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Dynamic optimization of district energy grid

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DYNAMIC OPTIMIZATION OF DISTRICT ENERGY GRID

by

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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ABSTRACT

The University of Iowa Power Plant operates utility generation and distribution for campus facilities, including electricity, steam, and chilled water. It is desirable to evaluate the optimal load combination of boilers, engines and chillers to meet the demand at minimal cost, particularly for future demand scenarios. An algorithm has been developed which takes into account the performance of individual units as part of the mix which ultimately supplies the campus and determine the degree that each should be operating to most efficiently meet demand. The algorithm is part of an integrated simulation tool which is specifically designed to apply traditional optimization techniques for a given (both current and possible) circumstance. The second component is to couple the algorithm with accurate estimates and historical data through which expected demand could be predicted. The simulation tool can account for any theoretical circumstance, which will be highly beneficial for strategic planning. As part of the process it is also necessary to determine the unique operating characteristics of the system components. The algorithms rely upon performance curves of individual system components (boiler, chiller, etc.) and those must be developed and refined when possible from experimental testing and commissioning or manufacturer supplied data.

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CHAPTER 1
INTRODUCTION AND BACKGROUND

1.1 Introduction

This project is motivated by a request from the Facilities Management Department at the University of Iowa for a tool that they could use to postulate future energy scenarios, specifically at the Oakdale Research Park, and then evaluate the suitability of the current utility generation system to satisfy demand. The simulation model has to determine the most cost efficient means of providing chilled water, electricity, and steam to the campus. An additional requirement was that the tool be portable in nature from a software standpoint so that typical workstations on campus would be able to use it. Full scale simulation tools and commercial software are available that can accurately describe process and thermodynamic systems and reach highly complex solutions. However, such programs typically take from several minutes to a few hours to set up a problem and then take several minutes to several hours to reach a solution depending on the software and the problem being solved. The goal here is to have a more nimble tool that is purpose built for use as an interactive strategic planning tool that is capable of fast solution times and is operable on common computers. The model will need to be run and rerun with modified initial conditions frequently and in timely fashion. Once the modeling tool is functional, its results could then be compared with those of more sophisticated software when there is a need for the greater detail such a program provides.

The project calls for initially developing a model based on current infrastructure that can later be enhanced so that additional, theoretical, future facilities (based on known utility use characteristics of existing structures) can be inserted and old buildings removed. Thus, the tool is intended to be used for strategic planning to help determine if, and when, additional utility generation components should be acquired to either replace or supplement those that currently exist at the research campus. The components of the problem are as follows: develop a simple but relatively accurate algorithm to determine optimum system load for a given case, characterize the current generation system in VBA form so that the model could be applied to it, integrate available data streams into the simulation as an option, and develop an interface that would also provide a means for addition or removal of sources of demand as well as characteristics of and sources for supply.

1.2 Background

The Oakdale Research Park includes some twenty buildings that are currently supplied by on campus generation of chilled water, electricity and steam. Electricity can be generated using natural gas turbines or it can be purchased from a utility company. Prior to recent construction, the power plant housed four natural gas boilers producing low pressure steam, one of which has been replaced with a new boiler that can also burn bio mass. Two natural gas engines which generate electricity directly were added as well as a chiller which is driven by electricity. There are discussions about adding a steam turbine to convert steam to electricity as well as a provision for steam driven chillers which would require boiler capacity for high pressure steam. The system is quickly becoming quite complicated from a modeling standpoint which has driven the decision to start at a simple level and work to incorporate more complex features as needed. Therefore, the model was created for steam only although the concept could be expanded. Operating data could be recorded once monitoring equipment is in place for each component in order to quantify the energy value output relative to the energy value input across the operating range. The University of Iowa, Department of Facilities Management already uses several means of monitoring systems and managing such data across each campus. The issue is merely adding components to the monitoring system so that data can be collected.

