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Mathematical Model to Optimize the Energy Consumed by a Semiconductors Manufacturing Industry – An Application

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Abstract

A recently developed mathematical model to optimize energy consumption in manufacturing companies was used in a semiconductor industry to generate alternatives for the illumination and air conditioning systems. To solve the algorithm, the software Lingo 12.0 was used and the feasible alternatives were identified. The results of the mixed integer linear program guided the company in the selection of cost-effective equipment to reduce the energy consumed. Additional recommendations regarding the logistics of their daily operations were considered to increase the expected savings in energy for the illumination and air conditioning systems. Potential savings in energy consumption were found and recommended to company management. This application showed the usability of mathematical modeling to solve enormous problems (i.e., utilities cost) in manufacturing industries that create a burden in their product cost. Results presented to management showed the different recommendations analyzed and their impact in energy cost reduction depending on the alternatives they chose. Potential savings would fluctuate from over $28,000 to over $58,000 per year depending on recommendations chosen by company management. The use of the mathematical model to solve the energy cost problem demonstrated how real world variables and constraints can be used to analyze day to day problems and help manufacturing industries to be cost competitive. Moreover, the results from this research effort can be disseminated as mathematical modeling applications within industrial environments with the example of a semiconductor manufacturing industry.

1. Introduction

With the purpose of expanding the use and application of a recently created mathematical model to optimize the consumption of energy in a manufacturing environment (1), an application of the model was performed in a semiconductors manufacturing industry. Due to the high overhead costs incurred by manufacturing companies nowadays and being the energy cost one of the highest, there was a true motivation to seek for alternatives to reduce this particular cost. Considering this realistic scenario, a semiconductors manufacturing company was looking for alternatives to reduce their energy consumption cost.

The main objective of this study was to choose a cost-effective way to optimize the consumption of energy within this manufacturing environment and to replace the existing equipment with alternatives that reduce energy consumption thus maximizing the economic benefits while reducing product cost. Secondary objectives included the analysis of how was the energy being consumed in the company to pinpoint the opportunities to reduce the consumption without any significant capital investment. Similarly, a significant contribution can be made to academic literature by showing real applications of mathematical modeling in industrial environments.

Considering the different systems that consume energy in a manufacturing facility (i.e., illumination, compressed air, air conditioning, etc.) and ranking them based on cumulative data of energy consumed, the illumination and air conditioning system were selected to apply the mathematical model. To study the feasibility of the considered alternatives, the payback method (2) was used because this is the economic analysis method that the company regularly uses to evaluate their capital investments.

2. Methodology

The areas of interest were identified within the manufacturing company and it was decided to divide the study in the following areas: offices, production, warehouse, and exterior. Based on the availability of historical data some offices, production areas, and the warehouse were analyzed. There was not enough data to include the exterior areas in the analysis. For three office areas, one production area, and the finished goods warehouse the illumination system was analyzed (refer to Table 1). For two office areas and eleven production areas, the air conditioning system was studied (refer to Table 2). The mathematical model was then applied to evaluate the air conditioning and illumination systems. The algorithm also considered when evaluated areas were located in different buildings.

Table 1: Illumination system evaluation

Areas	**Sub-areas**	
Office	1	Cubicles
	2	Office Area
	3	Open Office Area
Production	1	Production area
Warehouse	1	Finished Goods

The alternative equipment considered to substitute the currently used equipment for the illumination system was energy efficient bulbs. In the case of the air conditioning system analysis the chosen alternative was to locate a thermostat to control the hours the systems were in use because it was found that air conditioners were turned on for a period of time larger than the time the areas were occupied.

Table 2: Air conditioning system evaluation

Areas	**Sub-areas**	
Office	1	Computer Rooms
	2	Office Area
Production	1	Manufacturing
	2	Manufacturing
	3	Manufacturing
	4	Utility Pad
	5	Utility Pad
	6	Utility Pad
	7	Utility Pad
	8	Utility Pad
	9	Utility Pad
	10	Utility Pad
	11	Utility Pad

2.1 Optimization Algorithm

The optimization algorithm used in the study had an objective function to maximize the economic benefits per year through the implementation of feasible alternatives that contributed to reduce energy consumption by replacing existing equipment with more efficient equipment in the areas identified (3). The algorithm had three general equations. Their general format is presented next under the equations numbered [1], [2], and [3].

