Proceedings of MARCON 2005:
The University of Tennessee
Maintenance and Reliability Conference (MARCON)
Knoxville, Tennessee, USA
May 3-6, 2005

Enterprise Derivative Application: Flexible Software for Optimizing Production while Minimizing Costs

Glenn O. Allgood, Ph.D., P.E., John Knox, Richard C. Ward, Ph.D.
Oak Ridge National Laboratory
Computational Sciences and Engineering Division
P.O. Box 2008, Oak Ridge, Tennessee 37831-6085

Abstract

A Microsoft (MS) Access application, the Enterprise-Derivative (ED) Application, implements Enterprise-Derivative analysis (EDA) for optimization of an industrial process (Allgood and Manges, 2001). It is a tool to help industry planners choose the most productive way of making their products while minimizing their cost. Developed in MS Access, the application allows users to input initial data ranging from raw material to variable costs and enables the tracking of specific information as material is passed from one process to another.

EDA is based on calculating Enterprise-Derivative sensitivity parameters. For the specific application of steel production these include the cost to product sensitivity, the product to energy sensitivity, the energy to efficiency sensitivity, and the efficiency to cost sensitivity. Using the ED Application, the user can display a particular sensitivity parameter or all sensitivity parameters can be compared for all processes.

Although EDA was originally designed for use by the steel industry, it is flexible enough to be applied to many other industrial processes. Examples of processes where EDA would be useful are wireless monitoring of processes in the petroleum cracking industry and wireless monitoring of motor failure for determining the optimum time to replace motor parts.

One advantage of the MS Access ED Application is its flexibility in defining the process flow, namely establishing the relationships between parent and child processes and between a process and the products resulting from a process. Due to the general design of the program, a process can be anything that occurs over time with resulting output (products). So the application can be easily modified for many different industrial and organizational environments. Another advantage is the flexibility of defining sensitivity parameters. Sensitivities can be determined between all possible variables in the process flow as a function of time. Thus the dynamic development of the process can be tracked over time and optimized. The EDA is a uniquely flexible and efficient way for planners to choose the most productive way to optimize production while minimizing costs.

Introduction

In today's manufacturing environment, systems and equipment are being asked to perform at levels not thought possible a decade ago. The intent is to push process operations, product quality, and equipment reliability to unprecedented levels while pursuing cost reduction initiatives. Industries see a tremendous amount of uncertainty associated with calculating total process impact, and fear undertaking such a venture. What is needed is a methodology that takes the guesswork out of calculating the total cost/benefit for any new technology or innovation. The Enterprise-Derivative analysis (EDA) provides a solution to this problem - a new tool for developing and managing investment strategies and risks.

The EDA mitigates risks by first identifying the potential benefits for all processes and sub-processes associated with new technologies. This is realized by calculating approximations for the first order sensitivity parameters (first derivatives) obtained from a Taylor Series expansion about the plant's operating point. These sensitivity parameters are invariant economic and operational indicators that quantify the impact of any proposed technology in terms of material throughput, efficiency changes, energy use, environmental effects, and costs. A set of coupled equations using these parameters links the entire enterprise system together, so that total impact can be calculated. The key to the model is evaluating the sensitivity parameters.

The EDA will have a major impact on business and engineering decisions to select and incorporate new technologies and innovations into processes. The measures of performance that are derived from the model are well defined, and they can be used to track technology impacts across the enterprise and over extended periods of operation.

The ED Application is used here for optimizing industrial processes. It is a tool to help industry planners choose the most productive way of making their products while minimizing their cost. Developed in MS Access, the application allows users to input initial data ranging from raw material to variable costs and enables the tracking of specific information as material is passed from one process to another.

In this paper we give an overview of the ED Application using process flow in mini-mill steel manufacturing (J. Torres, 2002). This example consists of twelve processes producing five products. Screenshots of the MS-Access application will demonstrate how EDA has been implemented for this specific case.

Enterprise-Derivative Analysis

The basis of EDA is the calculation of a set of ED sensitivity parameters that are used in a coupled set of equations to calculate the impacts on a process from a proposed technology. The assumption is that the proposed technology will not change the way manufacturing is done, but will affect the operational efficiencies about its current operating point. Given this assumption, the process can then be modeled as a first-order Taylor Series expansion about the operating point with changes being influenced by the first differential of a derived benefit. Process gains (production, efficiency, energy, and quality) are estimated as incremental changes from the operating point.

The mathematical formulation for any process gain, ***f***, is

$$f(x) = f(\chi_0) + f'(\chi_0)(x - \chi_0) + .. + \frac{f^n(\chi_0)(x - x_o)^n}{n!} + Rn, \qquad (1)$$

where χ_0 is the current plant operating point and Rn is a remainder and is ignored in this formulation. In this expansion, we are only interested in the first term, $f'(x_0)$, which is the generalized differential approximation or ED sensitivity term.

