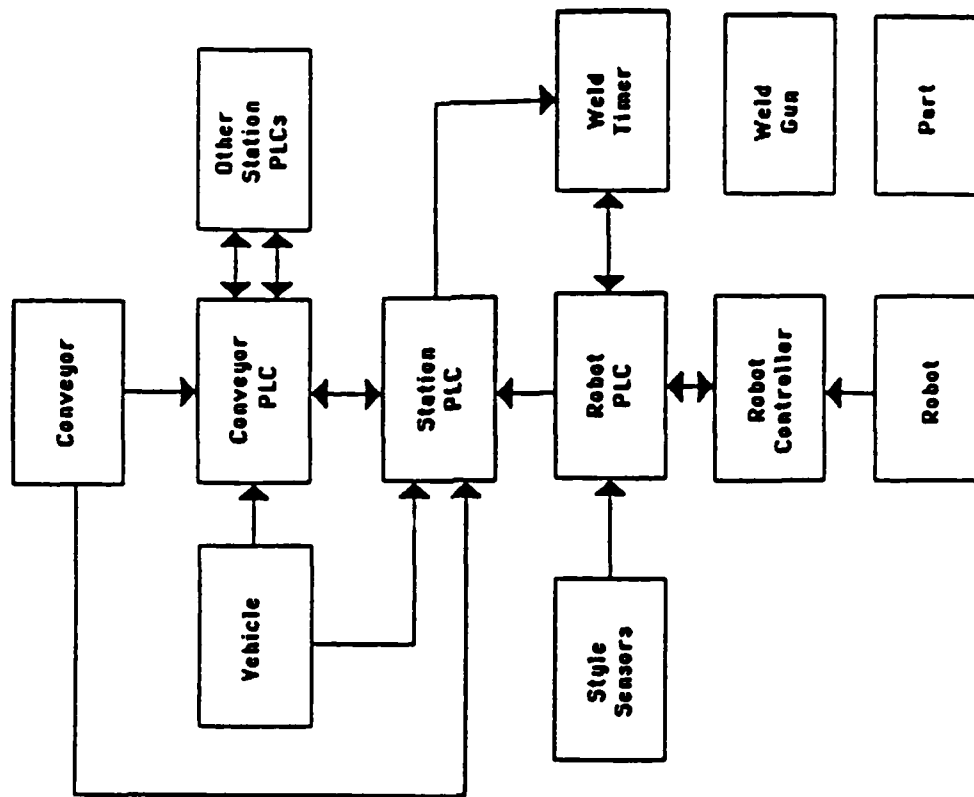
Figure 3

Paths of Information Flow Required to Execute Welding Operations with Robots

Old Process



New Process

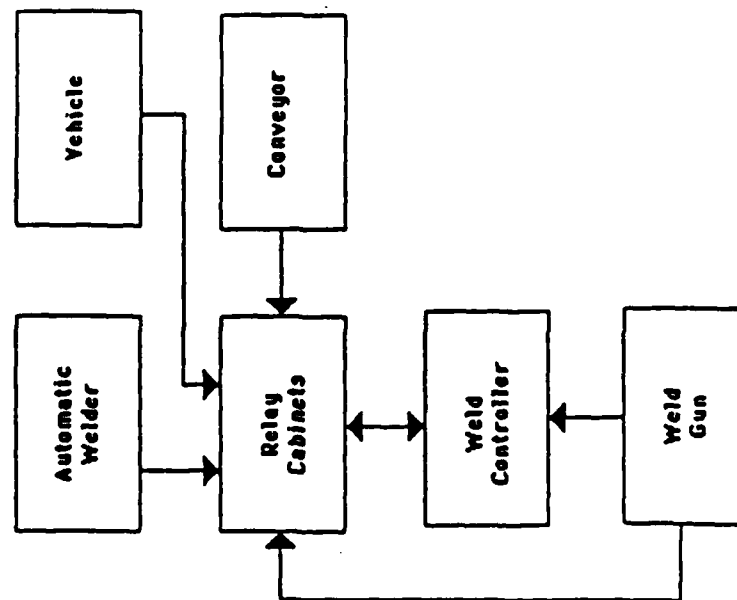


See Appendix I for explanation.

