Title

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A Decision-Based Analysis of Compressed Air Usage Patterns in Automotive Manufacturing

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Abstract

This study is an evaluation of the use and supply of compressed air, which is one of the most expensive energy sources in manufacturing, at Ford Motor Company's Livonia (Mich.) Transmission Plant. The aim of the study is to make recommendations to improve environmental and economic efficiency in future facilities. This paper presents a quantitative analysis of three compressed air supply patterns—plant air, point of use (POU), and local generation—as alternatives for future compressed air usage. Environmental Value systems (EnVS) tools are employed to analyze the economic and environmental performance of the three alternative supply patterns by using cost of ownership and environmental impact matrices. The results favor local generation over the other two alternatives in terms of economic and environmental considerations.

Keywords: *Compressed Air, Cost of Ownership, Environmental Impact, Plant Air, Local Generation*

Introduction

Background

Compressed air is regarded as the fourth utility, after electricity, natural gas, and water, in facilitating production activities. In manufacturing plants, compressed air is widely used for such operations as actuating, cleaning, cooling, drying parts, and removing metal chips (Sweeney 2002). However, the cost of compressed air production is one of the most expensive and least-understood processes in a manufacturing facility (Risi 1995). The cost of electric power used to operate an air compressor continuously for a year (about 8,200 h) is usually greater than the initial price of the equipment (Kaya et al. 2002). Per million British Thermal Units of energy delivered, compressed air is more expensive than the other three utilities, as shown in *Figure 1*.

Besides cost issues, compressed air production consumes huge amount of energies. It is estimated that about 3% to 9% of total energy consumed in US in 1997 was for air compression in manufacturing (Curtner et al. 1997). The consumed energy directly or indirectly contributes to large amounts of facility CO_2 emissions per vehicle built from automotive manufacturing facilities, which in 2003 was 1.32 metric tons from Ford Motor Company (2005) and 2.35 metric tons from General Motors Corporation (2004).

Compressed Air in Automotive Manufacturing

Compressed air is used relatively indiscriminately in automotive manufacturing due to its ease of setup. There is no need for additional maintenance or spe-

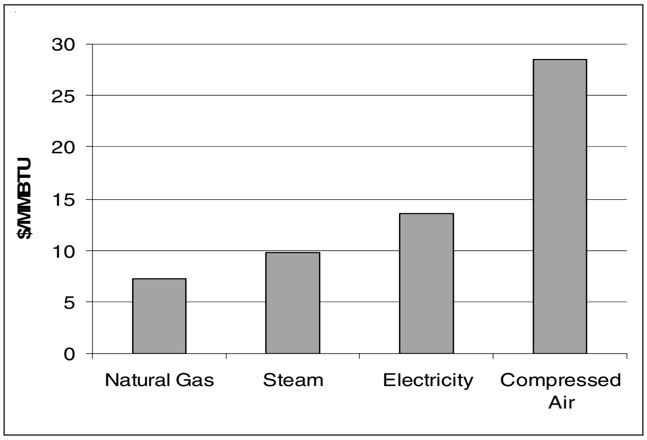

Figure 1
Cost of Energy Delivery Modes

cial machines; the task can be accomplished by adding piping. In addition, as a form of energy, compressed air represents no fire or explosion hazard; as the most natural of substances, it is clean and safe and regarded as totally "green" (Cox 1996).

At Ford Motor Company's Livonia (Mich.) Transmission Plant, the compressed air system has been identified as a source of potential cost and environmental impact savings. *Figure 2* illustrates the largest five compressed air consuming processes during transmission manufacturing, among which case and valve body machining are two processes that make particularly extensive use of compressed air. Together, they consume 56% of all compressed air used.

At Ford's Livonia Transmission Plant, there are 24 Ex-Cell-O CNC milling machines used for case and valve body machining. In this project, quantitative analysis is conducted on the compressed air usage patterns for all of these 24 Ex-Cell-O machines.