The generalized differential approximation (sensitivity) is expanded in general terms as a linear combination of ratios of total differentials of the process changes due to technology innovations, i.e. product, energy, and efficiency. The total differential is:

$$\Delta f_{Tech} = \frac{\partial E}{\partial \eta}\Delta\eta + \frac{\partial \eta}{\partial C}\Delta C + \frac{\partial C}{\partial \mathrm{P}}\Delta \mathrm{P} + \frac{\partial \mathrm{P}}{\partial E}\Delta E + \varepsilon \ , \qquad (2)$$

where, E, η, C, P are the energy, efficiency, savings, and product, respectively and ε is the error associated with the approximation and is ignored in the EDA.

These sensitivity parameters are based on a total derivative calculation and are approximations to the first partial derivatives of a multiple variable function. The sensitivity parameters are defined below.

$\frac{\partial E}{\partial \eta}$ is the change in process energy per unit change in efficiency

$\frac{\partial \eta}{\partial C}$ is the change in process efficiency per unit change in costs

$\frac{\partial C}{\partial \mathrm{P}}$ is the change in process costs per unit change in product

The remaining sensitivity parameter, $\frac{\partial \mathrm{P}}{\partial E}$, can be calculated directly or derived as ratios of other sensitivity parameters.

Conducting an EDA involves the following four steps:

1. Develop the process flow
2. Compute the sensitivity parameters of the enterprise
3. Conduct a technology assessment and impact analysis
4. Optimization (what-if strategies)

Each step will be described in detail for an example problem (Torres, 2002) which describes process flow in mini-mill steel manufacturing. The entire process consists of twelve sub-processes as shown below.

Electric Arc Furnace → Ladle Metallurgy → Caster → Tunnel Furnace (TF) →Hot Strip Mill (HSM).

Process HSM splits: HSM → Acid Pickling → Cold Mill Reduction (CMR) A → Galvanized (GAL)

HSM → Temper A (TEMP A)

Process TEMP A splits: TEMPA → Cold Mill Reduction B

TEMPA → Annealing → Temper B (TEMP B)

Step 1 – Develop the Process Flow

A requirement for conducting an EDA is to develop a complete understanding of the process: its product flow, material changes, and procedural steps used to make the product. This includes identifying energy use, material residence time, and maintenance and operational procedures. This microscopic view of the process is needed to understand energy, material, and time management as it applies to the current process. In the course of conducting the EDA, a detailed process flow diagram is developed. Roll-ups from these process flow diagrams are then developed along with energy and time management diagrams. Some of the process variables extracted from the diagrams are used in the calculation of the first order Enterprise-Derivative sensitivity parameters.

In the ED Application, the user can interactively design the process flow by dragging the process icons into place (Fig. 1). Likewise the user drags the product icons where desired (in this example there are products out of these processes: TF, GAL, TEMP A, TEMP B and CMR B). Once the user has specified the processes and products and connected the process icons, the user must create the parent-child relationships, name the processes, and save the process flow. In this example there are twelve processes and five products. There is also a “process zero” which is the initial feed. The diagram represents the flow of material from the initial feed to successive processes with production of products P1 through P5.

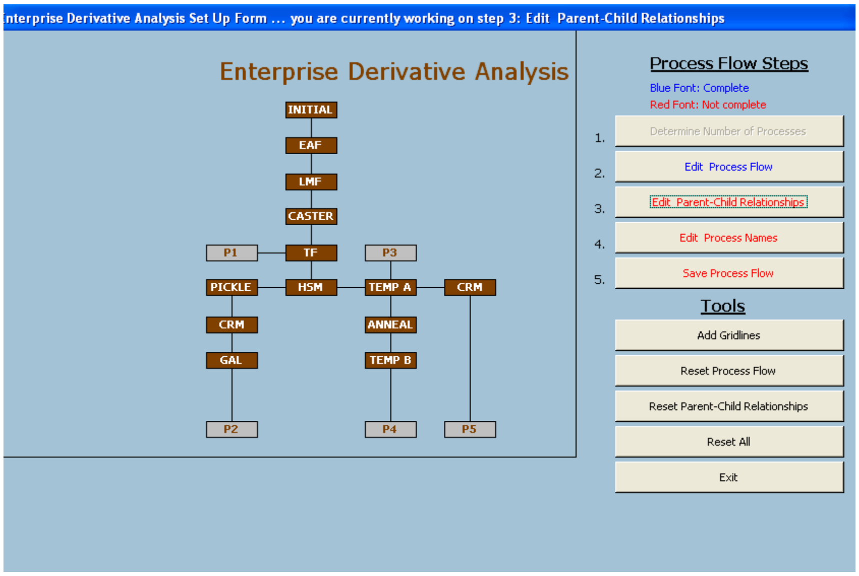


Figure 1. EDA Form for creating the process flow. User can drag process icons into place and connect processes in an any desired manner.

