Nortel Redefines Factory Information Technology: An OR-Driven Approach

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Nortel recruited a team of operations researchers and engineers to develop and implement an enterprise information system for Nortel’s new PCS1900-cellular-equipment manufacturing operation. This system provides online access to quality, inventory, and cycle-time measurements, as well as linked analysis tools that provide real-time decision support. Production workers, managers, and engineers can access these tools through the Nortel intranet using Netscape. Inexpensive access to current factory information eliminated the costly delays formerly experienced gathering, analyzing, and transferring data. The OR specialists developed and implemented the network and decision-support system in less than one year. This marked a major shift from traditional shop-floor systems deployment within Nortel and within the industry in general and demonstrates an opportunity for OR to assume a leadership role in systems implementation in manufacturing operations.

Northern Telecom is a leading global provider of digital network hardware and software solutions for communications, information, entertainment, education, and commerce. From its modest beginnings in the late 1800s as a small Canadian telephone-equipment supplier, the company has evolved into an architect of integrated networks for public and private enterprises with revenues of $12.85 billion.
in 1996. The company consists of four principal divisions employing 68,000 people worldwide: Public Carrier Networks, which provides communications networks that enable telephone and data services for business and residential customers; Broadband Networks, which provides high capacity local and long-distance voice and data transmission and interactive home, office, and educational applications; Enterprise Networks, which provides business and private institutions with networks that support high-speed data transfer, multimedia applications, computer-integrated telephony, and in-building wireless voice service; and Wireless Networks, which provides hardware and software solutions that enable advanced digital personal communications services (PCS), cellular, and fixed wireless access communications.

**Business Case**

In 1995, the US Federal Communications Commission began auctioning a section of frequency bandwidth reserved for advanced digital cellular communications. Known as personal communications services (PCS), this technology combines the security and voice clarity associated with digital-signal transmission with the convenience of mobile voice service and such features as voice messaging and digital paging. PCS service represents an advance in mobile voice service over common cellular telephone service, which uses analog technology to transmit voice signals over the airwaves. Analog cellular technology is prone to service theft and has limited capability to provide such enhanced services as voice messaging, paging, and data transmission. The FCC’s auctioning of the available frequency spectrum to service providers created a sudden high demand for networks capable of supporting PCS service.

To address this demand, Nortel’s Wireless Networks Division launched a manufacturing operation, Wireless Networks Raleigh (WNR), in Research Triangle Park, North Carolina. The plant is dedicated to manufacturing advanced cell-site base-station and antenna equipment based on a PCS design protocol known as GSM (global system for mobile communications), a technology originally deployed in Europe in the early 1990s. The Nortel business units that designed the products manufactured by WNR are based in Paris, France, and Paignton, UK. Nortel approved the site in the fall of 1994 and began hiring management teams and purchasing electronics assembly and test equipment shortly thereafter. With a new customer base of wireless service providers seeking network hardware solutions that would be implemented in time for network launches in late 1995 and early 1996, Nortel sought to transfer a European design into a new manufacturing site, to hire engineering, planning, and production employees, and to establish manufacturing processes capable of sustaining full production loads by the second quarter of 1996.

From the beginning of the factory-launch process, senior managers realized that to provide customers with reliable, high-quality PCS1900 network solutions at the lowest possible cost, they would need state-of-the-art manufacturing practices. These practices would include just-in-time, demand-flow production control philoso-
phies in which demand at the shipping dock triggers production upstream, minimizing shop floor inventory. They would need team-oriented production management, in which self-directed work teams under minimal supervision perform all shop-floor production activities, such as machine operation, manual electronic assembly, and product configuration and testing, to minimize overhead costs. Finally, statistical quality control would ensure optimal quality throughout all stages of production. To support each of these initiatives, the managers realized they needed an information-technology backbone capable of tracking and routing product through production and providing real-time feedback regarding factory inventory and quality metrics. Ideally this information system would also provide managers with decision support to enable them to make quick and accurate decisions.

Proposed IT Implementation Philosophy

Traditionally within Nortel, as with most large manufacturing enterprises, implementing information-technology solutions in manufacturing is the primary role of programmers or specialists in management information systems (MIS). The rapid evolution of information technology during the past two decades makes this reliance on software programming specialists understandable. For most of the brief history of IT, organizations have often developed custom systems internally, programming them in core languages to achieve the functionality they wanted. When they have purchased packaged software solutions, they have often customized the code and made ongoing investments to maintain and enhance functionality. Companies have maintained programming or information-systems departments to support the legacy systems developed over the years, to refine existing systems, and to develop new IT tools. This approach has been unavoidable for companies that wanted to automate operations, but it is very costly over time.