Figure 1.1: Satellite view of Oakdale Research Campus

Source: Google Earth Software

The optimization problem is to determine the best combination of generation options to satisfy a given level of demand for one particular utility or a set of utilities. Given continuously differentiable performance curves and possible load levels as a percentage of each generation source maximum capacity, there are hundreds of combinations of loadings and a large set of those combinations which will satisfy the demand. The algorithm was written such that the overall cost of operation is minimized by determining the optimal combination of system component loads. The system has been characterized in the code such that constraints limit possible load levels for each system component between 0 and 100 as previously mentioned by definition of percentage. Other constraints include satisfaction of some specified levels of demand for each utility.

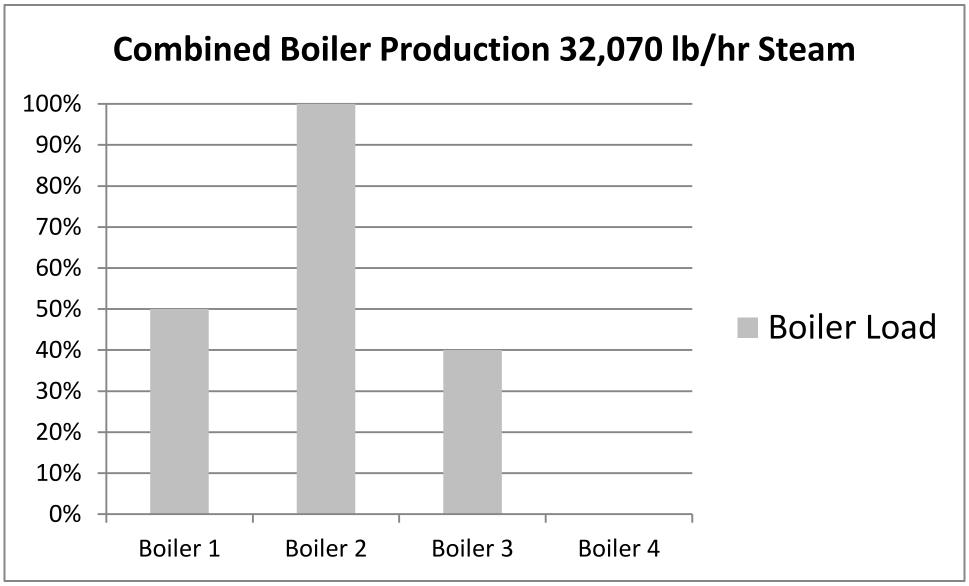

Figure 1.2: Combined boiler loading to produce target steam supply

For example, it may be the case that engines #1 and #2 can easily generate enough power to meet the demand for electricity; so one possible combination for the system would have these two components are fully loaded and the four boilers (that are available) are off. This combination may not be a feasible solution if there is demand for steam, which the engines cannot provide. So a feasible solution for a plant encompassing model would include any components and percentage of load of each component such that the steam and electricity needs are satisfied (the third utility, chilled water, can also be included in the future). An optimal solution would then be limited to the combination of components running and the degree of their capacity at which they run which satisfies the demand requirements at a minimal value for the objective function, evaluated in terms of operating cost per hour when multiplied by the value of the fuel in dollars per million

British Thermal Unit (BTU) per unit fuel consumed. Multiple fuel types will be allowed and will be incorporated into a weighted average fuel cost relative to the output of a given generation unit.

1.3 Applied Optimization Theory

An overview of the workspace for optimization begins with the concept of solution space and the features thereof. The solution space is the set of all possible solutions to a given function. Conceptually, the function can be considered to have some number of peaks and valleys. Each peak is referred to as a maximum of the function and each valley is referred to as a minimum of the function. The most important peak is the tallest peak and bears the title of global maximum since it is the highest point anywhere in the function. The inverse is true for the lowest valley as it is the lowest point anywhere in the function and thus the global minimum (Arora, 2004).