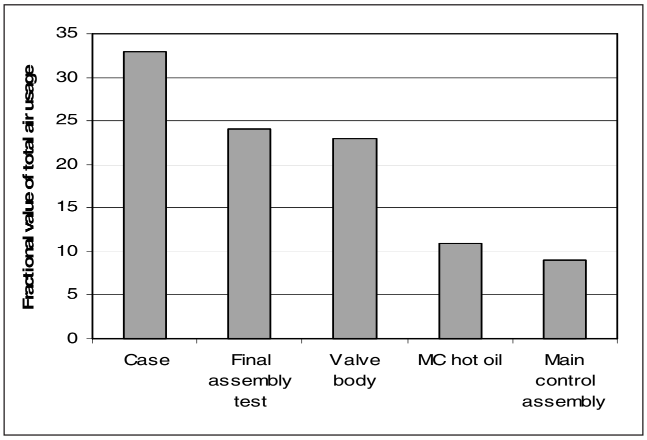

Figure 2
Compressed Air Usage Pareto Chart

The following three alternative supply patterns are considered, as shown in *Figure 3*:

(1) **Plant Air:** the whole plant is supplied with compressed air from the air house, with pipelines spread out in the plant to provide compressed air to all facilities.
(2) **Point-of-Use (POU):** each machine is exclusively supplied by an independently installed air compressor.
(3) **Local Generation:** a certain number of machines are grouped together and supplied by an air compressor.

Alternative Usage Patterns

Plant Air

Plant air is the option currently being used at Ford's Livonia Transmission Plant, although there are a number of problems with this supply option:

(1) **Infrastructure Complexity:** A plant air system is very complicated, especially in large-scale use like that of Ford's Livonia Transmission Plant. The complexity of the system not only brings challenges in layout and supply of the compressed air through the pipelines, but also creates high cost and difficulties in subsequent maintenance and operations.
(2) **Low Efficiency:** The plant air system operates at low efficiency. Typically, less than 60% of the total compressed air consumed contributes directly to the goods and services for which production was intended (Foss 2002). While Ford's Livonia Trans-

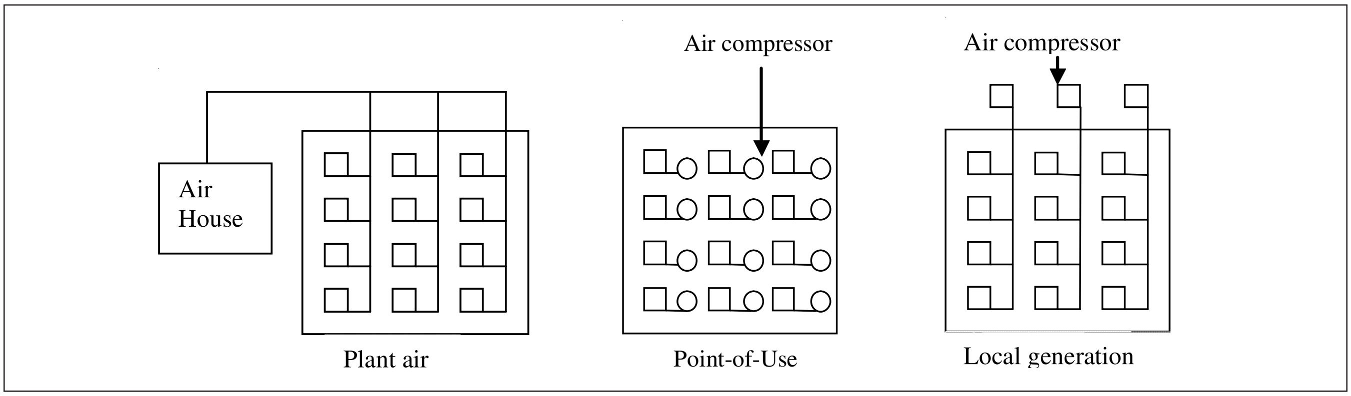

Figure 3
Air Configuration Diagrams

mission Plant operates at greater than average efficiency of 72% usage for real operations, further improvements are still trying to be made. Leaks are a major problem in plant air supply. They can occur anywhere along the pipeline, especially at interfaces and connectors of supply lines such as couplings, fittings, filters, regulators, valves, and thread sealants. Eliminating leaks entirely is not feasible, and the system infrastructure often makes ongoing repair costly and difficult.