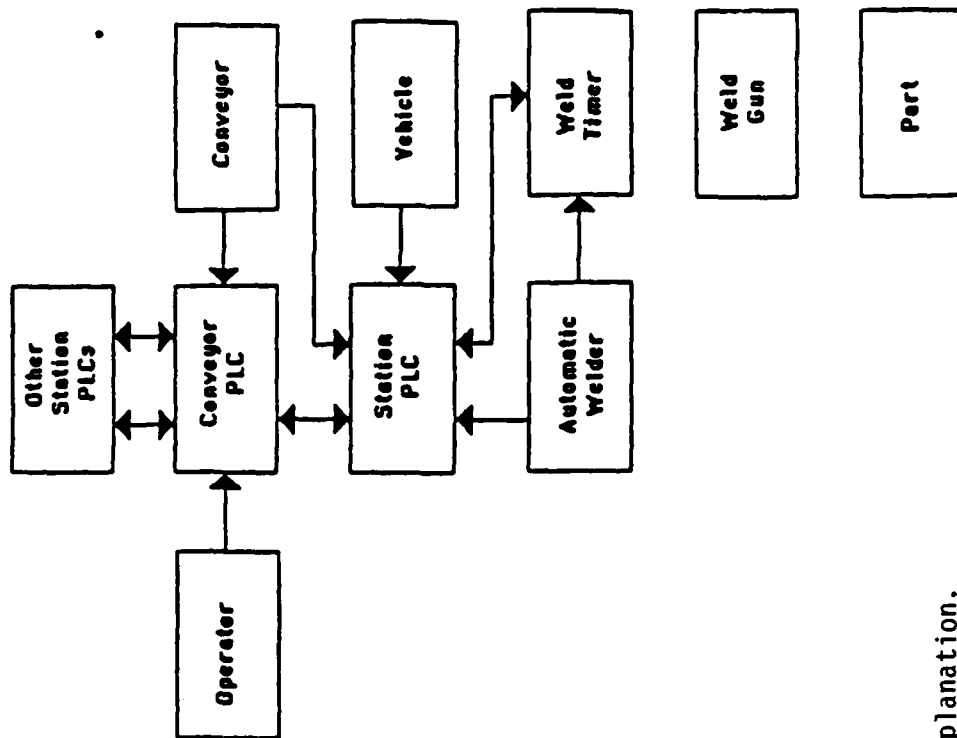
Figure 4

Paths of Information Flow Required to Execute Welding Operations with Automatic Press Welders

Old Process



New Process



See Appendix I for explanation.

Figure 5

only be used for certain kinds of information at certain points in the process. Also, we found a need to describe the transformation of information, which cannot be easily described with information flow diagrams that only describe the transfers of information.

We decided that a convenient way to describe process control was in terms of the decisions made and the information required to support each decision. Information could be identified by its content, as well as its source and destination. Timing could be included by describing a certain ordering of the sequences of decisions. The decisions themselves could represent the transformation of information.

Once we decided to compare the systems in terms of process control decision-making, we searched for a methodology to structure the data into a process model. The mathematical models used in traditional control engineering are well suited for describing and analyzing systems where the process being controlled is continuous in nature, and can be described by differential equations, such as processes for chemical processing or for continuous metal casting. However, these tools are not well developed for describing and analyzing a process that is discrete in nature and cannot be conveniently modelled in terms of continuous mathematical functions, such as the functions of the body shop in the vehicle assembly plant studied here.²

2. See (Kuo, 1982) for an overview of concepts and tools used to model the control of continuous processes. Nof and Williams (1982) show that the basic closed loop control model can be used to model and analyze the operation of many types of processes. However, when they apply the framework to model a system that is not continuous in nature, such as the functioning of a general purpose information system in an organization, the closed-loop feedback model is essentially used as a conceptual and a descriptive tool, rather than as a means to formally model how the system functions.

Engineering methodologies for analyzing discrete part production systems have emerged, but these models are designed for different classes of problems than the ones we are interested in. For example, models have been developed to do "time-space" simulations of individual machine cells in order to detect and eliminate physical crashes (Kretch, 1983). Yet, these models do not help in coordinating the information processing equipment to insure against *logical* "crashes" (in problems such as controller interlocks, where more than one processor tries to control the the same aspects of the same piece of equipment at the same time). Beck and Krogh (1986) have used modified Petri Nets to describe the decision-making concerning the sequencing and timing of process control actions in discrete event processes. In their model, a sequencing decision is made and the appropriate control actions are carried out as soon as the decision-maker receives all the necessary information indicating that the system is ready for the control action. Although such a model describes a significant portion of the control decision-making, it does not describe the decision-making concerning the selection of process parameters.

There are numerous management science methodologies for modeling and analyzing discrete parts manufacturing systems. However, many of these methodologies focus on maximizing or minimizing some aspect of product flow, such as throughput, work-in-process, or tardiness through a set of machines or workstations.³ Simulations based on these types of methodologies seek to identify problems such as bottlenecks in material flow, or to calculate system wide throughput or levels of machine utilization (Talavage, 1983; Pritsker, 1984). Because the focus of these types of methodologies is on workpiece flow

3. See (Buzacott, 1986) for an overview of management science related methodologies used to model and analyze production system performance.

across machines, they typically do not analyze the flow of information within machines required to make the product flow take place. A machine's operation is identified by parameters such as processing time and setup time. Thus, these methodologies do not provide concepts or tools for analyzing the information flow and decision-making required to coordinate multiple processors used to control the functioning within a single workstation.

Systems analysis methodologies have been developed to specify requirements for information flow in organizations (Colter, 1982). A systems analysis methodology specifically designed to describe information and material flow in discrete parts manufacturing systems is the IDEF family of models developed by the U.S. Air Force's Integrated Computer-Aided Manufacturing (ICAM) Program (1981). One of their models, the IDEFO function model, describes a process using five basic concepts: functions (processing activities), inputs (data or physical objects), controls (describe the conditions that govern the function), mechanisms (persons or devices that carry out the function) and outputs (information or physical objects). The IDEFO framework treats the function as a "black box." The model *does not* explicitly show how the controls govern the mechanisms in converting the inputs to outputs. Therefore, while one can use the framework to describe the flow of materials and information through a system, the framework is not well suited to describing and quantifying process control decision-making.