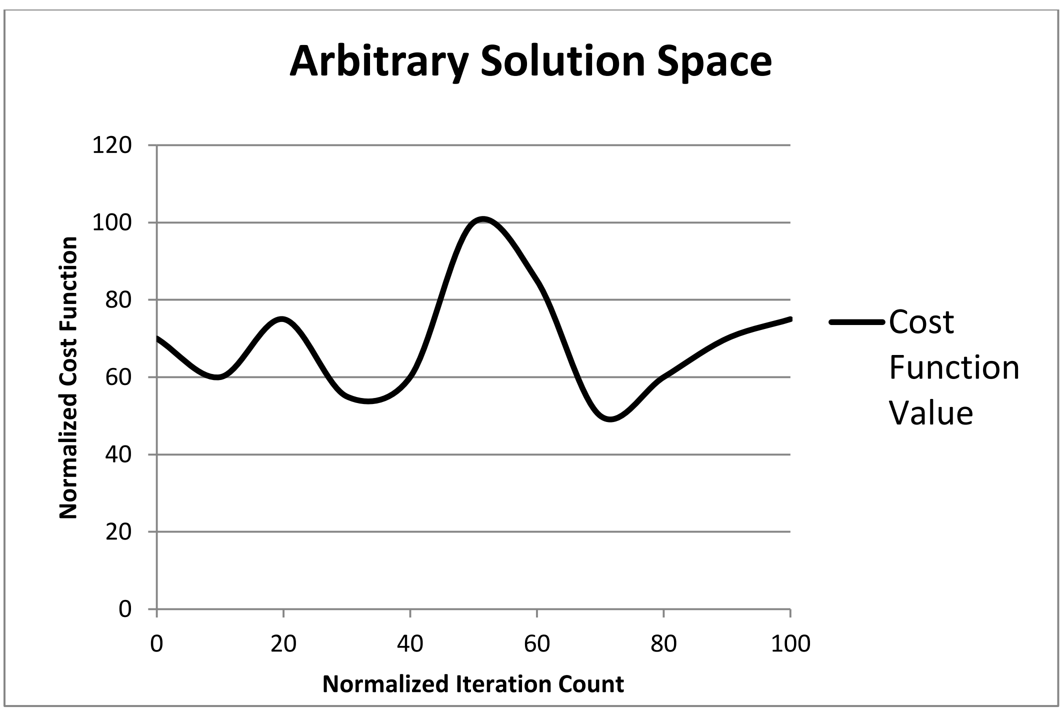

Figure 1.3: Arbitrary solution space depicting ‘valleys’ as minima

In optimization, the goal is to maximize or minimize some objective function. If cost is the basis for the objective function, typically the goal would be to minimize the value of that function or find the combination of factors which leads to the lowest value of that function (Arora, 2004). Two mechanics are employed which basically are to determine a start point for the algorithm and then try to find a minimum from there. A start point can selected as a random value or some specified value that is the equivalent of making an educated guess. The method by which the algorithm then leaves the start point and attempts to find a minimum is called a local search (Burke & Kendall, 2005).

The objective function for the problem discussed in this paper is the sum total hourly cost of operation of each system component. The profiles created to represent the different components are sixth-order polynomial fits of a non-linear boiler profile. The reason for this is to create the closest fit possible while maintaining differentiability. The first derivative of a load profile gives the marginal fuel cost per increment boiler load. Continuous differentiability ensures that this derivative may be calculated for any load level.