The first set of equations [1] defined the binary decisional variables for the alternatives because the alternatives evaluated would either be chosen or not. The second set of equations [2] represented the calculation of the economic savings ($ per day) that the alternative could generate if implemented considering all the variables used when calculating energy consumption cost. The last set of equations [3] represented the payback investment constraints. In summary, equation [1] was the decisional equation; equation [2] was a calculation equation considering all parameters of interest, and equation [3] were the constraints that must be met to optimize. Specific details about the optimization algorithm, its variables, parameters, constraints, and equations could be found in Ms. Colón-Vázquez MS thesis document (1).

$$@\,bin\,(decisional\ variable)[1]$$

$$Decisional\ variable \times Energy\ reduction \times Operating\ hrs \times \$\ of\ energy = Economic\ savings\ \ [2][2]$$

$$Economic\ savings \times Working\ days\ to\ recover\ \$ \geq Decisional\ variable \times Investment\ \$[3]$$

2.1.1 Data and Assumptions

The following is the important data from the manufacturing company used in the algorithm. Also, relevant assumptions are mentioned below:

- There were 336 working days per year.
- The acceptable payback period for the company was one year.
- The cost of energy used is based on local tariffs (4)
- In the areas where they worked three shifts, the air conditioner systems and the bulbs for the illumination systems were turned on twenty-four hours a day.
- In the areas where there was a single shift, the air conditioner systems and the bulbs for the illumination systems were turned on twelve hours per day.
- The energy efficient bulbs cost used were from local stores; $3.20 each bulb. Installation cost is negligible because it is actually done by employees.
- The thermostat to be installed in the air conditioning systems was priced at $275 each.

2.2 Lingo Software

To evaluate the performance of the mathematical model, the software Lingo 12.0 (5) was used. This software is recognized as an effective tool to solve problems regarding optimization models. It helps to understand how the mathematical model is solving the problem because it generates a solver status review about the models. With the status review the feasible alternatives can be easily identified as well as their impact in the objective function. Therefore, results from Lingo 12.0 are directly used to interpret the performance of the mathematical model.

3. Results

The optimization algorithm was run several times using Lingo 12.0. The software showed that the model to select cost-effective alternatives to reduce energy consumption was classified as a Mixed Integer Linear Program (MILP). This classification demonstrated that all equations of the model were linear and a subset of the variables was restricted to integer values. In addition to the demonstrated classification, the solutions review showed that the software used a *branch-and-bound* specialized solver (6).

The following tables summarize the results from Lingo 12.0 regarding the mathematical model. Table 3 shows the results for the illumination system which considers the replacement of the actual bulbs with energy efficient bulbs. These results did not include the cubicles in the office area because they were already using energy efficient bulbs. The total of the savings per year presented in Table 3 is *$15,082* with an initial capital investment of *$4,512*.

Table 3: Results for the illumination systems

Area	kWh consumed daily by equipment (actual)	kWh consumed daily by equipment (alternative)	kWh daily savings	Savings per year ($)	Investment	Payback period (years)
Office 12	0.032	0.025	0.007	$395	$356	0.90*
Office 13	0.032	0.025	0.007	$1,849	$500	0.27*
Production 21	0.032	0.025	0.007	$10,811	$2,925	0.27*
Warehouse 31	0.032	0.025	0.007	$2,027	$731	0.36*

*Feasible alternative (payback less than a year)

Tables 4, 5, and 6 show the results for the analysis of the air conditioning systems in the offices and production (prod) areas. In Table 4, placing a thermostat in the air conditioning system was considered to turn the units off during *one* hour per shift. This would have created a total savings per year for the feasible alternatives of *$13,139* with an initial capital investment of *$1,650*. Similarly, Table 5 show the results if the air conditioning units were turned off during *two* hours per shift. The total savings per year for this scenario was *$28,920* with an initial capital investment of *$3,300*. Table 6 is showing the results if the thermostat was used to turn off the air conditioning units during *three* hours per shift. In this case the total savings per year were *$43,703* with a corresponding initial capital investment of *$3,575*.

Table 4: Results for the air conditioning systems (turning them off during *one* hour per shift)

Area	**kWh consumed daily by equipment (actual)**	**Hours per day (actual)**	**Hours per day (reduced)**	**kWh daily savings**	**Savings per year($)**	**Investment**	**Payback period (years)**
Office 11	0.51	24	21	1.53	$108	$275	2.55
Office 12	7.5	24	21	22.5	$1,588	$275	0.17*
Prod 21	1.72	24	21	5.16	$364	$275	0.76*
Prod 22	10.3	24	21	30.9	$2,180	$275	0.13*
Prod 23	5.32	24	21	15.96	$1,126	$275	0.24*
Prod 24	3.15	12	11	3.15	$222	$275	1.24
Prod 25	3.18	12	11	3.18	$224	$275	1.23
Prod 26	3.2	12	11	3.2	$226	$275	1.22
Prod 27	3.13	12	11	3.13	$221	$275	1.25
Prod 28	3.05	12	11	3.05	$215	$275	1.28
Prod 29	3	12	11	3	$212	$275	1.30
Prod 210	59.7	12	11	59.7	$4,212	$275	0.07*
Prod 211	52	12	11	52	$3,669	$275	0.07*

*Feasible alternative (payback less than a year)

Table 5: Results for the air conditioning systems (turning them off during *two* hours per shift)