We could not find an existing methodology that we could easily use to structure our comparisons of the old and new system in terms of our definition of process control decision-making, so we developed our own framework to describe process control. This framework is described in the following chapter.

Chapter 3

Methodology for Comparing Process Control Decision-making

Although the two processes being compared are very different, they are still the same at certain levels. For example, 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 have also stayed the same: loading and assembling metal parts, welding, piercing, polishing and finishing metal, applying sealer, and transferring workpieces between conveyors.

For this study, 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 described each of these basic operations as a sequence of decisions. A decision in this context is a choice between alternatives. Some choices are related to sequencing and timing operations and some choices are related to selecting parameter and sequence options. Each decision involves three steps: receiving all the information required to make the decision, making the choice between alternatives, and performing the control actions associated with that choice. Information flow is a necessary part of the decision, for otherwise the choice is really non-existent, as in the operations of a fixed-sequence

transfer line. All decisions culminate in a control action, which can be a physical action such as firing a weld gun, or it can be the transfer of the decision choice to another processor. Figure 6 is a list of the decisions associated with each basic operation we studied.

In our framework, the types of process control decisions required to execute a basic operation remain basically the same across technological alternatives.⁴ 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, a robot, or an automatic press welder. 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 decisions are not considered in this study.

The primary differences between decisions in the old and new systems are related to the characteristics of the decisions. For each decision, we collected the following information:

- The decision being made (e.g., when to fire the weld gun)
- The purpose of the decision (synchronization, quality, or flexibility)
- The decision-maker (a human operator or a particular machine. For comparison purposes, we aggregated the decision-makers into two categories: human or machine.)

4. There are examples of decisions which are made in the new system which are not made in the old system. For example, in the old system, the conveyor moved continuously between stations and the decision "When to move the conveyor to the next station" was not made. In the new system, the conveyor stops at each station, and the decision of when to move the conveyor is part of the process control. In this case, the decision is included in the general process control framework, and it is disregarded in those alternatives where it is not used.

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

Figure 6

- The information required by the decision-maker to make the decision, the source of this information, and the way the information is acquired (e.g., limit switches signal to a programmable logic controller that a vehicle is in position to be welded)
- The control actions that occur once the decision is made (e.g., a microcomputer that controls weld gun fires the gun)
- The frequency of the decision (e.g., once per weld spot or once per station)

We categorized the types of decisions made according to three purposes: synchronization, flexibility, and quality. Synchronization decisions are those concerned with coordinating the 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 of which sequence of welds 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 the background behind the inclusion of the decisions is understood. For example, coordinating 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 to make 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 information requirements are the pieces of information needed by the decision-maker in order to make the decision. The information can come from human operators, other computerized processors, or sensors and limit switches used to detect the status of the workpiece or the process.

The control actions are the actions taken by the decision-maker once the decision is made. Most control actions are physical, such as the activation of actuators to move a robot arm or to fire a weld gun. Some control actions are information transfers rather than physical actions, such as the communication of a particular choice of parameters to a lower-level processor that controls physical actions.

Examples of the kinds of information collected for each decision are shown in Figure 7. This figure shows the characteristics of a particular decision: "Which sequence of weld spots to weld" for the automatic press welding operations in the old and new processes. Comparison of the old and new processes at this level of detail can also be informative. For example, the decision criteria changed from a simple decision based on one piece of information in the old process to a more complex verification and decision based on information from two independent sources in the new process. However, acquiring an understanding of the changes in the process as a whole is difficult to obtain from an analysis of such details.

To summarize system-level changes, we put the basic operations into a system-wide framework for the entire production process. The following

Basic Operation: Automatic Press Welding
 Decision: Which sequence of weld spots to weld
 Decision Purpose: Flexibility

Old Process

Decision-Maker: Relay cabinet
 Information: What are vehicle style options?
 Source: spring switches
 How Information Is Acquired: Movement of springs
 as vehicle travels over them signals options of
 each vehicle to the relay cabinet
 Decision Criteria: Relay cabinet has stored in it a table
 that indicates which weld sequence is to be used for
 each set of style options
 How Decision Is Carried Out: Relay cabinet actuates
 automatic press welder to begin weld sequence
 Frequency: Once per station

New Process

Decision-Maker: Station Programmable Logic Controller
 Information: What are vehicle style options?
 Source 1: shift register on Conveyor Programmable
 Logic Controller
 How Information Is Acquired: Conveyor PLC updates
 its shift register each time it moves the
 vehicles forward to a new station, and sends
 the updated information to the Station PLC
 Source 2: proximity switches on automatic welder
 How Information Is Acquired: proximity switches
 are tripped when vehicle moves into
 position on automatic press welder. These
 switches signal the Station PLC
 Decision Criteria: Station PLC compares redundant
 information from both sources. If the information
 do not agree, Station PLC signals an error to the
 conveyor PLC and shuts down. If the information
 agree, station PLC has programmed in it a table
 that indicates which weld sequence is to be used for
 each set of style options
 How Decision is Carried Out: Station PLC actuates
 automatic welder to move into position and instructs
 the weld timer of weld parameters for each weld spot
 Frequency: Once per station