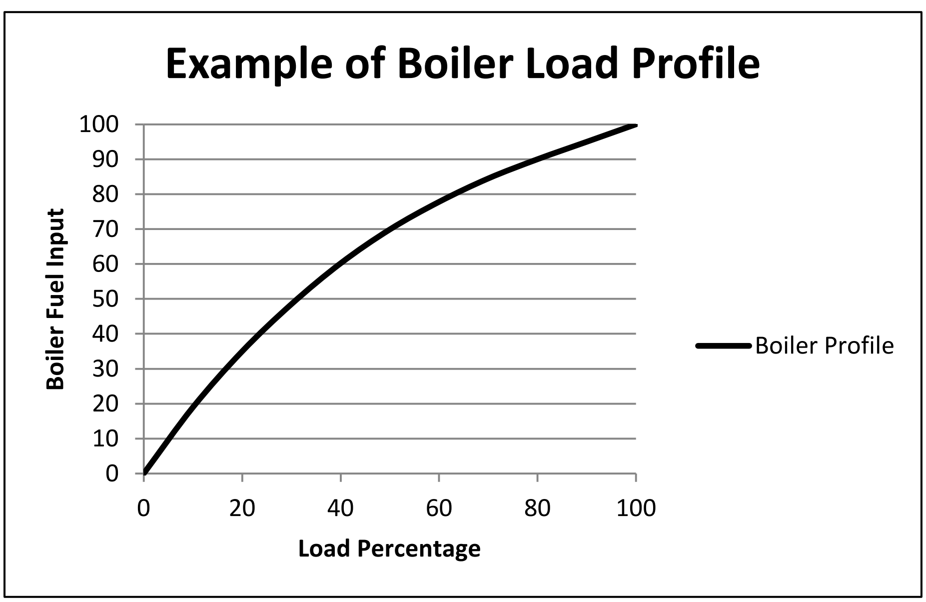

Figure 1.4: Example of boiler load profile

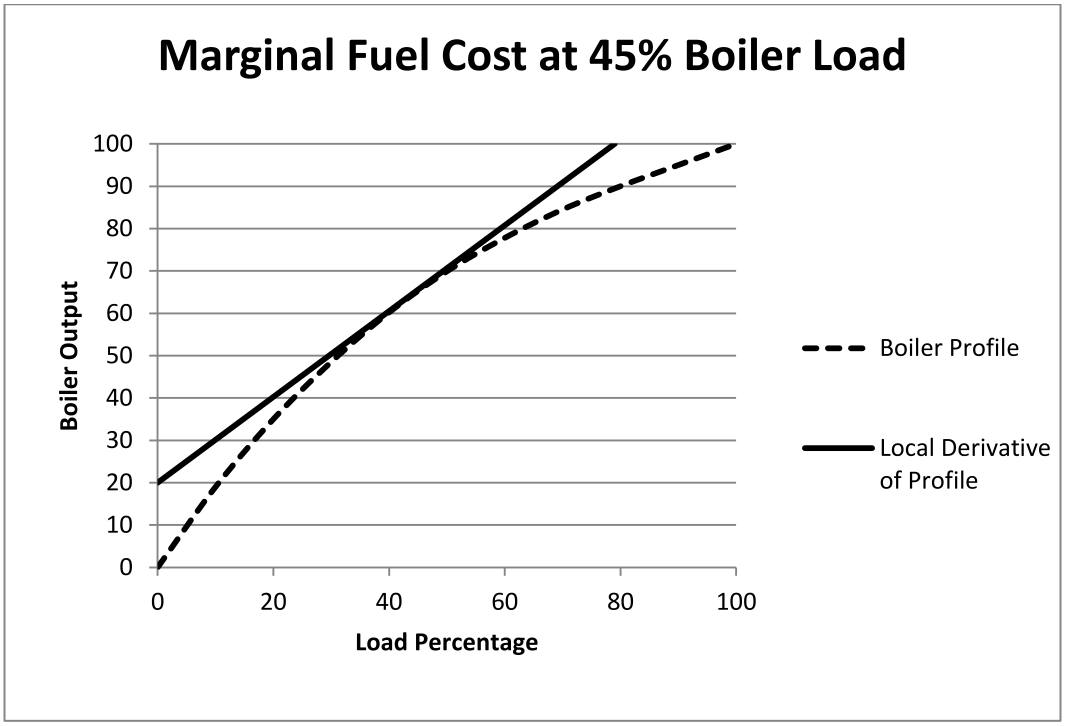

Figure 1.5: Sample local derivative of boiler profile yielding marginal fuel cost

The marginal fuel cost of each boiler allows the determination of the magnitude of change of fuel use for either increasing or decreasing the boiler load by a single increment at that local point. Each particular operating level or load percentage has a corresponding local derivative which manifests as a line tangent to the boiler profile at the current operating level. Areas that are non-differentiable can be encountered when increasing or decreasing boiler power requires a change to the nature of the boiler. This can include activation or deactivation of different burners, fuel and air streams or exhaust systems. These changes may cause a sharp change to the load profile which is alleviated by using a high order polynomial fit of the profile data to smooth any sharp points at which the local derivative cannot be evaluated. These fits may be updated and replaced when updated experimental data characterizing the units accurately becomes available.

