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PROTOTYPE DIRECT NUMERICAL CONTROL
SYSTEM EVALUATION

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Milestone Report

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BDX-613-1585 (Rev.), UNCLASSIFIED Milestone Report, Published
June 1977

Prepared by G. L. Finlay, D/821, under PDO 6984718

Evaluation results from a four-machine prototype Direct Numerical Control (DNC) system that has been constructed at Bendix Kansas City indicate both economic and operational advantages over the present NC systems. The behind-the-tape-reader interfacing approach that was used has proven to be the most suitable interfacing method for Bendix machining operations. The prototype DNC system is being modified and expanded into a production system having a potential for more than 40 continuous-path NC machine tools.

WPC-dvh

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SUMMARY

This project was initiated to study the publicized advantages of Direct Numerical Control (DNC), and to determine whether its use would prove beneficial to machining operations at Bendix Kansas City. As a result of the initial investigation, the recommendation was made that a four-machine prototype DNC system based on the most appropriate interfacing method be developed. An available Control Data Corporation (CDC) 1700 computer was chosen as the DNC computer, and a behind-the-tape-reader (BTR) interfacing approach was selected. A detailed evaluation then was made of the prototype system.

CDC was chosen initially to provide the equipment required to interface the existing NC equipment with the DNC process-control computer. A two-axis Ex-Cell-O Model 920 mill and a three-axis Ex-Cell-O Model 982 bridgemill were interfaced to the CDC 1700 computer. The first production part was machined under DNC computer control in April, 1971, and on August 13, 1971, these two machines were cycled simultaneously for the first time under DNC control.

In December, 1973, and January, 1974, the second two machines (a three-axis Ex-Cell-O Model 921 mill and a Model 4025 American lathe, respectively) were connected to the DNC system. In the time that had elapsed between the purchase of the two sets of equipment, CDC had developed a standard line of transmission hardware which offered a considerable cost-savings potential for a production system. Because of these potential savings, the decision was made on the second set of interfaces to change to the standard equipment in order to evaluate the new approach.

To evaluate the reliability of the transmission system and the interface equipment, maximum utilization has been made of the DNC capabilities for both production and development operations. Over 16,300 operating hours have been accumulated under DNC, including 3,500 hours of two-machine and 800 hours of three-machine simultaneous operation. No transmission errors have been experienced, and no time has been lost because of interface problems with the new units.

The collection of data associated with machine usage and downtime is an additional capability which is offered by connecting a computer to the machine tools. This data can be compiled into Management Information System (MIS) reports for analysis to improve machine utilization. CDC 1700 computer software has been prepared for collecting the data, and CDC 6600 computer software has been prepared for analyzing the data and preparing the preliminary reports. The final evaluation of this capability will be conducted upon the completion of pending software modifications.

The evaluation of the tape-editing capability was begun in January, 1974. Since that time, 77 tapes have been edited for optimization, correction of errors, fine-tuning data, incorporation of product-design changes, correction of cutting-tool problems, creation of rework tapes, process improvements, or changes to overcome fixture problems. The 14 tapes which were optimized have resulted in an average cycle-time reduction of 46 percent and an average standard-hour reduction of 45 percent.

Several manufacturers and users of DNC equipment were contacted to aid in a re-evaluation of the available commercial systems, and some of the other ERDA contractors were contacted for an evaluation of the new systems they were developing. Based upon the information received during these visits, the users of DNC have found that its capabilities significantly improve their operations, and most of them are planning for expansion. The evaluation of both commercially available and ERDA-developed systems indicates that all of these systems would require considerable modification to meet the editing and MIS requirements established for DNC operation at Bendix Kansas City before they could provide the same capabilities as the Bendix-developed prototype system.

The potential savings offered by the system were analyzed. Based on a cost of \$15 per standard hour saved (the 1974 direct production labor charges), the analysis, which included escalating and projecting the savings over the remaining scheduled parts, indicated that the 14 tape optimizations which have been performed have saved Bendix Kansas City approximately \$72,000. If these changes had been made when the tapes were first put in work, the saving would have amounted to more than \$92,000.

To determine the potential savings from the system due only to optimization, an extrapolation was made assuming that the 33 existing machines that are candidates for DNC were connected to the system instantaneously. Based on 455 active jobs on the 33 machines, the escalated potential saving is approximately \$214,000 for the existing tape operations. The future on-going savings, based on 440 new tapes that were made last year for the 33 machines, would amount to approximately \$456,000 (escalated) each year due to tape optimization. These savings would be spread out over the life of the production parts rather than being realized in the year of optimization.

The savings described, plus those realized through reduced setup time, are the potential DNC system savings that can be identified and assigned a dollar value. Other advantages upon which a dollar value cannot be placed include reductions in tape-handling problems, increased programming efficiency, increased machine-tool utilization, and processing improvements.

Based on the results of the operation of the prototype system, the decision has been made to expand the present Bendix prototype DNC system to a total complement of 41 NC machine tools. This expansion was planned to occur during fiscal years 1975 through 1979 at a projected cost of \$934,000 (escalated); however, a proposed price increase was received from CDC that would increase the cost by more than \$141,000. Because of this and earlier increases, the prototype study was extended to evaluate the use of a minicomputer as an interface in an attempt to reduce capital equipment costs.

The results of the further evaluation indicate that a minicomputer is a suitable replacement for the CDC equipment as the BTR interface between the CDC 1700 computer and the Machine Control Unit (MCU). No capabilities will be lost by the replacement and, based on the use of a PDP-11/05 minicomputer, projected capital equipment expenditures would be reduced by more than \$490,000. Because of these results, the CDC interfacing approach has been dropped, and an appropriation package has been initiated for the purchase of minicomputers to connect 16 machine tools to the production DNC system. Implementation is now planned to begin in fiscal year 1976.

Work yet to be accomplished on this project includes determining the most useful format for the MIS information to aid in optimizing machine utilization, and completing the MIS evaluation.