The rapid evolution of object-oriented programming technology is changing the nature of systems implementation. Companies can now purchase, integrate, and deploy packaged software tools and systems, instead of developing their own automated tools. This shift is beginning to reduce the need for programmers and is creating a need for individuals who specialize in systems integration and the optimal use of available information to support decision processes.

Recognizing this shift, in early 1995 Brinkley proposed that Nortel broaden the traditional role of the operations research specialist beyond analyzing data and developing models. He proposed that the OR specialist direct and coordinate the implementation of systems and the deployment of decision-support tools. Where OR specialists often traditionally make up a small subset of an IT organization that focuses on programming, under the proposed structure OR analysts would control systems implementation (Table 1). This is a big shift for operations research but is logical given the background of the OR specialist compared to that of the software programmer.

Modern OR education includes programming and other computer skills but focuses on analysis of data and develop-
Table 1: The proposed information-technology implementation strategy for Nortel placed leadership in the hands of OR specialists instead of software programmers. This approach broke the traditional systems-implementation philosophy. The OR-centric focus is on implementing decision-support systems quickly as opposed to developing software.

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<th>Core competency</th>
<th>Standard Approach</th>
<th>Proposed Approach</th>
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<td>Core competency</td>
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<td>Legacy systems</td>
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<td>Native software</td>
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Given responsibility for designing and implementing a system, the OR practitioner will program if necessary to implement or integrate a system that is needed to support a decision process, while the programmer will tend to customize or enhance an application because writing code is what programmers are trained to do. The OR practitioner, whose primary interest lies in decision processes and analytical tools, will focus on quickly achieving value from a system purchased to support decision making. This statement is a generalization, but it has an inherent logic. Traditionally OR is not integrated into factory operations but instead serves in a peripheral consulting, analytical role. By making the OR specialist more prominent, Nortel sought to eliminate this disconnection between OR and the factory, integrating the OR function into the daily decision processes of the business.

Solution Approach: Piloting the Philosophy

Establishing the PCS1900 factory in Research Triangle Park provided Nortel with an opportunity to avoid a traditional IT role and to allow OR specialists to control the implementation of decision tools. Beginning in April 1995, Nortel recruited a team of newly graduated and experienced OR practitioners and engineers for the new factory. Nortel gave this OR team principal responsibility for implementing factory-data-collection, decision-support,
and product-and-process-control systems. This group (Brinkley, Stepto, Haag, Wang, Folger, Liou, and Carr) demonstrated its effectiveness by developing and implementing a complete information and decision-support system in less than one year. This system played a key role in the successful launch of the WNR factory (driving 1996 revenues of $320M) and directly contributed to its low overhead costs.

**PCS1900 Manufacturing Process**

Production at WNR consists of a sequence of electronics assembly and testing operations, culminating in the shipment of finished cell-site base stations (Figure 1). First, machines assemble printed circuit boards, placing adhesives and surface-mount components on bare wired boards, subjecting the adhesives to high temperatures to create soldered bonds between components and circuitry. Workers then manually install additional components that are then wave-soldered to complete the process. The PCB-assembly operation is machine intensive, with very fine tolerances for plated component leads on integrated circuits, chip capacitors, and resistors. Each machining stage requires process control to ensure accurate placement and alignment and precise soldering, which prevents short circuits or poor circuit connections. Over 30 PCB designs pass through the board-assembly area, with each design requiring a unique machine sequence and unique machine parameters. Each board is given its own serial number at the beginning of the process so that it can be traced through production. Detailed tracking and routing is necessary to streamline product flow, to

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**Figure 1**: The sequence of steps for assembling a cell-site base transceiver station (BTS) is a manufacturing sequence common to most large electronic-systems-assembly processes. A cell-site BTS is not considered delivered until it is fully installed, tested, and operational at the installation site, at which point it is handed over to the customer.
ensure product quality, and to minimize work-in-process (WIP) inventory on the shop floor.

Following assembly, each PCB passes through a sequence of tests. In-circuit (IC) testing verifies that each completed circuit on the PCB is correct and checks component alignment, placement, and soldering quality. Defects located during the IC test typically result from the assembly process or from poor quality components. Following the IC test, a functional test is performed to verify that the PCB operates to design specifications. Data collected in functional testing is invaluable to designers, because it provides them with a large statistical sample of information that shows how well “centered” the design of a particular feature or operation is with respect to its specifications. For each PCB it manufactures, WNR tests hundreds of performance parameters, each reflecting whether the product performs to specifications. PCBs found to be defective exit the normal manufacturing process to enter a diagnosis-and-repair operation. All functional testing data is recorded for use by design engineers, and defective products are tracked and routed to ensure production control.