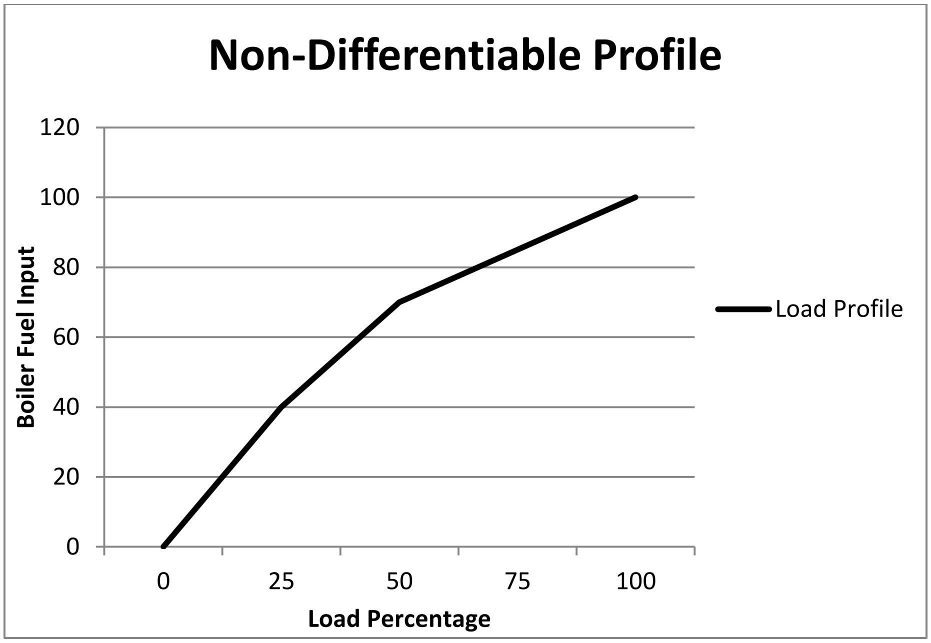

Figure 1.6: Sample non-differentiable boiler load profile

There are alternative optimization methods which may be applicable to this circumstance if it can be established that the mathematical prerequisites for their use are satisfied. The contrived profiles are convex and since the objective function is the sum of all the component profiles, it too is convex. Though there is favorable expectation that in reality, as opposed to the contrived situation, the operating profiles and, therefore, the cost function will ultimately be convex, it must be made certain to be the case. If the experimental data reinforces this, it will merit effort to investigate avenues with mathematical programming, likely integer programming, as an option to augment the model and increase accuracy of results or performance of the model. However, until such time that the system can be accurately described with experimental data and convexity of the system in all circumstances in reality confirmed, efforts are focused on the current methods which do not depend upon the condition.

CHAPTER 2

ALGORITHM

2.1 Development

The basis of the model was written around objective functions and constraint equations for steam only for the sake of simplicity to allow a focus on the heuristic process. The programming language used for the algorithm was Visual Basic for Applications in Microsoft Excel. A possible solution appears in the form of a list of cells in the output spreadsheet with percentage levels corresponding to the operating load of each generation unit in the system as well as the resulting supply of each utility and the final value of the cost function. For a purely theoretical example, a set of cells could list the numbers 0, 0, 100, 55. These would correspond to having the first two boilers off, the third boiler at full power and the fourth boiler at 55% power which combine to produce about 7 megawatts (MW) worth of steam at a theoretical cost of $131 per hour. The model was built to incorporate a fifth boiler, referred to as Boiler N, as an option which would facilitate further hypothetical analysis using a potential new boiler in lieu of or in addition to the current units without replacing profile data on the existing boilers. This would be useful in evaluating the utility of replacing any of the present units. Unfortunately, operating data for the existing boilers is not available but contrived data can be used in the meantime to develop code until power profiles of the boilers and other system components can be developed from recorded experimental data.