Figure 7

information was collected for each of approximately 30 supervisory areas in the body shop:

- The name of the each part that is loaded
- The product options that affect operations
- The total number of stations and the portion of these stations whose operations are affected by product option choices
- The basic operations carried out and the number of times each basic operation is carried out
- The number of unit operations
- The number of programmable machines
- The previous operation
- The next operation

The information related to the basic operations was used to calculate the total number of decisions made in producing the vehicle body. The remaining information was included so that the same model could be used as a documentation technique to describe the sequences of operations.⁵

This framework is hierarchical in nature, as shown by the model overview in Figure 8. In summary, the body shop production process is broken down into several supervisory areas, which are summarized by information on the

5. When the system was primarily manual, the complete sequence of operations was documented by describing the flow of workpieces between people and the operations these people perform. When many of the operations became automated, the industrial engineering department found that documenting only manual operations left major gaps in describing the sequence of operations. We collected additional information to provide the industrial engineering department with a more complete description of the process.

Descriptive Framework

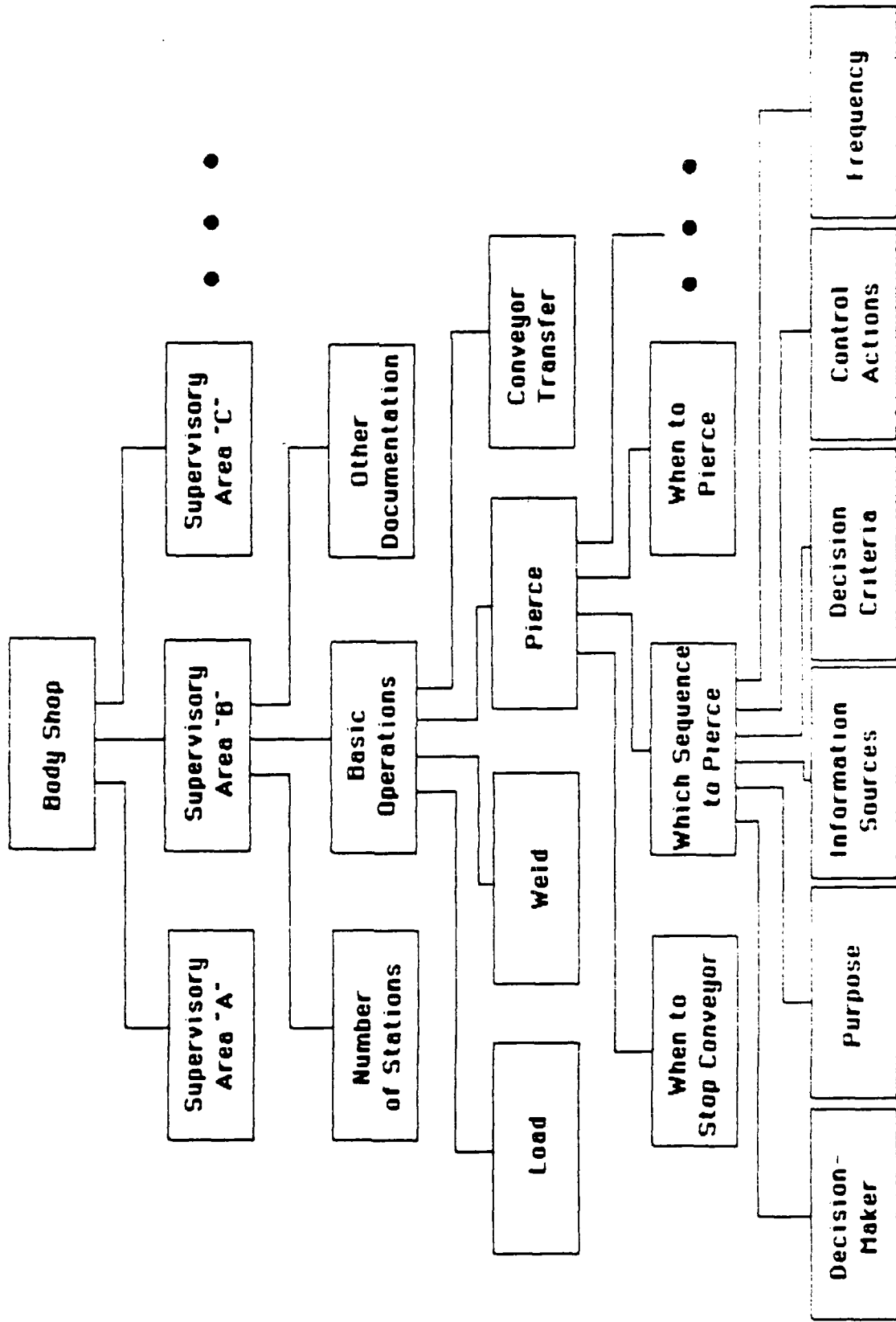


Figure 8

placement of that area within the process, and equipment at that area, and the number of times each basic operation is performed at that area. Each basic operation is described as a set of decisions. Some of the attributes of each decision contained in the framework include the decision-maker, the decision purpose, and the frequency of that decision (e.g., once per vehicle, once per weld spot).