(3) **Energy Storage:** The compressed air system works as a power source to the production facilities. Pressure is difficult to store due to inevitable leakage and limited storage space efficiency.

(4) **Excess Supply:** Stable air pressure is critical for the practical operation of production facilities. Further, the supply system must be able to meet maximum demand at all times. These demands require that excess compressed air be provided for the system, which not only consumes more energy than needed but also increases equipment wear and causes reduced equipment life and higher maintenance cost.

(5) **High Cost:** With the large amount of compressed air consumed daily for various operations at Ford's Livonia Transmission Plant, the total cost may be reduced by using other supply patterns.

For convenience, the subsequent comparison and evaluation of other two usage patterns are performed in comparison to plant air supply.

Point of Use (POU)

It is hypothesized that there is potential for further improvements in distributed compressed air generation, following trends in utilities generation moving from large-scale generation systems to high-efficiency point-of-use systems.

Ford envisions POU generation of compressed air in the future as a means to improve environmental image by eliminating the stacks common to plant power houses. The air compressor subject to analysis for the POU option is a Kaeser compressor, with data and information collected from its local supplier in Michigan. Information regarding the Kaeser compressor for the POU option is provided in *Table 1*.

Local Generation

Local generation is to group certain number of CNC machines together to be supplied by one air compressor. The advantage of this pattern is elimination of the problematic long, complicated pipelines in the plant air supply pattern, accordingly making the system easy and convenient in control and maintenance. In this project, local generation is analyzed in six options, namely LG1 through LG6, according to the number of CNC machines a single compressor is able to supply. The air compressors for the six local generation options are also from Kaeser, as listed in *Table 2*.

Table 1
POU Air Compressor Specifications

Option	Model	Pressure Rating (psi)	Flow Rate (ft^3/min.)	Equipment Life (years)	Floor Space Required (ft^2)	Motor Power (hp)	Noise Level
POU	SX4	110	15.5	15–20	3.6	4	66

Table 2
Local Generation Air Compressor Specifications

Option	Model	No. of CNCs Supplied	Pressure Rating (psi)	Flow Rate (ft^3/min.)	Equipment Life (years)	Floor Space/ Compressor (ft^2)	Motor Power (hp)	Noise Level
LG1	SM11	3	110	42	15–20	4.5	10	69
LG2	SK19	5	110	68	15–20	6.9	15	67
LG3	SK26	7	110	92	15–20	6.9	20	67
LG4	AS25	9	110	111	15–20	8.3	25	67
LG5	AS30	10	110	124	15–20	8.3	30	68
LG6	ASD40S	14	110	166	15–20	8.3	40	67

EnVS Analysis

Environmental Value systems (EnVS), developed at University of California–Berkeley, is an analytical tool to aid decision making through evaluation of the economic and environmental performance of manufacturing processes/products (Thurwachter 2000; Krishnan and Ayyagar 2002; Krishnan 2003). In this particular study, EnVS was configured to compare various solutions for compressed air generation using cost of ownership (CoO) and environmental impact matrices. The EnVS framework accounts for all of the controllable variables that affect outputs and is also equipped to perform sensitivity analysis on those variables.

EnVS analysis is divided into several stages, represented as a series of worksheets in an Excel document. Process identification, the first step, is the analysis of the demand side of requirements for compressed air in various components of the 24 Ex-Cell-O machines. The step following is the collection of the performance specifications of the supply side of compressed air. These are primarily the compressor characteristics, including energy and load efficiency. Facility information is obtained and utilized to perform the complete CoO study.

The problem is set up to perform the study for listed alternatives. The data obtained from various sources were entered into the EnVS and the results are presented in the following sections. A functional unit of cents or kilowatt-hours per 1,000 cubic feet of air was chosen to conform to industry standards.

Cost Estimate

The CoO study is a complete economic analysis of the two alternative usage patterns, to compare their cost of ownership with that of plant air in supplying the Ex-Cell-O machines. The costs considered are depreciable costs, setup costs, and annual costs for operation of the equipment annually. Depreciable costs are equipment cost divided by equipment life; setup costs include those for installation, transportation, and engineer training; annual costs include those for electricity, space consumed on the factory floor, maintenance, and some consumables.