After functional testing, PCBs are incorporated into receiver and transmitter modules, which are then assembled into complete radio units. At each stage of subassembly, people perform additional functional tests to verify performance to specification. The completed radios are wired into large insulated metal cabinets to create finished base stations capable of withstanding external weather and temperature conditions when deployed in the field. The plant then tests base stations as complete systems to ensure their performance to specifications. WNR ships the systems to customer sites, where it monitors their performance continually to ensure network reliability. The field performance data are valuable to designers seeking to improve the reliability of PCS1900 products. Once purchased systems are installed and fully operational, customer delivery is considered complete.

**Information System Requirements**

Because the production operation was complex and had to remain competitive, factory management wanted to automate all product-routing and inventory-tracking operations to reduce their costs. Also automating data-collection activities in manufacturing reduces human-resource requirements and helps managers to respond quickly to changing manufacturing conditions. From the beginning of WNR operations, it was clear that managers, designers, and customer-support personnel located around the globe would need access to WNR metrics to meet the demands of the new business (Figure 2). Based upon these needs, we developed a high-level IT architecture (Figure 3).

To manage factory operations, the system required data about the processes the product went through in its assembly and testing process. These data included discrete measures of unit performance, such as process yield, inventory status, cycle time, or stage of manufacturing. Other data were parametric in nature and represented continuous measures of either process or product performance, such as the temperature of a PCB-assembly heating oven at a specific time, or the performance
Figure 2: Nortel Wireless Networks GMS (Global System for Mobility) product line has management, engineering, and design sites located in North America and Europe. This created special challenges during the introduction of the GSM product for the North American PCS market. Nortel managers wanted systems in the Raleigh factory capable of delivering information immediately to design engineers and managers at any GSM site.

of a unit on a specific functional test. To address the two types of data, we installed two systems. We used a system marketed by Automated Technology Associates (ATA), QTS (Quality Tracking System), for tracking individual units of product by serial number through production, testing, and shipment to customer site. We used ATA’s RQM (Real-Time Quality Management) system for capturing and analyzing parametric data from machines and test processes online.

To make these metrics accessible globally, the implementation team took advantage of internet communication protocols to present information. By using the Nortel intranet to provide access to online metrics and tools, we avoided the need for purchasing new computing hardware for various Nortel locations. Because web browsers are platform independent, people at Nortel facilities worldwide using Macintosh, Windows, or Unix desktop machines could easily access any WNR information.

Three Key Drivers
The team implemented systems to achieve three primary goals: to control production and inventory, to ensure quality and reliability, and to provide real-time decision support. To implement and support JIT-based production, we needed to implement a system capable of routing individual product units (PCBs, radios, or complete systems) through the stages in manufacturing and testing. At each production operation, factory workers scan bar-coded serial numbers into QTS. QTS checks that the product is in the correct production stage based on predefined...
Operating Groups Using WNR Data and Decision Support Tools

Figure 3: The proposed solution implemented at WNR used three database systems to capture information and a set of reusable objects and scripts to interface these data to the presentation interface, Netscape. Using the web was a novel approach when this solution was proposed in early 1995. The internet explosion was just beginning to occur, and intranet was a term just starting to appear in the language of information technology. For a factory to deploy solutions for production workers using this technology was considered highly innovative at that time.

product routes entered into the system. The system rejects any product that is out of sequence, and reroutes it to the correct operation.

As a byproduct of these scanning operations, the system makes real-time data available online that show inventory and cycle time based on 100 percent of production. The QTS system also provides many standard reports. The OR team extended this reporting capability, developing Excel macros and Visual Basic objects to generate graphically formatted output in HTML and GIF formats, allowing web-browser access. The team linked these reports to corporate systems that contain financial information, providing current inventory reports that include costs.

Quality and Reliability Assurance

To provide quality-and-reliability-assurance information, the system relies on two types of data. It captures attribute data on the quality of the units moving through production to enable statistical quality control for manual assembly processes and for processes driven by discrete
data, such as defect counts at inspection points in production. It also captures parametric data continuously on product-and-process performance to enable real-time statistical process control (SPC) and capability analysis for design performance at functional test.

At each manual bar-code scanning point in production, the OR team provided workers with an online list of codes for potential defect categories to assign to products identified as nonconforming or defective. When a worker identifies a unit as nonconforming and assigns it a corresponding defect code, the status of the unit changes and it is rerouted to a diagnosis or repair operation. The system constantly compiles the data gathered at these scanning operations into yield reports by product, data, and time. It also provides online pareto analysis and attribute-based SPC charts, enabling workers to quickly analyze root causes and adjust processes to minimize the production of defective units. The OR team linked these reports to the Netscape interface to enable global access to this information (Figure 4). As with the inventory reports, we used Excel and Visual Basic objects to automatically download graphics and information into standard spreadsheets and graphics packages.