3.1 Data collection

Most of the effort spent in designing and completing the process control framework for the specific plant studied was spend acquiring, documenting, and verifying knowledge from experts. Through extensive conversations with system experts, we distilled what we thought was a complete set of decisions and supporting data for each part of the process. We documented the information collected, then returned to those same experts and to other experts for verification and clarification.

This process is termed "knowledge acquisition" or "knowledge engineering" by researchers in the field of artificial intelligence who are interested in embodying expert knowledge into knowledge-based computer systems. These researchers recognize that the process of knowledge acquisition is the key to building useful expert systems. Yet it is one of the most inherently unstructured, patience-stretching parts. Feigenbaum (1977) suggested that "knowledge engineering" is the principal bottleneck in the development of expert systems. Buchanan et. al. (1983) attribute this bottleneck to communication problems and to the difficulty of structuring the expert's domain knowledge and formalizing the domain concepts. There is a literature on task analysis, a form of knowledge acquisition that addresses the analysis of the ways people decompose complex problems into simpler components on which

to base decisions. According to Melone (1986), literature describing the specific activities in task analysis is sparse.

The process of data collection was iterative and relied on data from process documentation and interviews with many plant personnel including process engineers, industrial engineers, maintenance personnel, and machine operators. Since we began the study shortly after the startup of the new system, we were forced to rely on documentation and the memories of plant personnel in describing the old system. Since the old system had been in full operation until only a few months before we began our analysis, and it was relatively simple from a process control perspective; the people interviewed claimed to have a clear recollection of process details. In describing the new system, we found documentation to be incomplete and inadequate. We relied principally on the expertise of a few process engineers who had installed and debugged the new system. We also had the advantage of being able to physically observe the new production process and interview operators and maintenance personnel on the shop floor.

3.2 Comparison of the manual and computer-integrated systems

Simple measures of changes in process control brought on by the modernization are the total number of decisions executed per vehicle body, categorized by decision-maker and decision purpose. Quantification of the total number of decisions allows analysis of the differences in the amount of information processing involved in producing a vehicle body in the manual and computer-integrated processes. Categorizing the results by decision purpose allows analysis of differences in the kinds of decisions being made. Categorizing the results the decision-maker as either human or machine allows analysis of the division of process control responsibility between humans and

machines. Breakdown by both decision-maker and decision purpose allows analysis of the kinds of decisions that are being automated and the kinds of decisions that are still principally the responsibility of humans. The calculations take the following form:

$$A_{ij} = \sum_k B_{ijk} n_k + \sum_k C_{oijk} S_{ok} + \sum_k C_{ijk} S_k$$

where A_{ij} = the total number of decisions made by decision-maker
i for purpose j

B_{ijk} = the number of decisions per unit operation of basic operation
k, made by decision-maker i for the purpose j

C_{oijk} = the number of decisions per station with options
that performs basic operation k, made by decision-maker i for
the purpose j

C_{ijk} = the number of decisions per station without options
that performs basic operation k, made by decision-maker i for
the purpose j

n_k = the number of unit operations of basic operation k
(e.g., the number of weld spots)

S_{ok} = the number of stations that perform basic operation k
when options are taken into account

S_k = the number of stations that perform basic operation k
when options are not taken into account

i = the decision-maker

j = the decision purpose

k = the basic operation

The decisions made for each unit operation (e.g. at each weld spot) are counted in the first summation term. The decisions that are made only once per station (e.g. when to move the conveyor into position at that station) are counted in the second and third summation terms. The basic operations at some stations are affected by vehicle style options (e.g. if the parts loaded at a particular station depend on vehicle style options, then the processors at the station must decide which parts to load). The second summation term counts the decisions made at stations where style options affect decision-making. The third summation term counts the decisions at stations where style options do not affect processing. The results of those calculations are discussed in the next chapter.

Chapter 4

Results and Conclusions

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

Figure 9 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, except that decisions associated with conveyor stops have been categorized separately because they are noteworthy in the following discussion.⁶ The total number of process control decisions required to execute the four basic operations studied nearly tripled (from 6142 to 17,361). This increase is the result of the basic operations being executed more times, as well as more decisions per basic operation.

6. The decision "When to move the conveyor to the next station" is part of three of the four basic operations analyzed: loading, welding and piercing.

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 1,300 to over 3,000, 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 changes in both the size and design of the vehicle produced. Since vehicle produced in the new system was larger, it required more parts to be loaded and more weld spots to join parts.⁷ Increases due to the execution of more decisions per basic operation are due to the change in the nature of the process automation.

To determine the fraction of the increase due to the change in vehicle design versus the fraction due to the change in the nature of the process, we consider the number of decisions that would have been required to execute the basic operation for the new vehicle using the old process technology. For this hypothetical situation (new vehicle, old process), 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 is 73 percent of the total change. Thus, about three quarters of the increase is due to the fact that more basic are performed in the new system, and about one-quarter of the increase is due to a change in the nature of the process.

7. 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. Also, 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.