Step 2 – Compute the Sensitivity Parameters of the Enterprise

The next step is to compute the sensitivity parameters. The user must first enter the Enterprise information for each process as shown in Fig. 2. This information includes costs, energy usage, and revenue for each product. Once this information is completed, the sensitivities are computed and displayed as shown in Fig. 3. This EDA sensitivity form displays the sensitivity parameters for each associated process. The sensitivity parameters (and associated units) are the ones defined previously, $\frac{\partial E}{\partial \eta}$ (kW-h), $\frac{\partial \eta}{\partial C}$ (\$$^{-1}$), $\frac{\partial C}{\partial P}$ (\$/ton), $\frac{\partial P}{\partial E}$ (ton/kW-h), and two additional sensitivities which break the energy utilization into both an electricity sensitivity parameter, $\frac{\partial P}{\partial EC1}$ (ton/kW-h), and a natural gas sensitivity parameter, $\frac{\partial P}{\partial EC2}$ (ton/kW-h).

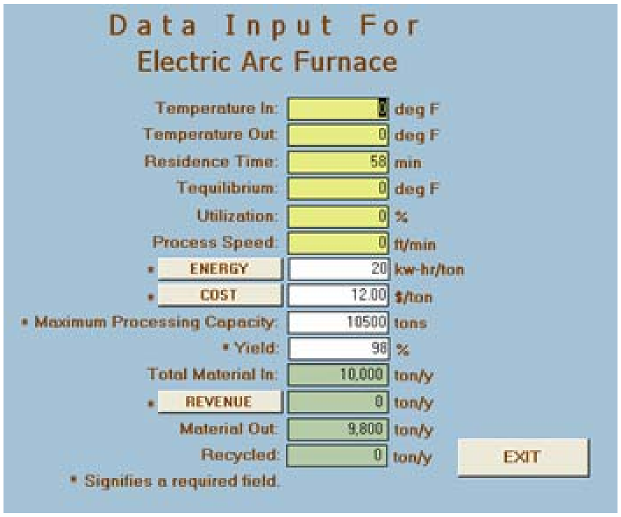
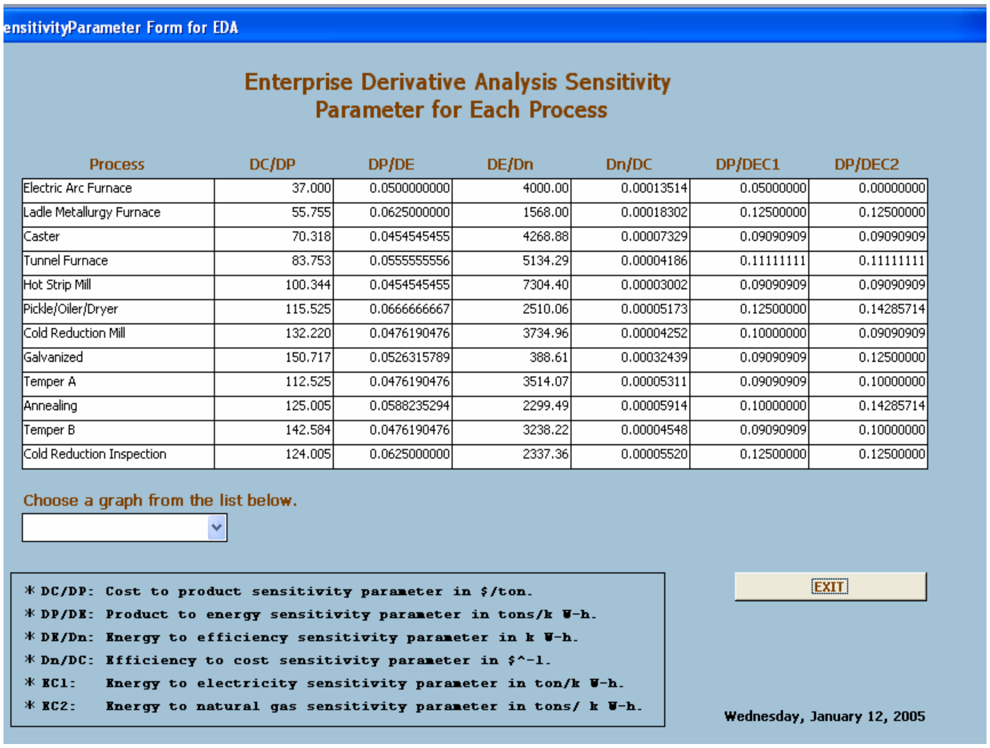


Figure 2. On this form the user enters the Enterprise information that consists of these required fields: energy, cost, maximum processing capacity, yield, and revenue. Other fields are not required, but the information is stored in the database.