To create profiles for the boilers to reflect real operating performance it is necessary to establish input fuel consumption rate relative to the range of output levels. This is done by operating at either the minimum or maximum output level for a given unit and recording the rate at which fuel is consumed in BTU per hour (BTU/hr) and then moving the output level incrementally to the other end of the range, recording corresponding fuel consumptions rates at each step. Smaller steps provide better resolution of the boiler profile and can allow for accurate representation of operating characteristics, which may in a strict sense cause discontinuity, such as activation or deactivation of burners. This data can then be input to a spreadsheet and a best fit curve derived. This is easily done by plotting the data points and then extracting a trend line. The model is set up to make best use of a polynomial fit up to the sixth order as this the maximum capability for the built in trend line in Excel. This also alleviates issues of slight discontinuity. The function can then be broken down and coefficients of associated ordered terms input on the model setup sheet. The model will reincorporate the coefficients into the full functions when it is run. This facilitates changing of profile data without requiring programming knowledge or the need to edit the code on the back end of the model. The values are stored in the cells and saved as part of the Excel file and allow infinite iterations of analysis for a particular system characterization in between changes to load profiles.

The model reads input data from specific cells of a setup spreadsheet within the Excel file. It will populate an extensive list of variables including coefficients of boiler profiles, desired fuel use proportions, fuel costs, enthalpy of steam and desired steam output or demand. It is possible to use up to three different fuels for analysis in each individual generation unit by setting a constituent percentage. This would, for example, allow simulation of a co-firing scenario in a boiler using coal and bio mass or natural gas and bio mass. The model will incorporate percentages of the fuel sources and calculate a weighted average fuel cost for each boiler to be used in the cost analysis. Enthalpy of steam is a property that is generally known ahead of time and is calculated based on the target steam supply characteristics including header pressure which is the pressure of the aggregated steam product of all operating boilers. It provides an effective estimate of how many pounds per hour (lb/hr) steam are produced from the BTU/hr of heat generated in the boiler. These values are quite suited to frequent modification with repeated running of the model to explore varied potential operating conditions.

	A	B	C	D	E	F	G	H	I	J
1	This simulation will determine the approximate hourly cost of operation given different boilers, fuel types/costs.									
2										
3	Desired steam output? (lb/hr steam)				Enthalpy of Steam? (BTU/lb)					
4	0				0					
5										
6	Which boilers should be running? 1=On, 0=Off									
7	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N	Run Simulation				
8	0	0	0	0	0					
9										
10	Boiler Maximum Output (lb/hr steam)									
11	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N					
12	0	0	0	0	0					
13										
14	Fuel Selection		Use this fuel in given boiler? What percentage share of total fuel value? (.25 = 25%, 1 = 100%)							
15	Fuel Type	Name	$/MMBtu	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N		
16	Fuel1	Ngas	0	0	0	0	0	0		
17	Fuel2	Bio	0	0	0	0	0	0		
18	Fuel3	Coal	0	0	0	0	0	0		
19										
20	Boiler	Boiler 1	Boiler 2	Boiler 3	Boiler 4	BoilerN	(not used for calculation			
21	Efficiency	0	0	0	0	0	factored in through profiles)			
22										
23		Input Data								
24		x^6	x^5	x^4	x^3	x^2	x^1	x^0		
25	boiler1	0	0	0	0	0	0	0		
26	dboiler1		0	0	0	0	0	0		
27	boiler2	0	0	0	0	0	0	0		
28	dboiler2		0	0	0	0	0	0		
29	boiler3	0	0	0	0	0	0	0		
30	dboiler3		0	0	0	0	0	0		
31	boiler4	0	0	0	0	0	0	0		
32	dboiler4		0	0	0	0	0	0		
33	boilerN	0	0	0	0	0	0	0		
34	dboilerN		0	0	0	0	0	0		