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

Figure 9

Increases in the number of times the vehicle body is transferred 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 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 in and out of accumulators is controlled automatically. This change modularizes the body shop to allow the movement of parts through each section to be controlled independently. The primary benefit of this change is that each major conveyor line can run independently of the others. A breakdown of one conveyor line does not necessarily halt the movement of parts on the other lines. The capability to control the transfer of the workpiece between modularized conveyors is an important requirement needed to replace the sequential flow of products by parallel flows and variable routing depending on demand patterns, and availabilities of parts and machines.

The remaining 27 percent of the increase is due to changes in the amount of decision-making involved in performing each basic operation. The use of programmable control is most responsible for this change. Decisions that were not technically or economically feasible to execute in the old system became practical to execute 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 the (human or machine) operators to follow the moving vehicles in order to perform the part loading and welding operations. While decision-making concerning 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.

The programmable control made it possible to make some decisions frequently in the new computer integrated system that were made only rarely in the old system, and this contributed to an increase in the number of decisions made per basic operation. An example is the selection of the 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 chose the 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, efforts were made by design engineers to minimize the number of situations where it was necessary for one operator 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. 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.

4.2 Changes in the types of decisions being made

Figure 10 shows change in the number of process control decisions required, expressed in a different way to show changes in the types of decisions being made.

Changes in The Types of Decisions

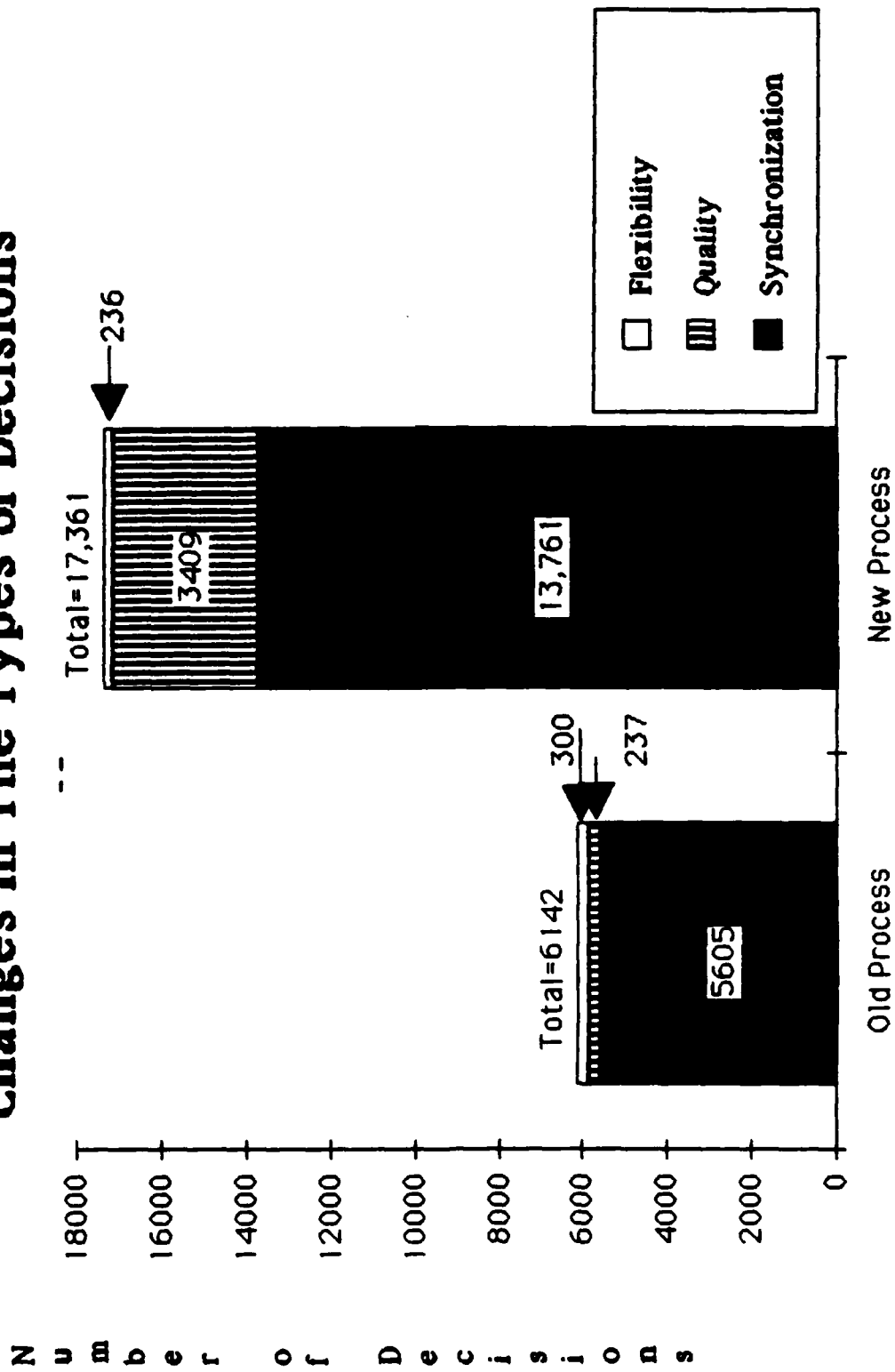


Figure 10

As a result of the modernization, the number of synchronization decisions more than doubled from 5605 to 13716. However, the relative proportion dropped from 92 percent to 79 percent. Almost all of the synchronization decisions in the new process (89 percent) are for the synchronization of the machinery used in robotic and automatic welding. Only one percent 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 four percent of the total in the old process to 20 percent in the new process. Almost all of the quality related decisions (89 percent) are for selecting weld parameter schedules for individual welds. Only three percent of the decisions are for controlling 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 five percent of the total number of decisions now account for only one percent. The decrease in the execution of 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 set of vehicles produced in the new process is much more uniform, 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 because of the difficulties of building automated systems to produce a variety of product options? While we do not know, we point out that the technological difficulties of building automated systems that can produce variations in the product mix are well recognized by researchers of factory automation.⁸