Figure 4: This simple yield and production-volume report available to any Nortel user via the intranet is one of over 70 similar reports representing quality and inventory information available from the WNR data network. The information is updated in real time, so that presented reports always represent current information. This sort of access to factory data reduced a significant amount of management and engineering effort devoted to compiling data manually, preparing them graphically, and sending them to users around the world.
The RQM system provides online graphical analysis tools that automatically process parametric data in real time. The OR team linked each automated assembly machine to this system, providing real-time SPC that allows workers to modify component-placement and soldering operations to ensure optimal quality (Figure 5). Factory workers monitor statistical process control charts and can take immediate corrective action if performance drifts from an optimal state. To provide global access to design-performance information, we linked each functional test to RQM and provided web access. With this feedback, designers can quickly modify design parameters for any product tested in the factory. This access also permits engineers to quickly evaluate the impact of supplier changes on product performance, to compare the suppliers of any component, and to determine whether changes in processes affect the quality of finished products. Figure 6 provides an example of a process capability curve for one test parameter for a WNR product based on data captured at functional testing. Because the system captures a vast amount of data for

**Temperature Preheater #1**

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Figure 5: Statistical process control was a primary driver for many of the tools made available to factory workers. This is one interface a production worker can access in real time from terminals strategically located on the shop floor. This graphical feedback about the state of manufacturing processes creates an empowered worker capable of immediately adjusting production processes to ensure optimal quality.
hundreds of test parameters for each WNR product, we created a separate database using Microsoft SQL-Server software for archiving historic parametric data.

**Building a User Community**

The biggest challenge in implementing any information-technology solution is developing a user community. This requires extensive training, selling of concept, and effort to convince users of the value of the system. To do this, the OR team spent a large amount of time training production staff, often engaging in personal, one-on-one training on the factory floor. Because the information system was an integral part of the WNR production process for routing product, tracking inventory, and ensuring quality, skilled and confident users were essential for the success of the project. Between May 1995 and January 1997, the initial usage rate of less than 50,000 transactions per month increased to the full-production usage rate of 350,000 transactions per month. This has been followed by a stable usage rate that varies somewhat because of production volume changes due to business cycles for the factory (Figure 7). Use of the web pages providing decision-support information by managers and engineers has also increased. Quality and reliability data are accessed primarily by designers overseas and by WNR test engineers seeking to improve product performance, with an aver-
age usage rate of six hits per day. Process-control data (inventory and so forth) are accessed primarily by factory managers and shop-floor workers, at a rate of 21 hits per day as of the spring of 1997 (Figure 8).

Decision Support Tools

The vast amount of data captured in the QTS/RQM systems and the SQL archive database provided us with an excellent opportunity to develop decision-support tools for WNR staff. To support resource-and-capacity planning and cycle-time-reduction initiatives, we used simulation modeling. Typically, the effectiveness of simulation modeling is limited by the availability of data. With inadequate data, accurate statistical distributions representing processing time, yield, and inventory levels are not available. Since the WNR information system captures data for all products manufactured at WNR, it was not necessary to perform time studies or manually gather data. We could produce statistical distributions that represent a near-exact fit to actual processing conditions. Furthermore, we wanted to remove simulation modeling from the hands of an OR analyst and place the tool in the hands of the manager or engineer seeking decision support. Once we had implemented the data-collection network, we began developing a simulation environment using Systems Modeling Corporation’s SIMAN as the simulation engine. We created a Netscape interface that managers or engineers can use to input scenarios (forecasted load, capacity, and so forth) and to obtain spreadsheets with post-processed output, including statistical analyses that include confidence intervals for critical
metrics. When someone submits a scenario to the simulation engine, it queries the factory network, which downloads current shop-floor-inventory, process-yield, and processing-time data to the simulation environment. The simulation engine then fits statistical distributions to each parameter and executes the model. The availability of real-time data obviates the need for start-up time in the simulation, as current factory status is loaded upon model initiation. We began developing this system after completing the enterprise information system in June 1996.