DISCUSSION

SCOPE AND PURPOSE

Direct Numerical Control (DNC) is a system for the manufacture of parts which uses a remotely located computer for the direct control of numerically controlled (NC) machine tools. Tape data is stored at the computer and, upon request from the interface equipment, the information is transmitted to the machine tool for execution.

This study was initiated to investigate the publicized advantages of DNC, and to determine whether the benefits would prove applicable to manufacturing operations at Bendix Kansas City. Included as a portion of the initial project was an evaluation to determine the advantages and disadvantages of the different approaches to DNC. After the applicability to Bendix operations had been established, the further evaluation of DNC consisted of the following endeavors:

- A determination of which basic interfacing approach appeared to offer the greatest advantage;
- The development of a four-machine prototype system for the study;
- Operation of the machine tools under computer control to determine the reliability of the transmission system;
- Assessment of the editing capability through its utilization;
- The gathering of data by the DNC computer for use in providing preliminary information on machine utilization;
- A reappraisal of both commercially available and ERDA-contractor-designed interfacing techniques;
- Discussions with commercial users of DNC systems regarding the benefits; and
- A determination, on the basis of all information obtained, of whether the apparent benefits warrant the expenditure required for DNC implementation and, if so, whether the initial approach chosen for the prototype system offers the most substantial advantages.

This report discusses the evaluation, the findings, and the rationale for implementing DNC on a production basis at Bendix Kansas City.

PRIOR WORK

A report on the results of the investigation to determine the various approaches to DNC and their advantages and disadvantages was made in May, 1971.¹ That preliminary investigation concluded that Bendix could benefit from the implementation of DNC and recommended that, of the three basic interfacing techniques available, the behind-the-tape-reader (BTR) interface should be used for the prototype system. Basic descriptions of the recommended prototype system and its potential advantages subsequently were published.²

ACTIVITY

Purchase of Initial Interface Units

After the decision had been made to continue the DNC evaluation with a prototype system using the BTR interfacing method, specifications were written assuming the use of an in-house Control Data Corporation (CDC) 1700 Process Control Computer as the DNC computer (Figure 1). A quotation from CDC for \$30,156, of which \$8,950 was design fees, was accepted, and the first two machine tools were connected to the prototype DNC system in April and August, 1971.

Three cables to the initial Machine Control Unit Interfaces (MCUIs) were required: a 16-twisted-pair shielded data cable; a 19-twisted-pair shielded cathode-ray-tube (CRT) data cable; and a CRT coaxial cable. In addition, cables were required between the CDC 1700 and CDC 6600 computers to provide for the planned Automatic Programmed Tools (APT) Source Editing capability.

Potential security problems for the initial system were overcome by an agreement that no classified tapes would be allowed on the prototype system. This eliminated the necessity for providing ferrous conduit protection for the prototype cables.

The first machine to be connected to the DNC prototype system was a two-axis Ex-Cell-O Model 920 mill (Figure 2). Prior to this installation, switches were added to each Machine Control Unit (MCU) to provide for the selection of either tape or computer operation (Figure 3). The installation of interface equipment on the first machine required approximately 860 man-hours to complete because of various design errors that required correction. With these modifications already made, the installation of the second interface on a three-axis Ex-Cell-O Model 982 mill required approximately 70 man-hours (Figure 4). The operation of the interfaces was described in detail in a CDC Engineering Specification.³

Figure 1. Control Data Corporation 1700 DNC Computer

Figure 3. Machine Control Unit Showing Tape/Computer Select Switch at Lower Right

The first production part to be machined under DNC computer control was completed on April 16, 1971, and on August 13, 1971, the initial two DNC machines were cycled simultaneously for the first time under DNC control.

Purchase of Two Additional MCUIs

Because of design problems associated with the first two interfaces, all electrical timing characteristics and relationships

Figure 4. Second DNC Machine: Ex-Cell-O Model 982 Mill
(Editing CRT is located at extreme left of photograph.)

between the tape reader signals for each new type of MCU added to the system had to be provided on succeeding interfaces. The necessary information was incorporated into the specification for additional interface hardware required to add an American Model 4025 NC engine lathe and an Ex-Cell-O Model 921 three-axis NC mill to the prototype system. A quotation was received from CDC for \$40,100 which established a cost of approximately \$12,000 to \$14,000 each for follow-up units and a design charge of approximately \$8,000 for the connection of new types of MCUs.

As an alternative to these higher costs, CDC presented information concerning a new system approach which offered a potential for reduced cost and increased reliability. This new approach used standard equipment which had been developed by CDC for other industrial applications, rather than the special-design, one-of-a-kind type of equipment such as the initial Bendix interfaces.

The approach offered the options for either buffered or non-buffered operation. The following anticipated advantages of buffered operation are some of those which were pointed out by CDC.

- Equipment is simpler and more standardized, thus making design changes and maintenance easier.
- Cable requirements are reduced.
- The computer capacity has a potential for more than the 20 to 24 machines initially estimated.
- Follow-up costs for additional identical MCUIs are lower.
- First-time engineering charges for new MCU types are lower.

Specifically, the potential savings would include the following items.

- Cable requirements would be reduced from a 3-cable bundle (one 16-twisted-pair, one 19-twisted-pair, and one coaxial cable) to a single 4-twisted-pair cable. The savings would be the reduction of cable and installation costs from an estimated \$15 per foot to \$5 per foot.
- The CRTs used in the computer room and at the machine-tool site would be teletype-compatible and would cost an estimated \$3000 each instead of \$4000.
- Maintenance would be simpler because standard circuit cards would be used instead of backplane wiring.
- Moving an MCUI from one type of MCU to another would require only the replacing of one circuit card instead of changing backplane wiring.
- Follow-up costs for identical MCUIs would be \$6,000 to \$10,000 per machine instead of \$12,000 to \$14,000 per machine.
- First-time engineering fees for interfacing new MCUs would be \$3,500 instead of \$8,000.