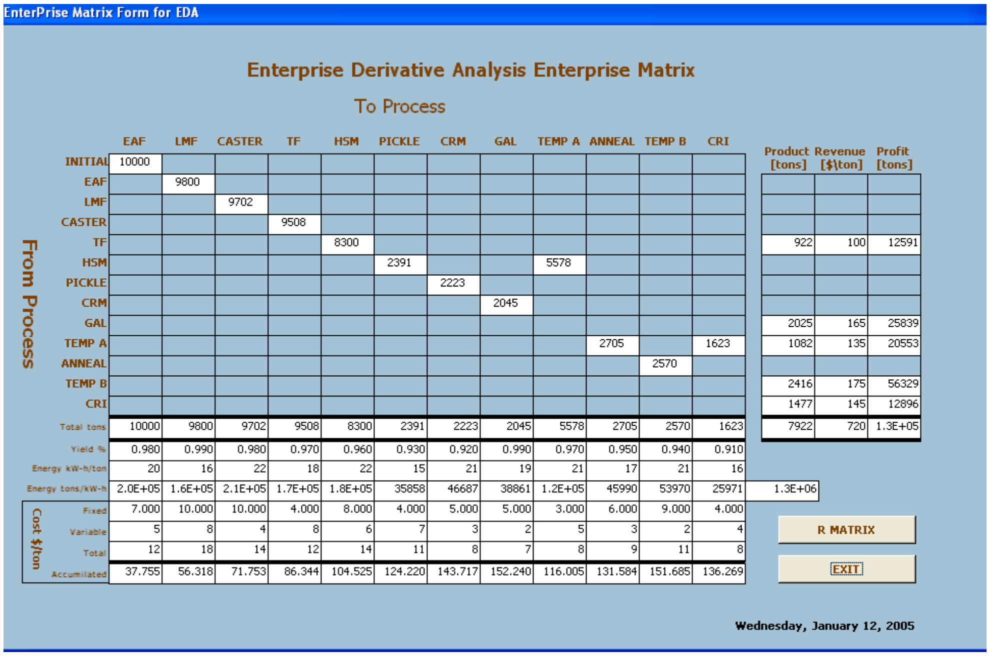


Process	DC/DP	DP/DE	DE/Dn	Dn/DC	DP/DEC1	DP/DEC2
Electric Arc Furnace	37.000	0.0500000000	4000.00	0.00013514	0.05000000	0.00000000
Ladle Metallurgy Furnace	55.755	0.0625000000	1568.00	0.00018302	0.12500000	0.12500000
Caster	70.318	0.0454545455	4268.88	0.00007329	0.09090909	0.09090909
Tunnel Furnace	83.753	0.0555555556	5134.29	0.00004186	0.11111111	0.11111111
Hot Strip Mill	100.344	0.0454545455	7304.40	0.00003002	0.09090909	0.09090909
Pickle/Oiler/Dryer	115.525	0.0666666667	2510.06	0.00005173	0.12500000	0.14285714
Cold Reduction Mill	132.220	0.0476190476	3734.96	0.00004252	0.10000000	0.09090909
Galvanized	150.717	0.0526315789	388.61	0.00032439	0.09090909	0.12500000
Temper A	112.525	0.0476190476	3514.07	0.00005311	0.09090909	0.10000000
Annealing	125.005	0.0588235294	2299.49	0.00005914	0.10000000	0.14285714
Temper B	142.584	0.0476190476	3238.22	0.00004548	0.09090909	0.10000000
Cold Reduction Inspection	124.005	0.0625000000	2337.36	0.00005520	0.12500000	0.12500000

Figure 3. The sensitivity parameters are computed and displayed once the user has entered all of the Enterprise information.

Enterprise Matrix

The user can select to display the Enterprise Matrix, an overview of the EDA application in matrix view (Fig. 4). The top half of the screen shot shows the flow of material from one process to another while the bottom half shows the process parameters. At the right of the form, the product, revenue and profit are displayed. The user can switch from this "Enterprise" View (E MATRIX), which shows transfer in terms of tons of material, to an “R Matrix” view in which displays the ratio of material moved from one process to next. To activate this feature, the user clicks the R MATRIX button in the lower right corner. This converts the top half of the form to reflect the material flow as a ratio.