Much of the current discussion of computerized process control focuses on increasing flexibility and its economic implications.⁹ 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, but not necessarily when compared to principally manual systems, since human sensing and information processing capabilities make people the most flexible "production technology" available. Given that 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.

8. (Solberg et. al., 1985)

9. (Abernathy, 1978) and (Ayres, 1984).

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

Figure 11 shows the increase in process control decisions expressed so that changes in the division of process control decision-making responsibility between human operators and machines is highlighted.

Overall the proportion of process control decisions per vehicle made by humans dropped from 73.6 percent of the total to only 8.3 percent. This indicates a shift from primarily manual process control to primarily automatic control. The proportion of synchronization decisions made by humans dropped from 71.2 percent to 7.9 percent. 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 percent. Apparently, significant portions of decision-making relating to parameter selection and precision in positioning can be automated. The distribution of flexibility decisions shifted from nearly all human to a 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.

4.4 Conclusions

The motivation for the 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. One contribution of the research is a framework for comparing the old and new system in terms of the process control decision making required to execute a set of basic operations which were

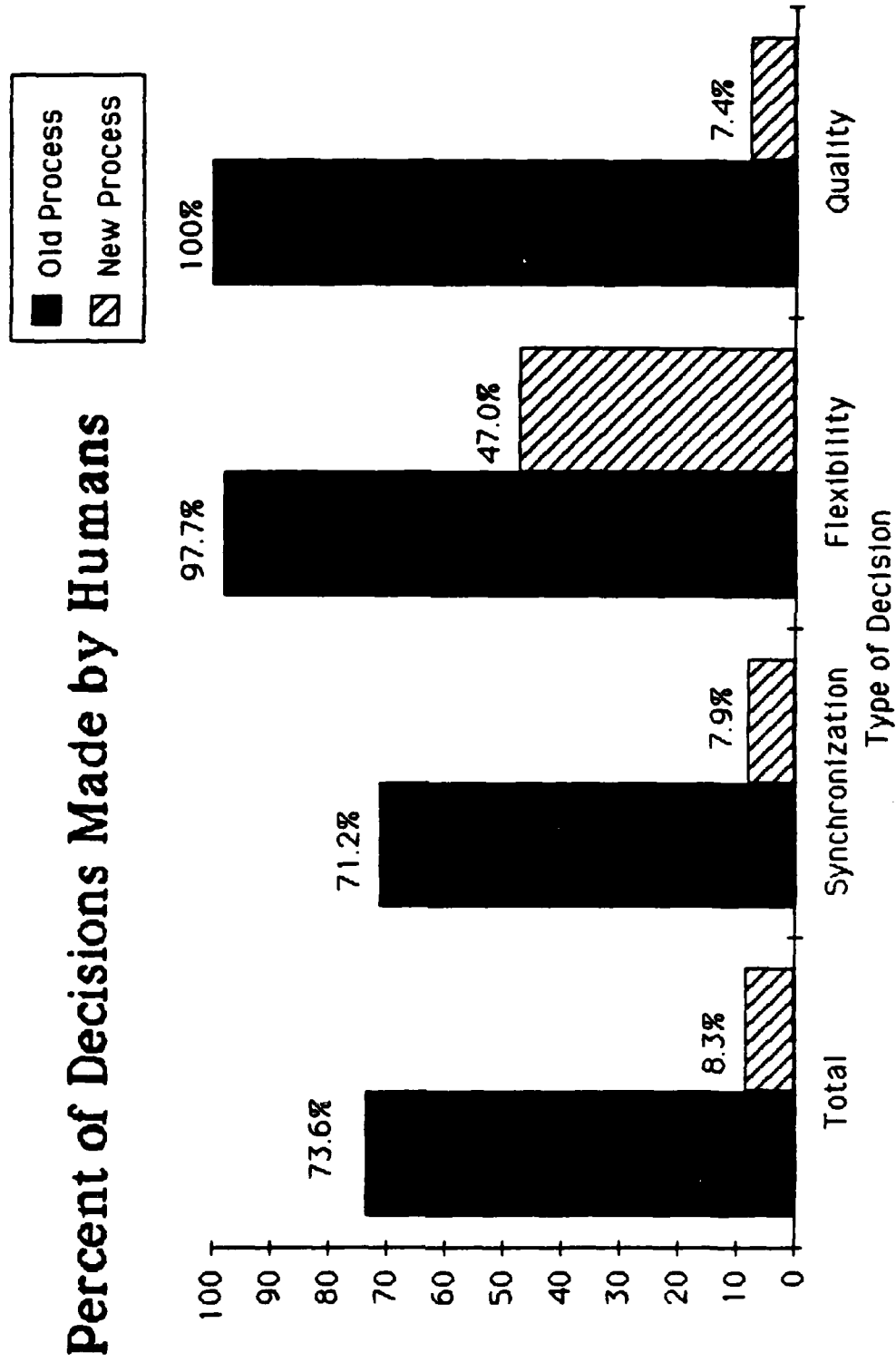


Figure 11

common to both systems. 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 functioning of the old and new process in a common framework, despite the differences in technologies used to execute the basic operations.