The prices quoted by CDC were \$45,100 for the nonbuffered system (including a \$20,000 one-time development charge) and \$58,170 for the buffered system (including a \$25,000 development charge). After the potential savings had been considered, the determination was made that the new system should be investigated. The specification then was revised to require that the next two MCUIs be redesigned to use the nonbuffered approach. This option was selected for the following reasons:

- It would permit an evaluation of all potential savings of the buffered approach except those due to an increased number of machines (these could be estimated);
- The cost of this system was only \$5000 more than the procurement of two follow-up MCUIs of the original design; and
- The later conversion of a production system from nonbuffered to buffered operation could be done with minimum risk and impact.

The major software impact was in changing from the original hardware to the new approach; reportedly, the change from one option to the other was small. The equipment costs to change from nonbuffered to buffered operation later were estimated to be \$5000 for additional development charges and \$8470 for a DNC buffered multiplexer.

During the fabrication of the equipment, CDC proposed some changes to the new equipment which would reinstate the echo-error-checking capability, make the software easier to prepare, and reduce the operation time. Although the incorporation of the planned changes would delay shipment for two months, the delay was approved after a study of the changes indicated that they would be beneficial.

The installation of the new DNC interfaces required approximately 320 man-hours and was much easier to complete than the first installation since only two design errors were encountered. Again, with this installation, unusual MCU reactions to special auxiliary functions which were encountered required special design considerations. The third and fourth machines, a three-axis Ex-Cell-O mill and an American lathe (Figures 5 and 6), were connected to the DNC system and put into production operation on December 3, 1973 and January 7, 1974, respectively.

Prototype System Utilization

During the study, maximum utilization of the DNC capabilities was made for both production and development operations so that the transmission system and interface hardware could be evaluated. Over a period of 4-1/2 years, the accumulated operational time under DNC control has been 16,384 hours, including 3,584 hours of two-machine and 862 hours of three-machine simultaneous operation (Appendix A). All of this operating time was performed without any transmission errors, thus proving the reliability of the transmission hardware, cabling, and technique.

During the same operational period, the DNC system was down for a total of 49 days: 6 days because of computer mainframe problems, and 43 days because of problems with the disk; the magnetic tape

Figure 5. Third DNC Machine: Ex-Cell-O Model 921 Mill

drives, and the interfaces. Ten days of the disk downtime were due to inadequate air conditioning; this will not be a problem when the computer is moved from its present temporary location to a new DNC computer room. Interface problems accounted for 14-1/2 days of the downtime and for the four parts that were scrapped on the system during that period. All of the downtime and scrapped parts occurred on the machines equipped with the original interfaces; no downtime or scrap has occurred with the new type of interfaces.

All downtimes were DNC-system downtimes only, since the backup capability offered by the tape reader permitted the machines to be switched to tape control for continued operation. The results of the system operation have substantiated the claims of increased system reliability due to the change to the new type of interfaces.

Figure 6. Fourth DNC Machine: American Model 4025 Lathe

Management Information System

The Management Information System (MIS) for the collection of data associated with machine usage and downtime is an additional capability that can be provided by connecting a computer to machine tools. The data can be collected both automatically and through operator inputs, and they can be used in the preparation of reports which can be analyzed to improve machine utilization. Through the use of a teletypewriter in each manufacturing area, manufacturing supervision can request and receive an up-to-date report on the activities of each DNC machine.

The operation of the MIS system is defined as follows.

- Collected data are stored in a Day File on the CDC 1700 DNC computer.
- Periodically, through INTERCOM, Day-File data from the CDC 1700 computer are automatically dumped to the CDC 6600 computer where they are maintained on-line for the preparation of partial-shift, full-shift, multiple-shift, daily, weekly, and monthly reports.
- To reduce the load on the DNC computer, teletypewriters are connected directly to the CDC 6600 computer which compiles the data into reports.
- Monthly, the CDC 6600 computer MIS data are dumped to off-line magnetic tape where a full year's information is stored. Reports developed from these data can be acquired only through a batch request to the Data Center.
- Year-old data are summarized and dumped to microfilm for permanent storage.

When the new style of interface was designed, the method for making manual MIS data inputs was changed from the use of thumb-wheel switches to the use of mutually exclusive pushbuttons (Figure 7). Instead of making 6 thumbwheel changes for each entry, the operator now is required to depress only a single button. Definitions of the 16 MIS input categories are provided in Appendix B.

If a manufacturing supervisor makes a request through the teletype, he can receive a summary report for all of the machines in his area showing 14 categories of machine activity (Figure 8). A breakdown of any category for any specific machine also can be provided by a request through the teletype. The breakdown of the MIS report categories is shown in Appendix C. If more detailed information is required, a complete print-out can be obtained from the Data Center.

Editing

From the earliest stages of the project, the greatest advantage of DNC was considered to be its tape-editing capability. This capability provides a means for immediate action to resolve problems concerning tape errors, cutting tools, stock removal, material variation, dimensional discrepancies, cutting rates, or lost time in the machining operations.