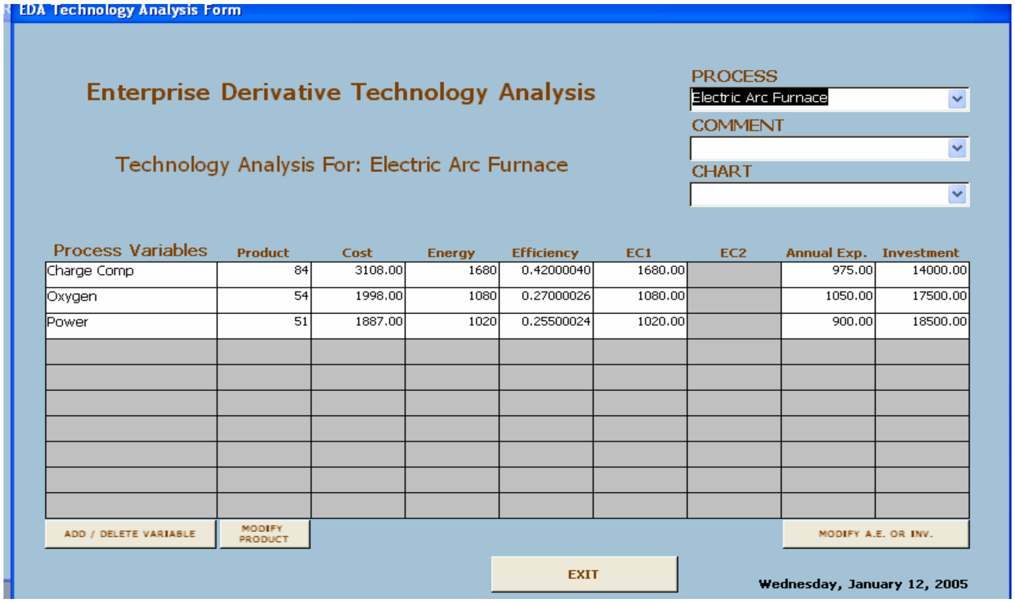
	EAF	LMF	CASTER	TF	HSM	PICKLE	CRM	GAL	TEMP A	ANNEAL	TEMP B	CRI	Product [tons]	Revenue [$\ton]	Profit [tons]
INITIAL	10000														
EAF		9800													
LMF			9702												
CASTER				9508											
TF					8300								922	100	12591
HSM						2391			5578						
PICKLE							2223								
CRM								2045							
GAL													2025	165	25839
TEMP A										2705		1623	1082	135	20553
ANNEAL											2570				
TEMP B													2416	175	56329
CRI													1477	145	12896
Total tons	10000	9800	9702	9508	8300	2391	2223	2045	5578	2705	2570	1623	7922	720	1.3E+05
Yield %	0.980	0.990	0.980	0.970	0.960	0.930	0.920	0.990	0.970	0.950	0.940	0.910			
Energy kW-h/ton	20	16	22	18	22	15	21	19	21	17	21	16			
Energy tons/kW-h	2.0E+05	1.6E+05	2.1E+05	1.7E+05	1.8E+05	35858	46687	38861	1.2E+05	45990	53970	25971	1.3E+06		
Fixed	7.000	10.000	10.000	4.000	8.000	4.000	5.000	5.000	3.000	6.000	9.000	4.000			
Variable	5	8	4	8	6	7	3	2	5	3	2	4			
Total	12	18	14	12	14	11	8	7	8	9	11	8			
Accumilated	37.755	56.318	71.753	86.344	104.525	124.220	143.717	152.240	116.005	131.584	151.685	136.269			

Figure 4. Once the user has entered all the Enterprise information and the sensitivity parameters have been computed, the E Matrix (products transferred from process to process in tons) or the R Matrix (ratio of material moved from one process to the next) can be displayed.

The Enterprise Matrix and the R Matrix represent the culmination of the Enterprise computation. The ED Application has all the information needed to compute the plant operating point. The user now moves on to conduct a technology assessment and impact analysis, where changes in technology are introduced, and products produced by processes are increased or decreased and the impact analysis is made about the original plant operating point.

Step 3 - Conduct a Technology Assessment and Impact Analysis

Using the information extracted from the process flow diagrams, a technology assessment can be conducted for each manufacturer or company. Plant managers and technical representatives identify new technologies and needs (or innovations) that are considered important to enhancing their operational performance or increasing overall process efficiency. The program requires the change in the product for each process for every specified technology modification (Fig. 5). This analysis should identify all operational impacts that these technologies will have on the Enterprise.



Process Variables	Product	Cost	Energy	Efficiency	EC1	EC2	Annual Exp.	Investment
Charge Comp	84	3108.00	1680	0.42000040	1680.00		975.00	14000.00
Oxygen	54	1998.00	1080	0.27000026	1080.00		1050.00	17500.00
Power	51	1887.00	1020	0.25500024	1020.00		900.00	18500.00

Figure 5. Once the Enterprise has been defined, the user enters the desired technology improvements and their associated product increases (or decreases) for all technology modifications for each process. This form then displays the differential in the sensitivity parameters derived from the associated product change, using the previously computed sensitivity parameters.

The Technology Analysis form allows the user to add or delete new technologies, annual expenses, and investments for each process. After the new technologies and innovations have been identified, the economic and process impacts are calculated for the Enterprise system. These measures of performance will be in terms of cost saving or yield increases if the innovations are deployed.

Given these economic indicators, the model then calculates three additional parameters; energy, efficiency, and per-process cost savings. Energy savings are computed for electricity, natural gas and for total energy. These parameters, along with other process data, are used in the subsequent analysis and comparison.