For each alternative:

$$CoO = \frac{(C_1 + C_2 + C_3) \times M \times 100}{A \times N} \times 1000 \tag{1}$$

in cents/1000 ft^3

where

Depreciable cost:

$$C_1 = \frac{D}{Y} \quad \text{\$/year}$$

D: equipment cost, \$
Y: equipment life, years

Setup cost:

$$C_2 = I + T + \sum P \times F \quad \text{\$ in first year}$$

I: installation fee, \$
T: transportation fee, \$
P: number of people to be trained
F: training fee for each person, \$

Annual cost:

$$C_3 = S \times R_S + E \times R_E + \sum O + H \times R_M \quad \text{\$/year}$$

S: footprint for the equipment, ft^2
R_S: footprint cost rate, \$/ft^2/year
E: electricity consumed, KWH/year
R_E: electricity rate, \$/KWH
O: cost of various consumables, \$
H: downtime, hours
R_M: maintenance cost, \$/hour
M: number of air compressors needed to supply all 24 Ex-Cell-O CNC machines
A: total amount of compressed air consumed by all 24 Ex-Cell-O machines, ft^3/year
N: total number of Ex-Cell-O CNC machines

In the numerical analysis, Eq. (1) is used to calculate CoO in cents per 1,000 ft^3 for POU and local generations based on data shown in *Table 3*. Meanwhile, CoO for plant air, at a rate of 24 cents per 1,000 ft^3, is collected directly from Ford's Livonia Transmission Plant. Data used for CoO calculations are listed in *Table 3*.

For the CoO result, the collected plant air supply data reflects losses due to leaks in the pipelines, while POU and local generation compressor specs do not. Here it is assumed that there are negligible losses in POU and local generations because of short connections and fewer interfaces in the two applications.

Compressors used for both POU and local generation are assumed to have an operational life of five years, which is one third or one quarter of their designed life. Accordingly, a higher reliability and better working performance could be ensured. The

Table 3
CoO Calculation Data on POU and Local Generations

Usage Pattern Options	POU	LG1	LG2	LG3	LG4	LG5	LG6
Pressure rating (psi)	110	110	110	110	110	110	110
Flow rate (ft^3/min.)	21	42	68	92	111	124	166
CNC machines per group	1	3	5	7	9	10	14
Price ($)	4,050	6,298	7,833	8,889	9,360	10,120	12,252
Installation fees ($)	1,000	1,200	1,200	1,200	1,300	1,300	1,300
Transportation fees ($)	136	168	194	215	250	270	285
Consumables (filters, etc) ($/year)	170	190	245	245	412	412	477
Life time (years)	15–20	15–20	15–20	15–20	15–20	15–20	15–20
Maintenance hours per year	8	10	10	10	10	10	10
Floor space required (ft^2)	3.5	4.5	6.9	6.9	8.3	8.3	8.3
Driven motor power (hp)	4	10	15	20	25	30	40
Motor efficiency (%)	0.875	90.2	91.7	91.7	91.7	91.7	92.4

Table 4
First-Year Cost of Ownership Values of Three Usage Patterns (unit: cents/1,000 ft^3)

Option	POU	LG1	LG2	LG3	LG4	LG5	LG6
Annual cost	25.93	17.69	15.05	14.54	13.72	15.60	13.01
Setup cost	47.58	18.61	11.83	6.08	7.79	7.88	5.30
Depreciable cost	18.85	14.95	11.62	10.55	8.33	9.01	7.27
Cost of Ownership	102.36	51.25	38.50	31.18	29.85	32.49	25.58