With the Bendix DNC system, the part programmer can make corrections by editing in either Mylar Image or APT Source. Mylar Image is data in the same form as normally would be found on

Figure 7. DNC Operator Panel

MIS PRØDUCTION SUMMARY REPØRT FØR D/821

24 HØUR REPØRT RUN DATE 04/02/74

REPØRT FØR FEB 6,74 AS ØF 12:00 PM FØR SHIFT ALL 22.5 HØURS

	ØPER	SETP	REWK	MIDT	MADT	TINC	TØDT	PRDT	GAGE	LØAD	FRØR	NØNP	MEFF	TDT
1	23.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.5	0.0	0.0
2	23.8	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	4.7	0.0	19.8	.1	0.0
3	2.0	7.9	0.0	0.0	1.5	.9	0.0	0.0	0.0	.1	0.0	21.6	.0	1.5
4	6.9	16.6	0.0	0.0	0.0	6.3	.3	.0	0.0	2.3	0.0	16.2	.3	.3

01 824 EXCELLØ 920 LATHE CAP. EQ. 33940

02 95 EXCELLØ 982 MILL CAP. EQ. 23754

03 20 AMERICAN 4025 LATHE CAP. EQ. 34954

04 93 EXCELLØ 921 MILL CAP. EQ. 34887

Figure 8. Typical MIS Production Summary Report

punched Mylar to which simple changes can be readily made by editing. Changes made to part geometry, cutting feedrates, and cutter size or motion normally require changes to the APT Source program. While Mylar Image editing can be accomplished through the use of only the CDC 1700 computer system, APT Source editing must be made through the CDC 6600 computer system.

The following capabilities are required to fully utilize the APT Source editing capability from portable CRTs at the machine-tool sites:

- Obtain access to an APT Source file on the CDC 6600 computer;
- Add, delete, or alter the Source file;
- Cause the newly created file to be executed through APT;
- Retain both the new Source file and the resulting postprocessor output file;
- Examine the resulting postprocessor output;
- Create a backup Mylar of the postprocessor output; and
- Transmit the postprocessor output from the CDC 6600 to the CDC 1700 system.

To perform these editing functions, several new computer programs and modifications to some of the existing programs were required for full operation.

The editing capability was put to use immediately after it became available in January, 1974. Since that time, the DNC editing capability has been used to edit 77 separate NC operations. In addition, the examination of six other tapes for possible optimization indicated that little or no benefit could be obtained by editing.

Of the 77 DNC edits that were performed, 69 were edited in APT Source while the other 8 were edited in Mylar Image. The time required for the 77 editing operations ranged from 1 hour to 2-1/2 days of elapsed shop time. This included all of the time the part programmer spent in the shop determining the changes to be made, performing the editing and its related functions, and observing at least one machine-tool cycle. These steps were repeated, as necessary, until the final tool path was satisfactory to the process engineer, the part programmer, and the concerned manufacturing personnel. The job which required 2-1/2 days involved nine separate runs through APT and the

resulting machine cycles in an effort to completely reprogram a problem milling operation. Despite the fact that the operation of the machine was interrupted to try the results of each edit, the production during those 2-1/2 days exceeded the normal production for the operation, since editing and the machining of a part under DNC can be done simultaneously. This capability for continuing machining operations permits taking advantage of intermediate improvements while further editing is being performed.

The 77 editing functions that were performed involved 16 different part programmers and 15 different process engineers. This is mentioned merely to emphasize the fact that no attempt was made to utilize an editing specialist; whoever was originally responsible for a particular job performed the required editing.

Initially, the greatest advantage of a DNC system was considered by Bendix personnel to be in its APT Source editing capability. This was contrary to most commercial approaches that used either special languages or only a Mylar Image form of editing. The APT Source editing capability was considered especially advantageous for the following four areas of use:

- The correction of tape errors;
- The optimization of tool path;
- The fine-tuning of data to bring parts into tolerance; and
- The immediate incorporation of product design changes.

Since implementation of the APT Source editing capability, not only have changes been made in these four anticipated areas, but four additional types of changes have been made:

- Corrections for cutting-tool problems;
- Creation of new tapes or tapes for rework;
- Process improvements; and
- Changes to overcome fixture problems.

The 69 APT Source edits that were performed can be separated into the eight categories described. A detailed breakdown of each category is given in Appendix D. Undoubtedly there are still other types of changes to be realized.

As each DNC edit is completed, a DNC Editing Analysis sheet (Figure 9) is filled in by the part programmer to provide data for later review and analysis, and to provide a record of how the

DNC EDITING ANALYSIS

TAPE # _____ (FINAL VERSION ISSUE) DATE ____/____/____
 PART # _____ OPERATION # _____
 EDITING TYPE: APT SOURCE ☐ ANALYST _____
 MYLAR IMAGE ☐ PROC. ENG. _____

PREVIOUS ISSUE ACTUAL TRAVELER STANDARD HOURS _____
 CYCLE TIME _____
 FINAL EDITED VERSION ACTUAL STANDARD HOURS _____
 CYCLE TIME _____ REVISED STANDARD HOURS _____

INITIAL REASON FOR MAKING CHANGE: _____

NUMBER OF CHANGES OR RUNS TO ARRIVE AT FINAL VERSION

Thru APT _____
 Data Transfers _____
 Machine Cycles _____

ANALYST ELAPSED SHOP TIME _____

Estimated elapsed time to make same or similar modifications by normal tape request methods. _____

----- TYPES OF CHANGES MADE:

☐ Feedrates (+ or -) ☐ No. of passes (+ or -) ☐ Remove air cuts
☐ Cutter config. ☐ Surface feet ☐ Positioning moves
☐ Cutter comp. ☐ Depth of cuts (+ or -) ☐ Other (explain) _____

PROBLEMS WHICH WERE INCURRED (Machining or Computer orientated).

☐ Computer down temporarily (6600 or 1700) ☐ Machine tool failures
☐ Data transfer problem ☐ CRT generated APT errors
☐ Slow computer response ☐ Other (explain) _____
☐ Intercom replies not complete _____

NARRATIVE OF CHANGES ON BACK OF SHEET.

Figure 9. DNC Editing Analysis Sheet

system was used, what types of changes were made, and what types of problems, if any, were encountered.

The value of the editing capability can be seen most readily in the tapes that were optimized. The machining time that was saved can be calculated by comparing the actual machining time before and after optimization. While editing results in other areas are somewhat intangible and extremely difficult to express in dollar amounts, they are no less significant. Editing capabilities have already proven helpful in the following situations.