Area	**kWh consumed daily by equipment (actual)**	**Hours per day (actual)**	**Hours per day (reduced)**	**kWh daily savings**	**Savings per year ($)**	**Investment**	**Payback period (years)**
Office 11	0.51	24	18	3.06	$216	$275	1.27
Office 12	7.5	24	18	45	$3,175	$275	0.09*
Prod 21	1.72	24	18	10.32	$728	$275	0.38*
Prod 22	10.3	24	18	61.8	$4,361	$275	0.06*
Prod 23	5.32	24	18	31.92	$2,252	$275	0.12*
Prod 24	3.15	12	10	6.3	$445	$275	0.62*
Prod 25	3.18	12	10	6.36	$449	$275	0.61*
Prod 26	3.2	12	10	6.4	$452	$275	0.61*
Prod 27	3.13	12	10	6.26	$442	$275	0.62*
Prod 28	3.05	12	10	6.1	$430	$275	0.64*
Prod 29	3	12	10	6	$423	$275	0.65*
Prod 210	59.7	12	10	119.4	$8,425	$275	0.03*

Prod 211	52	12	10	104	$7,338	$275	0.04[*]

[*]Feasible alternative (payback less than a year)

Table 6: Results for the air conditioning systems (turning them off during *three* hours per shift)

Area	kWh consumed daily by equipment (actual)	Hours per day (actual)	Hours per day (reduced)	kWh daily savings	Savings per year ($)	Investment	Payback period (years)
Office 11	0.51	24	15	4.59	$324	$275	0.85[*]
Office 12	7.5	24	15	67.5	$4,763	$275	0.06[*]
Prod 21	1.72	24	15	15.48	$1,092	$275	0.25[*]
Prod 22	10.3	24	15	92.7	$6,541	$275	0.04[*]
Prod 23	5.32	24	15	47.88	$3,378	$275	0.08[*]
Prod 24	3.15	12	9	9.45	$667	$275	0.41[*]
Prod 25	3.18	12	9	9.54	$673	$275	0.41[*]
Prod 26	3.2	12	9	9.6	$677	$275	0.41[*]
Prod 27	3.13	12	9	9.39	$663	$275	0.42[*]
Prod 28	3.05	12	9	9.15	$646	$275	0.43[*]
Prod 29	3	12	9	9	$635	$275	0.43[*]
Prod 210	59.7	12	9	179.1	$12,637	$275	0.02[*]
Prod 211	52	12	9	156	$11,007	$275	0.02[*]

[*]Feasible alternative (payback less than a year)

4. Discussion

The long-term impact of the savings shown on the results presented above would be based on the useful life of the equipment bought (i.e., thermostats). This is because after the first year that the feasible alternatives are implemented, there will be additional savings without having to invest any additional amount of money until the useful life of the equipment comes to an end.

For the illumination systems, the savings of *$15,082* per year would continue while the energy efficient bulbs do not need to be replaced. In the case of the three scenarios presented for the air conditioning system, the total annual savings presented above *($13,139, $28,920, and $43,703*) would continue while the thermostats are still in good condition to be used and if the company continue to use the air conditioning systems as recommended.

The various combinations of the scenarios presented to reduce energy consumption by the illumination and air conditioning systems can be summarized as presented in Table 7.

Table 7: Summary of energy consumption savings per year

Scenarios	Illumination systems savings	Air conditioning systems savings	Total initial investment	Total savings per year
Energy efficient bulbs and thermostats turning off A/C *one* hour per shift	$15,082	$13,139	$4,512 + $1,650 = *$6,162*	*$28,221*
Energy efficient bulbs and thermostats turning off A/C *two* hours per shift	$15,082	$28,920	$4,512 + $3,300 = *$7,812*	*$44,002*
Energy efficient bulbs and thermostats turning off A/C *three* hours per shift	$15,082	$43,703	$4,512 + $3,575 = *$7,787*	*$58,785*

5. Conclusions

Studies showing that optimization models can be used to optimize the energy consumed by industrialized processes in companies without decreasing the entire plant utilization currently exist. This research has contributed by adding a real application of a mathematical model developed to optimize energy consumption. When the optimization algorithm was used with real data of a semiconductors industry, it performed as expected choosing feasible alternatives based on the payback method. It was demonstrated that a Mixed Integer Linear Program optimization model can be used to identify economically feasible alternatives to replace some of the equipment used for the air conditioning and illumination systems with equipment that consume less energy. The solution generated by the Lingo 12.0 software showed significant potential savings for the industry with comparatively small capital investments.

The major contribution of this research effort is the realization that a mathematical model considering real world variables and constraints can be used to analyze real word problems. It was shown that mathematical modeling can be used with real data and generate feasible alternatives to solve an enormous problem manufacturing industries are facing today: high energy costs. Also, the mathematical model helped the industry to identify the opportunities to reduce energy consumption without investing, but by being energy conscious. This kind of research effort can substantially help to disseminate results of mathematical modeling applications within industrial environments, in this particular case for a semiconductor manufacturing industry.

In the particular application presented in this article it was seen that if the semiconductor manufacturing industry decided to implement any of the recommendations presented, depending on what they chose, the annual savings in energy consumption would fluctuate from over *$28,000* to over *$58,000*. These annual savings would directly impact the company’s overhead costs which should be reflected in a production cost reduction and in an increase on their net income.

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