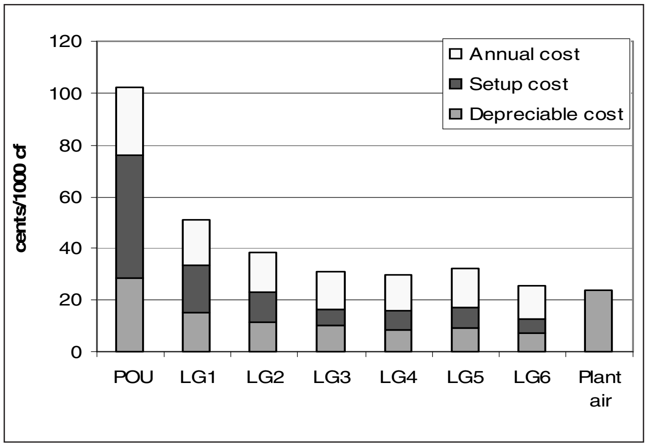

Figure 4
First-Year Cost of Supply Configurations (with setup cost)

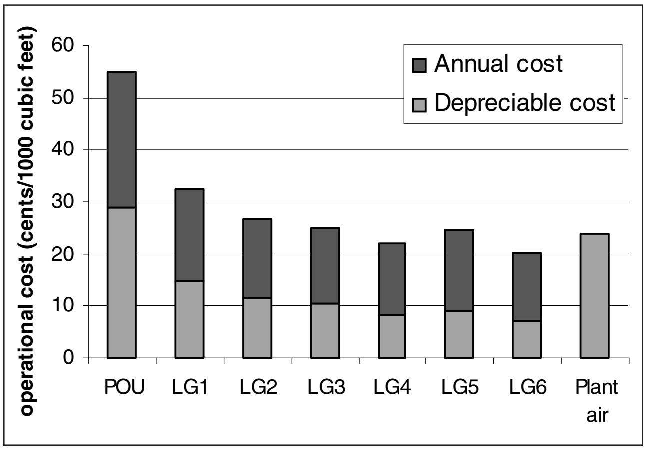

Figure 5
Follow-On Year Cost of Supply Configurations (without setup cost)

calculated CoO results for the first year are shown in *Table 4* and plotted in *Figure 4*.

The POU generation is the most expensive solution in terms of the costs associated with generating 1,000 cubic feet of air. It is five times more expensive than plant air. The primary cost drivers for POU system are the original equipment and setup costs. The costs associated with generating 1,000 cubic feet of compressed air through local generation are very much comparable to the current operational cost from the plant air supply pattern even in the first year. With the setup cost removed from above CoO calculations, the follow-on operational cost of the local generation option could be lower than that of plant air supply, as shown in *Figure 5*.

The operation cost comes down after the first year of operation, as there are many one-time costs such as installation, transportation, and training. There is a nearly 40% drop in total costs of POU supply following the stage of initial investment, while the cost drops for plant air and local generations are not that significant. As a demonstration, the operational costs are calculated with a 4% inflation rate assumed for the follow-on years, as shown in *Table 5*.

Table 5
Operation Cost of Compressed Air Supply Options
(unit: cents/1,000 ft^3)

Options	Year 1	Year 2	Year 3	Year 4	Year 5
POU	102.36	55.82	56.89	58.02	59.18
LG1	51.25	33.35	34.08	34.85	35.64
LG2	38.50	27.28	27.90	28.55	29.23
LG3	31.18	25.67	26.28	26.91	27.56
LG4	29.85	22.60	23.18	23.77	24.39
LG5	32.49	25.23	25.88	26.55	27.26
LG6	25.58	20.81	21.35	21.91	22.50
Plant air	24.00	24.96	25.96	27.00	28.08

Figure 6 shows that operation costs associated with generating 1,000 cubic feet of compressed air are very high for POU, while the operation costs are comparable between plant air and local generations. The yearly operational cost of LG4 and LG6 are even a little bit lower than that of plant air in a five-year running period.

By the calculations, taking the LG4 option instead of plant air could save an average of $2,031 each year on the 24 CNC machines, while the LG6 option could save an average of $3,273 each year for all of these CNC machines.

Environmental Impact Analysis

Environmental impact assessment is complicated due to the amount of data necessary for performing a complete analysis. However, it was clear that the energy used for generation during regular operation has the most serious environmental impact compared to compressor use or end of life. Energy required for producing 1,000 cubic feet of air was used for comparing the relative environmental impact of each system.