- The operator can switch quickly from one tape issue to another to overcome machining problems.
- Tape errors can be corrected while machine operators are at lunch or completing setup of the machine.
- Part programmers can maintain thought continuity without having to review a job before checkout or making additional program changes.
- Machine downtime caused by waiting for revised tapes is reduced.
- A rapid edit and retrieval capability permits the part programmer to make successive changes until the operation is improved to its optimum.
- Improvements to manufacturing processes can be made easier and more frequently, since the results of a change can be viewed immediately instead of delaying production or gambling that the parts will not be completed before the revised tape is received.
- The system is extremely beneficial for use with development parts for which the configuration is in a state of evolution.

Reappraisal of Commercial and ERDA-Contractor-Designed Interfacing Techniques

Commercially available DNC systems were re-evaluated to determine whether the original system that had been selected was still the most advantageous system for Bendix Kansas City requirements. Also, since some of the other ERDA contractors were developing their own DNC systems, these approaches needed to be considered. The necessary evaluations were made by visiting some of the manufacturers and users of commercial DNC systems and some of the other ERDA contractors.

The re-evaluation of ERDA-developed and commercially available DNC systems failed to disclose any system meeting established

Bendix operational requirements that was superior in capabilities or cost to the one that had been developed for the prototype evaluation. The prototype system has been tailored to meet the Bendix objectives and, as suspected from the start, considerable work would be needed to make any commercial system meet the Bendix requirements.

While none of the systems studied appeared directly applicable to Bendix needs, some did offer capabilities that were appealing. The addition of core storage and a Burrows inert gas display to the interfaces at the machine site to relieve the load on the DNC computer and to improve communication with the operator were discussed with CDC, but the ideas were discarded because of the high cost of design and implementation.

Discussions With Users Regarding Benefits of DNC Systems

Three commercial users of DNC were contacted to discuss the benefits derived from their systems. Tape editing and optimization were the leading advantages given; others were improved programmer efficiency, increased machine efficiency, improved reliability, reduced tape handling, and reduced storage requirements. One user had created a family-of-parts programming concept. Two of the three users had abandoned MIS reporting, but only after machine utilization had reached a peak and leveled off. The remaining user plans to tie the MIS into another reporting system so that it can be used for scheduling work.

All three users stated that remaining competitive would be exceedingly more difficult without DNC. Two are planning expansions of their DNC systems.

Projected Savings

Potential cost savings have been analyzed to determine the merits of DNC implementation on a large scale. Optimization of tape data has been shown to offer a substantial reduction in cycle time. Experience at Bendix Kansas City, based on 14 tape optimizations, has shown that the average tape-cycle-time reduction has been 46.5 percent, and the average standard-hour reduction has been 45.7 percent. At a savings of \$15 per standard hour (the 1974 direct production labor charge), escalating and projecting the achieved standard hour reduction over present scheduling for the revised parts indicates that approximately \$72,000 has been saved due to optimization. If these same changes had been made when the parts first were put into production, an additional saving of approximately \$21,000 would have been realized on parts that already had been machined, thus making a projected total savings exceeding \$92,000.

To determine the additional savings that can be realized from the DNC system due to optimization, an extrapolation will be made. If the 33 existing machines could be instantaneously connected to the DNC system, the active jobs on the machines could be examined for optimization. Assuming that the prototype-established relationships of optimized tapes to examined tapes are valid and that the reduction in standard hours would be the average determined in the sample, a determination of the potential savings from the 33 machines could be made if the number of standard hours that were involved in the completion of the active jobs were known.

An examination of the Engineering Machine Load Forecast dated August 17, 1975 showed that 455 active jobs were scheduled for the 33 machines with 125,324 standard hours remaining. For the calculation, the machines were divided into three groups: lathes, mills, and mills doing precision small-part work. This division was made because differences had been noted in the optimization results from these groups of machines. By assuming an equal distribution of standard hours and using ratios encountered to date for the different machine types, the potential savings shown in Table 1 were computed for the existing tape operations on the 33 machines.

For estimating future on-going savings, 440 new "A" issue tapes were made last year for the 33 machines. Again, by using findings of the study and dividing the machines into three groups, the potential savings shown in Table 2 would be generated each year. These savings would be realized over the entire production of the parts rather than in the year accomplished.

These standard-hour reductions due to optimization represent tangible savings that can be identified with a dollar value. In addition to the previously described intangible advantages that already have been experienced, other savings, probably equally important, upon which a dollar value cannot be placed have been identified through the evaluation. Operators will not have to locate tapes and load them onto the tape reader. Time will not be lost in waiting for the replacement of tapes that have been punched incorrectly, damaged, or lost. Through experience, programmers will become more optimization-conscious and better tapes will be produced for other machines. Product configuration changes can be quickly implemented, and programmers can improve part quality by correcting areas of nominal control by fine-tuning the part programs. Since the source will be located on the CDC 6600 computer, downtime, sometimes as much as 1/2 day, for retrieval of a source deck for a tape from Records Retirement will be eliminated.

Machine-tool utilization will be improved through the use of MIS reports containing current machine-operation data and a downtime history to pinpoint problem areas. The overall time required

Table 1. Potential DNC System Savings for Active Jobs as of August 17, 1975

Machine Type	Computation	Potential Savings (\$)	Savings Escalated Over 3 Years (\$)
Lathes	(5/21)(38,367)(0.545)(15.00)(1.11)(1.06)	87,872	93,250
Small Mills	(1/26)(21,634)(0.195)(15.00)(1.11)(1.06)	2,864	3,039
Other Mills	(8/36)(65,323)(0.436)(15.00)(1.11)(1.06)	111,706	118,542
		<u>202,442</u>	<u>214,831</u>

Table 2. Estimated Future Potential DNC System Savings

Machine Type	Computation	Potential Savings (\$)	Savings Escalated Over 5 Years (\$)
Lathes	(5/21)(87)(53,870)(1/5)	223,176	251,612
Small Mills	(1/26)(191)(2,815)(1/1)	20,679	23,314
Other Mills	(8/36)(162)(35,763)(1/8)	160,934	181,440
		<u>404,789</u>	<u>456,366</u>

from the initial tape to the final, usable tape will be reduced, and less downtime while waiting for revised tapes will be required. The tearing down of machine setups because of tape errors will be reduced and, by having optimized, fine-tuned initial tapes, the amount of rework required will be decreased.