We also developed expert systems for use in diagnosing product failures shown during in-circuit and functional tests. Printed circuit boards typically have thousands of alternative failure modes, each with a unique coded identifier generated by automated test equipment. Interpreting these codes and identifying correct repair operations requires a great deal of technical skill. Allocating human resources is a problem, because test-failure diagnostic operations consume technician time. To address this problem, we developed a discrete-event expert system that accessed test-failure data stored in MS-SQL, inferred a diagnosis of failure, and provided repair operators with recommended repair operations. Inferences are based on data entered by experienced technicians for specific prior occurrences of failure codes. For new failure codes, the system provides best guesses regarding the causes of failure, based upon similar failure codes with identified causes from the database.

Each of these decision-support tools can help managers and production associates to quickly take the best actions in factory operations. The examples we describe here show the benefits of a data-collection infrastructure developed from an OR view-
point. We are currently working on further uses for the tools described above to further exploit the data available.

Implementation
The OR team developed and implemented the systems and tools described here between the spring of 1995 and the spring of 1996 (Figure 9). Team members integrated the systems, linking machines and test equipment to the data-collection infrastructure. We trained the entire shop-floor staff (approximately 200 production associates) to use the system and provided classroom training in statistical process control to all production workers. We developed and implemented data-access objects, home pages, Excel graphics, and spreadsheet-output tools. The cost of hardware and software for the WNR data-collection network was $500,000.

Benefits
The benefits fall into four categories:
—Installation and support savings,
—Ongoing projects enabled by the data-collection infrastructure,
—Direct impact to business, and
—Qualitative benefits.

Installation and Ongoing Support Savings
The OR approach to systems implementation was less costly than a traditional, programmer-centric approach (Table 2). Based on estimates made by a sister factory that implemented a data-collection system using a traditional, development-oriented approach during 1995, the savings associated with the OR-driven approach are nearly $4 million annually. For the programmer-driven approach, the ongoing support staff will consist of software developers. For the OR-driven approach, the support staff are primarily OR analysts focusing on using and enhancing the decision-support capability of the systems.

Ongoing Projects and Benefits
The availability of real-time data makes possible a wide variety of projects that directly impact the business success of WNR. In February 1997, a critical objective for improving throughput was reduction of test-cycle time. Test engineers tried to identify test parameters that were so well
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Costs: $M

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Table 2: Implementation costs are broken into two categories: implementation and ongoing support, with the savings experienced by WNR clearly evident.

centered with regard to design specifications that they could eliminate the corresponding tests with no risk to product quality. As a result of this exercise, WNR reduced test-cycle time by 50 percent, thus avoiding the purchase of additional test equipment at a cost of $300,000.

In July 1996, a team of production workers used data collected from manufacturing equipment in real time to assess the quality of the placement of surface-mount components. Data indicated that they should change their storage of adhesive compounds. Correcting the problem immediately reduced rework costs by $100,000. Finally in early 1997, the entire product portfolio manufactured at WNR shifted to a new, second-generation cell-site base-station design. By using online reports and real-time information on product inventory, production managers avoided an estimated $500,000 in obsolete WIP inventory. There have been many other such projects during the past two years. We chose this small sample to illustrate the impact of the data-collection network on ongoing factory-improvement projects.

Direct Business Impact

WNR management estimates a direct impact to annual operating costs as follows:
—WIP-inventory reduction resulting from tracking, routing, and control (12 percent holding cost): $400,000;
—Resource savings resulting from automated WIP and quality tracking and reporting: $300,000;
—Rework and scrap reduction from improved route control and repair tracking: $350,000;

totaling $1,050,000.

Qualitative Benefits

In any project of this magnitude, some important benefits are difficult to quantify. Top Nortel managers cited the availability of real-time factory information as a key factor in the successful launch of the WNR factory. Operations grew from $20 million in revenue in 1995, primarily from prototype production, to $320 million in 1996. The impact on customer satisfaction of improved quality and reliability is immeasurable. Employee satisfaction gained from increasing factory workers’ knowledge is another major benefit.

The project demonstrates the value OR can provide a modern industrial organization in its daily operations. There are wide-open opportunities in WNR for OR
applications based on accurate data and information. In numerous joint projects with academia, WNR seeks to capitalize on these opportunities. Nortel is funding research by the North Carolina State University departments of statistics and operations research in scheduling, artificial intelligence, and statistical modeling. The National Science Foundation has recognized the data-collection infrastructure as a key element in awarding a grant to the NCSU statistics department for joint research with Nortel in multistage process optimization. Most important, OR is now an integrated part of the WNR business.

In recent years, many publications have focused on the proper place of OR in modern organizations. Many authors have documented the movement away from OR/MS in management programs at leading universities. As systems implementation shifts away from a programming-intensive activity, OR has a unique opportunity to claim a key position in today’s manufacturing organization. This opportunity, if realized, can reinvigorate the field of OR/MS, providing a vision for a bright future at the forefront of modern industrial organizations.