A second contribution of the research is the comparison of the amount of process control decision making required to assemble and weld a vehicle body. 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 so large and the system would have been so difficult to debug, maintain, and modify that it would have been so complicated, it would be practically impossible to achieve the same capabilities. Thus, the new form of programmable control, in conjunction with the automation, has made it possible to perform more operations and more complex operations in a given size facility.

The comparison of the types of process control decisions made reinforces the point 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) compared to the old system. Quality related decisions increased by the largest relative proportion, from four percent of the total number of process control

decisions in the old system, to nearly 20 percent in the new one. Management claimed that one of the major motivations for modernizing to programmable forms of automation and control in the body shop (and the plant in general) was to achieve a higher level of quality. This analysis gives some insight into why higher levels of quality for welded vehicle bodies would be realized.

A surprising result was that the number of process control decisions related to selecting options based on alternative product configurations (flexibility) actually decreased. It is not known whether this is the result of a reduction in the need for flexibility in vehicle body styles, due to the changed product mix, or due to limited capabilities of the technology to deal with an increase in product alternatives, especially in a process such as vehicle body welding where a lot of special tooling and fixturing is required to achieve very precise dimensional tolerances.¹⁰ In the one plant studied, the computerized control is not being used as extensively as one might expect to increase flexibility in the body shop. Primarily, the equipment is 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 the level of flexibility was not achieved (or might not have been a goal) in this particular manufacturing system, the increased ability to automate decisions to control synchronization and quality

10. 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.

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, of individual stations, and of 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 process 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 the building block capabilities are in place to move towards 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 amount of process control decisions made. This should provide some appreciation of 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 in addition to all of the other requirements. While some of the capabilities demonstrated in this example show that we are, in fact, moving closer to the reality of production processes that can produce a range of product configurations at high speeds (i.e., flexible mass production), the example also suggests that such a system would be even more complex than the one studied here. Given this system took nearly a year to "start-up,"¹¹ an even more complicated system requiring much more extensive process control decision making would be a formidable technical and managerial challenge.

11. See Miller and Bereiter (1985).

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Appendix I

Explanation for Figures 3, 4, and 5

These figures show the paths of information flow involved in performing three types of welding in the old and new processes. The arrows point in the direction of information flow. Each arrow originates at an information source and terminates at a decision-maker. At first glance, it is clear that the new process has more sources of information, more decision-makers, and more paths of information flow than the old process for all kinds of welding.

Figure 3

The principal decision-maker for manual welding in both the old and the new processes is the human operator, who collects information concerning the status of the process in order to coordinate the synchronization of his welding operations. Timing the firing of the weld gun after the operator squeezes the trigger is controlled by a weld controller in the old process and a modernized weld controller called a weld timer in the new process. In the new system, a series of programmable logic controllers (PLCs) controls the stopping of the conveyor at each station. Nearly all (93 percent) of the welding operations in the old process were manual, whereas only six percent of the welding operations in the new process are manual.

Figure 4

The decisions are distributed between several decision-makers in the robotic welding in the old and the new processes. The primary decision-makers in the old process were the relay cabinets for station-level coordination

between machines, the robot controller to control robot movement and squeezing of the weld gun, and the weld controller to control the timing of the firing once the robot triggered the weld gun. In the new process, the robot controller and a PLC (the "robot PLC") coordinate the timing of the triggering and the choice of weld parameters and sequences, the weld timer synchronizes the timing of the gun firing, and a set of PLCs coordinate the timing of the conveyor stops. Only 2 robot weld stations accounted for three percent percent of the welds in the old process, whereas 29 robot weld stations account for 27 percent of the welds in the new process.

Figure 5

In the old process, relay panel controlled the movement of the machinery and the weld controller controlled the firing of the weld gun. The decision-making is much more distributed in the new process, in which a PLC controls movement of the machinery, a weld timer controls the firing of the weld gun, and a set of PLCs coordinate to move the conveyor between stations. Two automatic press welding stations accounted for five percent of the welding operations in the old process. In the new process, 48 automatic press welders account for 67 percent of the welding.

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166 result of the modernization, the amount of process control decision-making nearly tripled, the emphasis on decisions to meet product quality specifications increased, and the emphasis on decisions related to flexibility in handling a variety of product options decreased. Decisions relating to meeting product quality specifications and to timing and synchronization of tasks were mostly taken on 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 percent of the decisions required to assemble and weld a vehicle body in the principally manual system, humans made fewer than ten percent of the comparable decisions in the automated system. The framework used to produce these results provides a general approach for comparing levels of technological sophistication in manufacturing systems in terms of the amount and type of information processing.

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