Projected DNC System Costs

After the nonbuffered DNC system had been implemented, further communication with CDC indicated that the proposed benefits to be gained from upgrading to the buffered system were no longer valid. The design fee for the change was increased from \$5,000 to approximately \$35,000, and the determination was made that the addition of the multiplexer would not increase the capacity of the computer as had been anticipated.

In trying to determine computer system requirements for a 41-machine CDC system based on the new information, the operation of the CDC 1700 computer was observed and an estimate was made of the number of machines that it could control. With consideration for the time required to service two machines, the capacity of the CDC 1700 computer appeared to be between 15 and 20 machines. Under the new restrictions, the best method for expanding the CDC system to the full complement of 41 machines appeared to be the connecting of two CDC System 17 computers, each directing 16 machine tools, to the CDC 1700 computer. The CDC 1700 would control 9 machine tools and act as a data director for the two System 17 computers.

Using this concept, the cost for implementing a 41-machine production DNC system was estimated to be \$823,000 (\$934,000 escalated). When CDC was contacted for a quotation on additional

interfaces, the response included a price increase that raised the cost of the projected system to \$926,000 (\$1,075,000 escalated), which represented an escalated increase exceeding \$141,000 for the 41 machines. Using the new estimate, a 46-machine system that was in the planning stage at the time would have cost \$994,000 (\$1,170,000 escalated).

Because the price increases appeared to be a continuing trend, and because of the reduction in the proposed computer capacity, alternatives for the CDC equipment were considered. The alternative chosen for study was the use of a minicomputer as the interface between the DNC computer and the MCUs.

Minicomputer Interface Evaluation

Since the start of the DNC study, minicomputer costs have decreased significantly until they now are an economically feasible alternative for the CDC equipment. Bendix personnel experienced in the use of minicomputers indicated that they also were a good alternative operational choice. However, before a definite decision could be made regarding the departure from CDC equipment, the minicomputer concept had to be evaluated to determine whether it could perform all functions of the CDC equipment without any capability loss.

A PDP-11/05 minicomputer, manufactured by Digital Equipment Corporation, was selected for study. The evaluation was planned to consist of a trial on each of two machines with different MCUs. This approach was selected to determine the difficulties that would be encountered in connecting a minicomputer to a machine and running it using the behind-the-tape-reader interfacing technique, and to determine what software problems would be encountered with different types of MCUs.

Within 12 hours, the first machine (Ex-Cell-O 920 lathe, Bendix 20 MCU) was being operated under minicomputer control with no problems. After the minicomputer had been moved to the second machine (Index three-axis mill, BR 3332 MCU), operation under minicomputer control was obtained with no problems within 20 hours. For additional proof of the compatibility of the minicomputer, an Ex-Cell-O 982 three-axis mill and a Sundstrand OM-3 five-axis mill, both equipped with Bendix 1000 Series MCUs, were connected individually to the minicomputer and successfully cycled.

The operation of these machines under minicomputer control has proven that this prototype-system modification is feasible and, based on the purchase price of the evaluation unit, the system can be implemented at a cost of approximately \$500,000 (\$525,000 escalated). This represents a saving of approximately \$490,000

in nonescalated capital equipment costs for a 46-machine system. As a result of the evaluation, an appropriation package has been prepared to purchase minicomputer interfaces for 16 machine tools.

The employment of the new interfacing technique has changed the concept for the proposed production system. Instead of having thumbwheel switches and pushbuttons at each machine for operator inputs, a CRT with which the operator can request tapes and make MIS inputs will be used. In addition, the system will be able to communicate with the operator if something appears to be wrong, and thus aid in keeping a better record of machine activities.

The minicomputers are being purchased with 8K cores, of which approximately 6 are anticipated to be available for tape storage. This will permit the storage of approximately 100 feet (30.48 m) of Mylar tape, which represents complete storage for approximately 50 percent of the tapes that have been made for the five-axis machines, and over 80 percent of those made for the small three-axis mills.

To accommodate the longer tapes, the core storage area will be divided into two buffers, either of which can be refilled by the CDC 1700 computer after being emptied by the machine. With this storage capability at the machine-tool site, the load on the CDC 1700 computer will be significantly reduced. One CDC 1700 computer is anticipated to be capable of controlling the entire projected DNC system.

By having the tape stored in the minicomputer, a search for the Mylar will no longer be necessary in case of a CDC 1700 failure. The machine can continue to operate directly from the minicomputers with only the MIS information being lost. Only Mylar tapes exceeding 100 feet (30.48 m) in length will require loading in the event of a CDC 1700 failure. In addition, if a setup needs to be changed while the CDC 1700 is inoperative, the design of the interface will permit the tape reader in the MCU to be used to load tape information into the minicomputer.

In the event of a minicomputer failure, the DNC capabilities will no longer be lost (as is the case with CDC units) while the DNC equipment is being repaired. The failing computer can be immediately replaced with a spare which can be quickly loaded with the tape information and put back into service while the defective computer is being repaired.

The decision to change interfacing techniques to the use of minicomputers, although occurring late in the evaluation, will provide a more economical system having more capabilities than the CDC system that was originally proposed.

ACCOMPLISHMENTS

The entire DNC system software for the operation of the machine tools from a computer has been written and upgraded. A 4-machine prototype DNC system has been implemented and successfully operated for over 16,300 hours. Most of the software and operational procedures for a Management Information System to improve machine utilization have been developed. The software necessary to provide an APT Source editing capability from the machine-tool site has been developed, and 77 NC tapes have been edited. Of the tapes edited, the optimization of 14 of them has produced a saving in direct labor costs which exceeds \$71,000.