Step 4 - Optimization

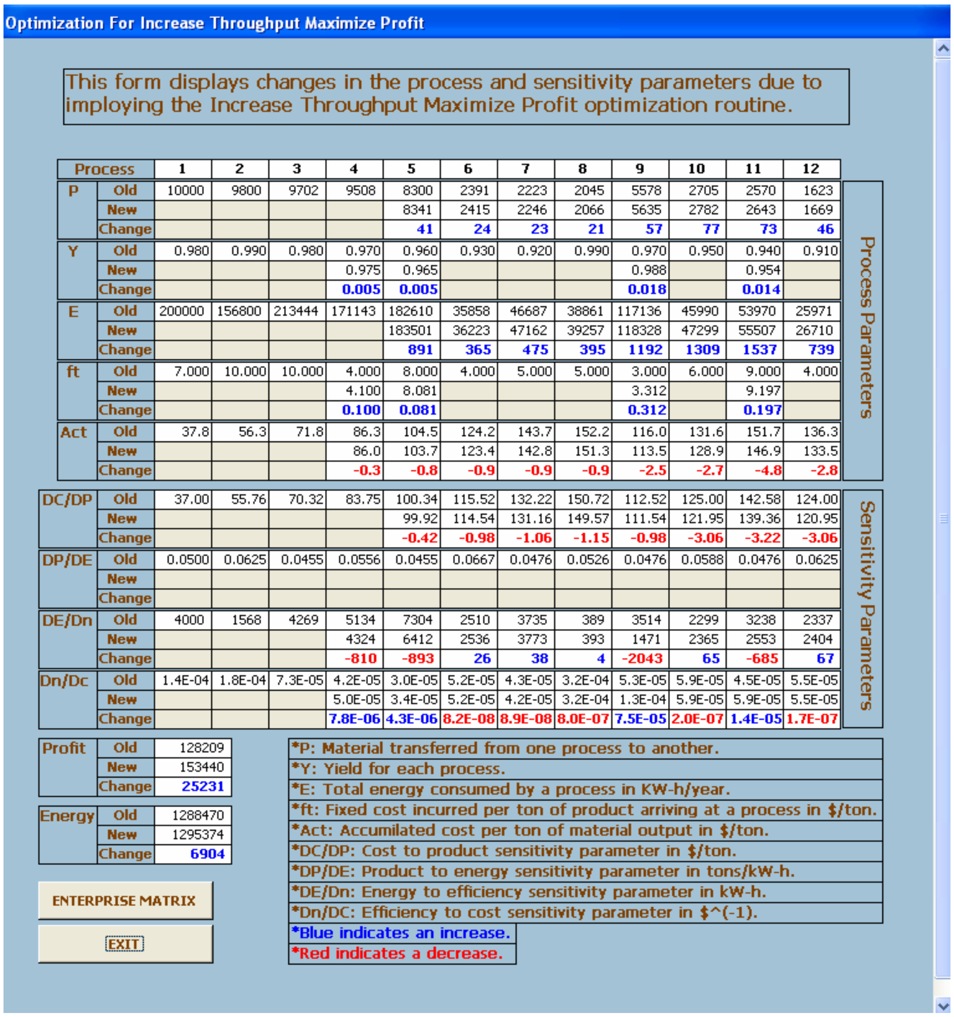
The last element in conducting the EDA is selecting the optimal mix of technologies based on some stated criteria. The optimization scheme (algorithm or heuristic) will use the economic and process impacts derived from the EDA coupled with the ED sensitivity parameters to search for an optimal solution in the value space for a given set of hard and soft constraints. The different optimization approaches include:

Risk Analysis: Risk Analysis determines the process and economic impact of a single new operational strategy. The process and economic impact analysis becomes straightforward, assuming the product mix ratios are maintained.

Alternative Analysis: Alternative Analysis deals with contrasting and comparing two or more operational strategies. The optimization module can calculate changes in $f(x)$ for each operational strategy using the coupled equations, and provide a ranking based on production cost savings, additional throughput and energy savings assuming the product mix ratios are not changed.

Enterprise Analysis: Enterprise Analysis selects the operational strategy or group of operational strategies that will maximize or minimize an objective function given a set of criteria.

For an example when profit is maximized while increasing throughput for the steel mini-mill, the user is presented with a form (Fig. 6) showing the differences between the original process sensitivity parameters and the optimized ones. Negative entries (colored red on the screen) signify a decrease in parameters and positive entries (colored blue on the screen) signify an increase in parameters. The user can click on the ENTERPRISE MATRIX button on the Optimization form to view an optimized Enterprise matrix (Fig. 7) showing the results of the optimization.


Optimization For Increase Throughput Maximize Profit

This form displays changes in the process and sensitivity parameters due to imploying the Increase Throughput Maximize Profit optimization routine.