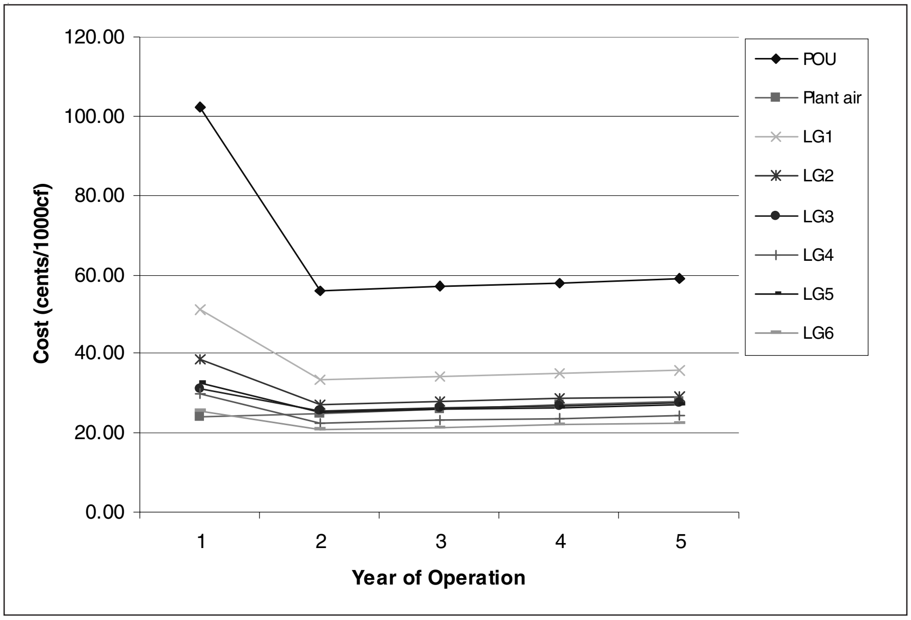

Figure 6
Yearly Costs for Air Supply Configurations

$$Energy = \frac{HP \times H \times T\% \times F\% \times L \times 0.746}{M_E \times A} \times 1000 \qquad (2)$$

where

HP: motor horsepower
H: operating hours per year
$T\%$: percent of time running at load level
$F\%$: percent of full load
L: load factor
M_E: motor efficiency
A: total amount of compressed air consumed by all CNC machines
0.746: horsepower-to-KWH coefficient

The collected data on POU and local generations are plugged into Eq. (2) to calculate the energy consumption of each option, in KWH/1,000 ft^3, to compare with energy consumption data of plant air, which is directly collected from Ford's Livonia Transmission Plant. The results are shown in *Table 6* and plotted in *Figure 7*.

Energy required for producing 1,000 cubic feet of air was used for comparing the relative environmental impact of each system. Plant air consumes the most energy among these options, with POU performing only slightly better, which is due to POU operated in a more efficient way. When compared, local generation is the best solution in terms of energy conservation.

From calculations, taking LG4 instead of plant air can save 95,764 KWH each year from the total 24 Ex-Cell-O CNC machines.

Conclusion

Compressed air is one of the most expensive energy sources in

Table 6
Energy Consumption of Compressed Air Supply Options

Option	POU	LG1	LG2	LG3	LG4	LG5	LG6	Plant Air
Energy (KWH/1,000 ft^3)	2.793	2.258	1.999	1.904	1.85	1.999	1.889	3.272