The initial decision that a backup capability be provided so that machine tools could be operated in the event of either a computer or interface failure has proved to be valid. During the evaluation, all machines controlled only by the DNC computer would have been unusable for 34-1/2 days, and individual machines would have been inoperative for up to 14-1/2 additional days had a backup capability not been provided.

The evaluation also has proved the soundness of the decision that the DNC system be developed at Bendix Kansas City. Of the commercially available behind-the-tape-reader interface approaches, none will meet all of the Bendix-established operational requirements without significant changes in software. Providing that the supplier would furnish the documentation, a significant amount of time still would be required for a Bendix programmer to familiarize himself with the software before he could make the necessary changes to a commercial system. Because the software for the prototype DNC system has been completely written at Bendix, changes for improvements or modifications can be made more easily.

Based on the operational results of the prototype DNC system, a decision was made to implement a production DNC system at Bendix Kansas City consisting of 41 machine tools. This was to have been accomplished during fiscal years 1975 through 1979 by expansion of the prototype system. Since this determination was made, an evaluation of minicomputers for use as the interface has resulted in a decision to change techniques. Although the change will require some modifications of the DNC software, the capabilities will remain the same. Implementation is now planned to begin in fiscal year 1976 and to be completed in 1979.

FUTURE WORK

Work yet to be accomplished on this project consists of modifying the MIS software and determining the most useful format for the MIS information to aid in optimizing machine utilization.

Although the primary planning emphasis for the use of DNC has been placed on production operations, the recommendation is made that consideration be given to providing the machine tools located in the Engineering Shops and Tool Room with DNC in order to take advantage of the editing capability. Numerous new tapes are continually being prepared for these machines.

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¹D. L. Setter and C. R. Miller, *DNC Committee Final Report*. UNCLASSIFIED. Bendix Kansas City: BDX-613-376, May, 1971 (Available from NTIS).

²G. L. Finlay, *Direct Numerical Control of Machine Tools* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-540, October, 1971 (Available from NTIS).

³"CDC Engineering Specification Describing DNC Interface Operation." Control Data Corporation, March 17, 1971.

Appendix A

DNC SYSTEM OPERATING TIME

Table A-1. System Operating Time as of November 30, 1975

Machine(s) Operated	Installation Date (Month, Year)	Total Time (Hours)
D/823 Ex-Cell-O Lathe	April, 1971	967.0
D/95 Ex-Cell-O Mill	August, 1971	4528.0
D/93 Ex-Cell-O Mill	December, 1973	7623.0
D/20 American Lathe	January, 1974	3266.5
2 Machines, Simultaneous		3584.0
3 Machines, Simultaneous		862.5

Appendix B

DEFINITIONS OF MANAGEMENT INFORMATION SYSTEM PUSHBUTTON INPUTS

The following pushbuttons are pressed upon completion of the machine setup. All future activities will continue to be logged as the type of operation indicated until the next setup operation is selected.

- PROD. TIME indicates that the parts in work are regular 300-type production parts.
- DEV. TIME indicates that the parts in work are DSE parts.
- OTHER TYPE OPER. indicates that the parts in work are neither 300- nor DSE-type parts. Example: factory order parts.

The following pushbuttons are pressed at the start of the indicated activity. Pressing the appropriate button for the next operation will conclude the activity previously indicated.

- ASSISTANCE RESPONSE TIME indicates that a problem has been encountered, the machine is down, and help has been requested from Process Engineering, Production Control, Maintenance, or the NC Tape Group.
- PROCESS ENG. DOWNTIME indicates that the machine either is down at the direction of Process Engineering, or it is awaiting corrective action by the Process Engineer.
- MAINTENANCE DOWNTIME indicates that the machine is down and awaiting repair by the Maintenance Department.
- N/C DOWNTIME indicates that the machine is down and awaiting a correction or modification of the NC tape data.
- SETUP indicates that the machine is in the process of being prepared for another job, including the teardown of the previous fixtures and tools and all first-piece checks.
- TOOL CHANGE indicates that the machine has been stopped to replace a cutting tool.
- WAITING FOR EQUIP. indicates that the machine is down and awaiting cutting tools, fixtures, or gages.

- NO OPER./PARTS AVAIL. indicates that the machine is down because either operator or parts is not available.
- MANUAL OPERATION indicates that the machine is being operated manually rather than by NC.
- MACH. WARMUP indicates that the machine is being warmed up prior to use for production.
- CLEANUP indicates that either personal or machine cleanup is being performed.

The following pushbuttons have special instructions.

- REWORK indicates that a part or group of parts is being remachined to correct a discrepancy.

For individual parts during a normal run, press the REWORK button just prior to remachining the part. Then, upon completion of the cut, press the PROD. TIME, DEV. TIME, or OTHER TYPE OPER. button, as applicable, to clear the rework indication.

For complete lots, groups of parts, or individual parts that require a special setup, press the OTHER TYPE OPER. button upon completion of the setup, followed by the REWORK button. All parts subsequently machined will be logged as "Other Type Oper.--Rework" until the next setup operation is indicated.

- DRY RUN indicates that the subsequent machine cycles will be dry runs.

If this occurs during a machine setup, press the SETUP pushbutton upon completion. If it occurs during a production run, press the PROD. TIME, DEV. TIME, or OTHER TYPE OPER. button, as applicable, to clear the dry-run indication.

- REINPUT ALL DATA (flashing light) indicates that either the computer has been down or the power to the interface equipment has been off.

If this occurs, the pushbutton indicating the current machine status should be pressed, followed by the SEND button. This procedure must be followed, even though the correct MIS pushbutton may be already illuminated.