Process		1	2	3	4	5	6	7	8	9	10	11	12
P	Old	10000	9800	9702	9508	8300	2391	2223	2045	5578	2705	2570	1623
	New					8341	2415	2246	2066	5635	2782	2643	1669
	Change					41	24	23	21	57	77	73	46
Y	Old	0.980	0.990	0.980	0.970	0.960	0.930	0.920	0.990	0.970	0.950	0.940	0.910
	New				0.975	0.965				0.988		0.954	
	Change				0.005	0.005				0.018		0.014	
E	Old	200000	156800	213444	171143	182610	35858	46687	38861	117136	45990	53970	25971
	New					183501	36223	47162	39257	118328	47299	55507	26710
	Change					891	365	475	395	1192	1309	1537	739
ft	Old	7.000	10.000	10.000	4.000	8.000	4.000	5.000	5.000	3.000	6.000	9.000	4.000
	New				4.100	8.081				3.312		9.197	
	Change				0.100	0.081				0.312		0.197	
Act	Old	37.8	56.3	71.8	86.3	104.5	124.2	143.7	152.2	116.0	131.6	151.7	136.3
	New				86.0	103.7	123.4	142.8	151.3	113.5	128.9	146.9	133.5
	Change				-0.3	-0.8	-0.9	-0.9	-0.9	-2.5	-2.7	-4.8	-2.8
DC/DP	Old	37.00	55.76	70.32	83.75	100.34	115.52	132.22	150.72	112.52	125.00	142.58	124.00
	New					99.92	114.54	131.16	149.57	111.54	121.95	139.36	120.95
	Change					-0.42	-0.98	-1.06	-1.15	-0.98	-3.06	-3.22	-3.06
DP/DE	Old	0.0500	0.0625	0.0455	0.0556	0.0455	0.0667	0.0476	0.0526	0.0476	0.0588	0.0476	0.0625
	New												
	Change												
DE/Dn	Old	4000	1568	4269	5134	7304	2510	3735	389	3514	2299	3238	2337
	New				4324	6412	2536	3773	393	1471	2365	2553	2404
	Change				-810	-893	26	38	4	-2043	65	-685	67
Dn/Dc	Old	1.4E-04	1.8E-04	7.3E-05	4.2E-05	3.0E-05	5.2E-05	4.3E-05	3.2E-04	5.3E-05	5.9E-05	4.5E-05	5.5E-05
	New				5.0E-05	3.4E-05	5.2E-05	4.2E-05	3.2E-04	1.3E-04	5.9E-05	5.9E-05	5.5E-05
	Change				7.8E-06	4.3E-06	8.2E-08	8.9E-08	8.0E-07	7.5E-05	2.0E-07	1.4E-05	1.7E-07

Process Parameters

Sensitivity Parameters

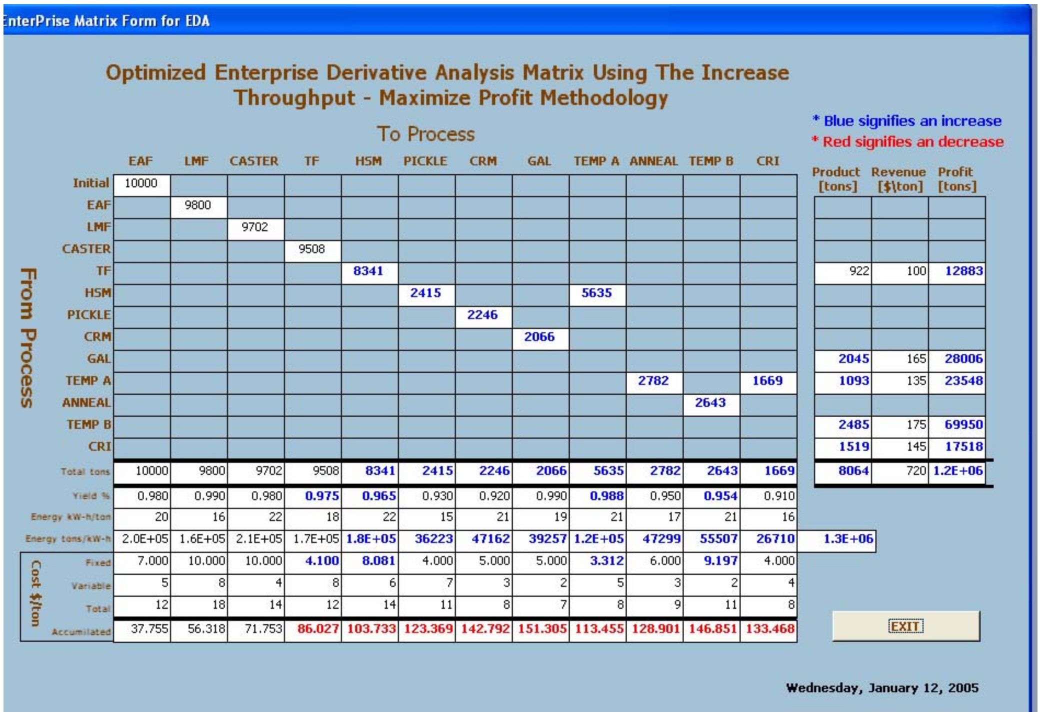
Profit	Old	128209
	New	153440
	Change	25231
Energy	Old	1288470
	New	1295374
	Change	6904

*P: Material transferred from one process to another.
*Y: Yield for each process.
*E: Total energy consumed by a process in KW-h/year.
*ft: Fixed cost incurred per ton of product arriving at a process in $/ton.
*Act: Accumilated cost per ton of material output in $/ton.
*DC/DP: Cost to product sensitivity parameter in $/ton.
*DP/DE: Product to energy sensitivity parameter in tons/kW-h.
*DE/Dn: Energy to efficiency sensitivity parameter in kW-h.
*Dn/DC: Efficiency to cost sensitivity parameter in $^(-1).
*Blue indicates an increase.
*Red indicates a decrease.