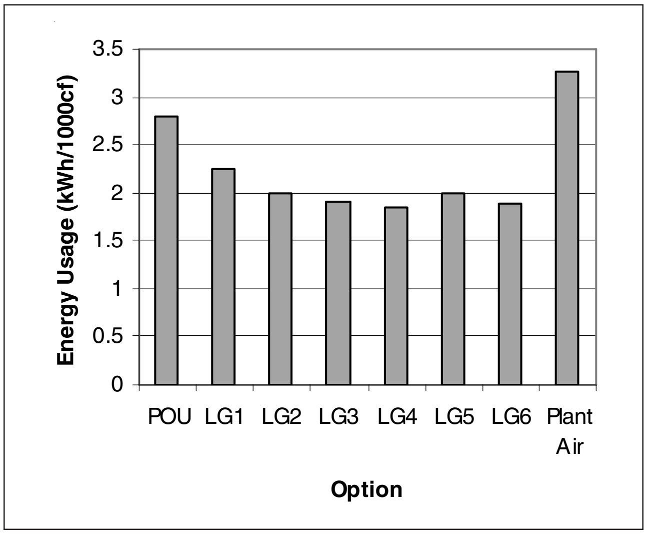

Figure 7
Energy Use of Supply Configurations

manufacturing. This paper presents a quantitative analysis on three compressed air supply patterns—plant air, point of use (POU), and local generation—as alternatives for future compressed air usage.

The Cost-of-Ownership and energy use analysis are performed on the three alternatives supplying the 24 Ex-Cell-O CNC milling machines at Ford's Livonia Transmission Plant.

The quantitative analysis favors local generation for cost consideration and energy efficiency. Employment of local generation instead of plant air could potentially save $2,000–$3,200 dollars and 95,000 KWH each year on the Ex-Cell-O CNC milling machines at Ford's Livonia Transmission Plant. Meanwhile, local generation offers numerous advantages over plant air in regard to reliability, simplicity, leakage prevention, and flexibility. Local generation is supplied by relatively short pipelines, which may lead to a significant reduction of losses due to leaks. Extra local compressors may be connected to the Ex-Cell-O machines in parallel, which automatically builds a great deal of redundancy into the system. Furthermore, the scale of local generation compressors enables greater flexibility as machines and processes change.

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Arvind Rangarajan is currently working as a mechanical engineer at GE Global Research. He received his BS in mechanical engineering from Indian Institute of Technology Madras and MS and PhD degrees in mechanical engineering from the University of California at Berkeley. Dr. Rangarajan's research is focused on tool path and process planning for machining applications.

David Dornfeld is professor of manufacturing engineering at the University of California at Berkeley and holds the first Will C. Hall Family Chair in Engineering. He is presently associate dean for interdisciplinary studies in the College of Engineering and holds an appointment as special division deputy, Engineering Division, Ernst Orlando Lawrence Berkeley National Laboratory. At UC Berkeley, Dr. Dornfeld leads the Laboratory for Manufacturing and Sustainability (LMAS) (*lmas.berkeley.edu*) with research activities in monitoring and analysis of manufacturing processes; precision manufacturing with specialization on chemical mechanical planarization for semiconductor manufacturing; green and sustainable manufacturing; and intelligent sensors and signal processing for process monitoring and optimization. He has published more than 300 papers in these fields, authored one research monograph, contributed chapters to several books, and holds six patents based on his research work. Dr. Dornfeld is a fellow of the Society of Manufacturing Engineers (SME), the American Society of Mechanical Engineers (ASME), and the CIRP (The International Academy for Production Engineering). He is a member of the Japan Society of Precision Engineering (JSPE), American Society of Precision Engineering (ASPE), Materials Research Society (MRS), and U.S. Acoustic Emission Working Group (AEWG). He is a past president of the North American Manufacturing Research Institution of SME.

Bill Ziemba was the supervisor of energy leadership for powertrain operations, Manufacturing Engineering, Global Engineering Alignment, for Ford Motor Company prior to his retirement in early 2006. The Manufacturing Engineering area is responsible for developing and implementing common practices and engineering methods for global powertrain operations (PTO) manufacturing processes. Ziemba was responsible for providing leadership for the PTO energy program, ensuring that business plan objectives were achieved, and was the PTO point of contact for energy matters. Bill has a BS in electrical engineering from Wayne State University and a MA in industrial management from Central Michigan University. He is a member of the Association of Energy Engineers.

Rod Whitbeck is a powertrain manufacturing technical specialist at Ford Motor Company in metal casting, forming, and post processing. He has also had extensive experience working with the U.S. Department of Energy on projects related to energy-efficient equipment design. Whitbeck has been with Ford Motor Company for more than 24 years, with more than 12 years of advanced manufacturing experience. He holds a master's degree in mechanical engineering from Northwestern University.