Appendix C

BREAKDOWN OF MIS REPORT CATEGORIES

SUMMARY OF OPERATION TIME (OPER)

Production Time
Development Time
Other Type Operation

SUMMARY OF SETUP TIME BY TAPE NUMBER (SETP)

Tape Number	Setup Time	Number of Dry Runs	Dry-Run Time
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SUMMARY OF REWORK TIME (REWK)

Tape Number	Rework Time
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SUMMARY OF MISCELLANEOUS DOWNTIME (MIDT)

Assistance Response Time
Process Engineering Downtime
Numerical Control Downtime
Computer Downtime

SUMMARY OF MAINTENANCE DOWNTIME (MADT)

Maintenance Downtime

SUMMARY OF TIME IN CUT (TINC)

Tape Number	Time in Cut
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SUMMARY OF TOOLING DOWNTIME (TODT)

Wait for Equipment
Tool Change

SUMMARY OF PRODUCTION DOWNTIME (PRDT)

Machine Warmup
Cleanup
No Operator or Parts Available

SUMMARY OF MANUAL OPERATION (MAOP)

Manual Operation

SUMMARY OF LOAD-UNLOAD TIME (LOAD)

Tape Number	Load-Unload Time	Number of Cycles
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SUMMARY OF FEEDRATE OVERRIDE TIME (FROR)

Tape Number	Percent Feedrate Used	Time in Cut
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SUMMARY OF NONPRODUCTIVE TIME (NONP)

Expired Shift Hours Minus Time in Cut

SUMMARY OF MACHINE EFFICIENCY (MEFF)

$(\text{Pieces Produced}) / (\text{Unit Standard} / \text{Expired Hours})$

SUMMARY OF TOTAL DOWNTIME (TDT)

Total of All Downtime

Appendix D

DETAILS OF EDITING PERFORMED ON THE DNC SYSTEM

MYLAR IMAGE EDITING

Of the eight Mylar Image edits that were performed, four were done to add cutter compensation ON and OFF at selected points in the operations. In one of these cases, 56 commands for cutter compensation were added.

The other four Mylar Image edits were done to correct a post-processor error which caused an erroneous output sequence of machine-tool commands for spindle control at re-entry points, and to add N codes to the data.

APT SOURCE EDITING

The 69 APT Source editing operations can be generally separated into the following eight change categories, each of which is described or further broken down after the total number of changes is shown.

- 10 tape-error corrections were made for the reasons indicated:
 - 2 corrections for postprocessor errors;
 - 1 correction for incorrect sequence of threading commands;
 - 1 stop added for tool change;
 - 3 parts did not clean up; and
 - 3 incorrect home-set positions.
- 3 tape changes were made in which the tool path was intentionally shifted from nominal print dimensions to compensate for tool deflection or other problems, thus permitting the part to gage closer to a mean tolerance condition (fine tuning).
- 1 tape change was made for a product design change which was received while the job was being run on the machine. Changes were incorporated immediately without the necessity of tearing down the setup, or the need for later rework to incorporate the change.

- 6 tape changes were made to resolve the following cutting-tool problems:
 - 2 changes to reduce cutter chatter;
 - 1 change to compensate for cutter flute-length variation;
 - 1 change to reorient cutter set lengths on a multiple tool setup because of differences in the lengths of purchased cutters; and
 - 2 changes to eliminate tool breakage.
- 2 tapes were created for rework or new production:
 - 1 rework tape which could be cycled in 1-1/2 minutes instead of reworking 40 parts by recycling the 10-minute production tape; and
 - 1 new tape for a special job.
- 31 changes involved the sequence or method of machining:
 - 9 changes involving the cutting sequence, the order of cuts, or the amount of stock removal;
 - 1 change to the cutter set length to add clearance between the turret and the part;
 - 1 change to the tool-change position;
 - 4 changes to incorporate additional passes for particular problem areas;
 - 2 changes to the feedrate;
 - 10 changes in milling-cutter diameter for a portion or all of an operation;
 - 2 changes to alter the direction of cuts; and
 - 2 changes to combine two operations.
- 1 change was made to overcome a fixture modification that had altered the orientation of the part on the fixture.
- 15 tape optimizations were made, one of which had no scheduled parts. Listed in Table D-1 are the 14 scheduled tapes, their resulting cycle times after optimization, their cycle-time-reduction percentages, and their standard-hour-reduction percentages.

Table D-1. Tape-Optimization Results

Tape Number	Resultant Cycle Time (Minutes)	Cycle-Time Reduction (Percent)	Standard-Hour Reduction (Percent)
A11500D	6.9	60.6	54.7
A11249C	3.8	19.1	38.8
A11486C	21.8	75.8	68.5
32041C	36.8	62.0	68.4
11034E	23.2	45.5	38.8
32017D	114.9	57.4	41.0
A11485C	13.6	79.1	75.0
32022C	16.9	74.7	67.0
32032B	23.1	41.2	52.4
32033D	68.8	17.6	43.5
A11606B	19.2	36.6	34.3
21302A	2.3	36.1	19.5
A11558C	7.1	34.0	28.0
A11471B	2.05	11.0	10.5
		46.5 Average	45.7 Average

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PROTOTYPE DIRECT NUMERICAL CONTROL SYSTEM EVALUATION, G. L. Finlay, D/821, UNCLAS Milestone, May 1976.

Evaluation results from a four-machine prototype Direct Numerical Control (DNC) system that has been constructed at Bendix Kansas City indicate both economic and operational advantages over the present NC systems. The behind-the-tape-reader interfacing approach that was used has proven to be the most suitable interfacing method for Bendix machining operations. The prototype DNC system is being modified and expanded into a production system having a potential for more than 40 continuous-path NC machine tools.

SPECIAL PROJECTS: Direct Numerical Control

PROTOTYPE DIRECT NUMERICAL CONTROL SYSTEM EVALUATION, G. L. Finlay, D/821, UNCLAS Milestone, PDO 6984718, BDX-613-1585 (Rev.), May 1976.

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