ENTERPRISE MATRIX

EXIT

Figure 6. The optimization form shows the differences between the original process sensitivity parameters and the optimized ones. Negative entries (colored red) signify a decrease in the parameter whereas positive entries (colored blue) signify an increase in parameter.



EnterPrise Matrix Form for EDA

Optimized Enterprise Derivative Analysis Matrix Using The Increase Throughput - Maximize Profit Methodology

* Blue signifies an increase
* Red signifies an decrease

From Process \ To Process	EAF	LMF	CASTER	TF	HSM	PICKLE	CRM	GAL	TEMP A	ANNEAL	TEMP B	CRI	Product [tons]	Revenue [$\ton]	Profit [tons]
Initial	10000														
EAF		9800													
LMF			9702												
CASTER				9508											
TF					8341								922	100	12883
HSM						2415			5635						
PICKLE							2246								
CRM								2066							
GAL													2045	165	28006
TEMP A										2782		1669	1093	135	23548
ANNEAL											2643				
TEMP B													2485	175	69950
CRI													1519	145	17518
Total tons	10000	9800	9702	9508	8341	2415	2246	2066	5635	2782	2643	1669	8064	720	1.2E+06
Yield %	0.980	0.990	0.980	0.975	0.965	0.930	0.920	0.990	0.988	0.950	0.954	0.910			
Energy kW-h/ton	20	16	22	18	22	15	21	19	21	17	21	16			
Energy tons/kW-h	2.0E+05	1.6E+05	2.1E+05	1.7E+05	1.8E+05	36223	47162	39257	1.2E+05	47299	55507	26710	1.3E+06		
Cost $/ton Fixed	7.000	10.000	10.000	4.100	8.081	4.000	5.000	5.000	3.312	6.000	9.197	4.000			
Cost $/ton Variable	5	8	4	8	6	7	3	2	5	3	2	4			
Cost $/ton Total	12	18	14	12	14	11	8	7	8	9	11	8			
Cost $/ton Accumilated	37.755	56.318	71.753	86.027	103.733	123.369	142.792	151.305	113.455	128.901	146.851	133.468			

EXIT

Wednesday, January 12, 2005

Figure 7. The Enterprise Matrix showing the processes which increased product transfer between processes (shown in blue) with corresponding decreases in costs (shown in red).

Conclusions

Companies are looking at R&D investments as a means to increase market share and equity along with revenue, profit, and dividends. They are concerned with understanding a technology's complete impact; its total cost of ownership, and what uncertainty and risk is associated with its R&D investments. Moreover, companies are looking for ways to determine and then reduce these risks.

The EDA can address these issues and have a major impact on how companies manage risk and make R&D investment decisions. The benefits derived from conducting an EDA are many and include:

- Quantifying the impact that a particular technology has on a plant in terms of economic benefits, energy savings, efficiency increases, and product gains.
- Providing metrics for a strategic decision making process.
- Identifying unique parameters that can be used to characterize a system's performance.
- Contrasting and comparing different technologies for a particular process or across the enterprise.
- Selecting the best technology mix based on a set of criteria (optimization).
- Calculating total impact on an enterprise and total cost of ownership.
- Tracking process and economic impact over time.

Using EDA, the MS Access ED Application makes available a new tool for developing and managing investment strategies and risks. The ED Application provides industry planners with a methodology to choose the most productive way of increasing product output while minimizing costs. Utilizing the Enterprise-Derivative sensitivity parameters, the ED Application provides various means to optimize the manufacturing process given the operational impacts of new technologies. This has been demonstrated for a specific application of a steel mini-mill manufacturing process.

Though applied here to model process flow in steel manufacturing, the EDA is flexible enough to be applicable to other industrial processes, examples of which are wireless monitoring of processes in the petroleum cracking industry and wireless monitoring of motor failure to determine the optimum time for replacing parts.

Other advantages of the MS Access ED Application are the flexibility with which the process flow is created and the sensitivity parameters defined. The ED Application is a uniquely flexible and efficient methodology for planners to use to optimize production while minimizing costs.

ACKNOWLEDGEMENTS:
Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Value Chain Analysis Program, under Contract DE-AC05-00OR22725 with UT-Battelle, LLC.

REFERNECES:

G. O. Allgood and W. W. Manges, (2001) "Value Chain Analysis (Value-Derivative) Model for the Steel Industry", Phase II Project Report for the U. S. Department of Energy, Office of Industrial Technologies.

J. A. Torres (2002) "An Integrated Value-Derivative Model for the Steel Industry to Evaluate and Optimize the Impact of Operational Strategies using Total Enterprise Performance Indicators", Dissertation for Doctor of Philosophy Degree, University of Tennessee, Knoxville, May, 2002.

Contact Address:
Dr. Glenn O. Allgood
Oak Ridge National Laboratory
Computational Science and Engineering Division
PO Box 2008, MS 6085
Oak Ridge, TN 37831-6085 USA

Phone: (865) 574-5673
Fax: (865) 576-0003
E-mail: allgoodgo@ornl.gov