Figure 2.1: Simulation tool setup

The main components for evaluation are the level of steam supply, steam demand, cost function and the variables of optimization. The boiler profiles are used to determine the fuel values consumed to supply a particular level of steam demand for each boiler which are then added together to form the total cost function which is the main objective for optimization. The level of steam supply is also used with the specified steam demand to determine whether or not the supply is sufficient which factors into criteria for convergence. Convergence criteria are ultimately how it is determined that the process is finished. The variables of optimization are the load percentages of individual generation units.

The main mechanic for determining an optimal solution involves selecting a start point and then employing a local search. A given method for performing this process is comprised of procedures for how the initial conditions are selected and how the solution is then reached. Starting points in the solution space can be randomly selected or specified based on outside knowledge. Local search is the process by which conversion is reached after beginning at the start points. Several methods were explored and are explained below. They are referred to as the gradient based approach, the exhaustive search and gradient based approach with intelligent starts.

It is important to introduce the problems that arise when attempting to use programming language. There are specific mechanics within each language that are combined in different ways to accomplish tasks. These mechanics have rules for their employment which must all be compatible. Previously, the concept of convergence criteria was introduced. Some programming mechanics require a condition to be specified so that the determination can be made that the process is complete. These are typically from a family called 'loops' and come in many forms. Problems arise when trying to find the right criterion to employ to determine when the condition is satisfied.

Criteria need to be created for each logical outcome to ensure broad applicability of the model. One commonly used criterion tracks the percentage change of the objective function between iterations of the process. When the percentage change becomes smaller than some value the process can be considered finished. Another possible criterion tracks the percentage change of some other objective value while depending on certain other conditions to be true. For example, to save energy one might turn the power down to lower the cost, but output must remain above some minimum level. Another criterion could be to build a recognition scheme around some foreseeable condition which may occur with some frequency and use a counting technique to dictate convergence when the condition is observed a certain number of times.

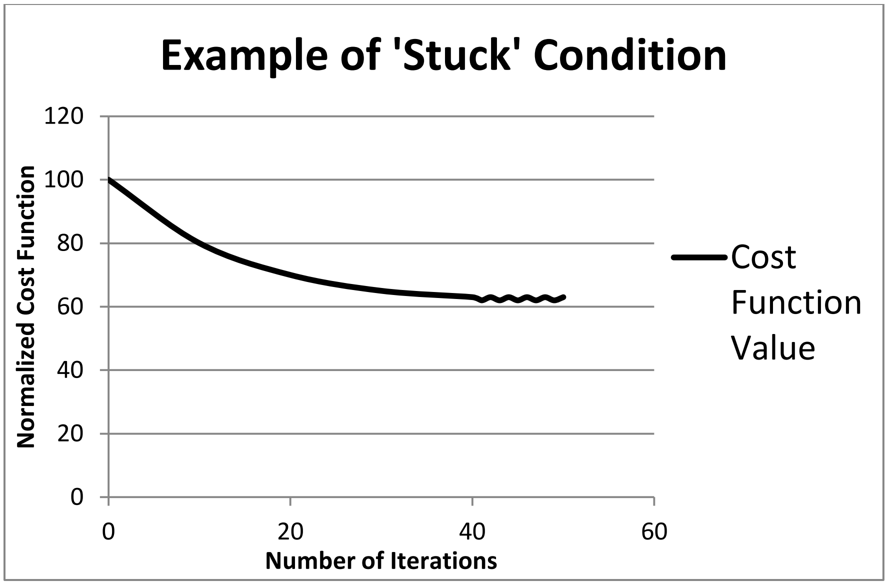

Figure 2.2: Depiction of ‘stuck’ model at a point in solution space

It can often be the case that the looping process becomes stuck on a certain value, prohibiting the primary form of convergence. In that case it is necessary to identify how and why it became stuck and devise escape rules to trigger in the event it occurs to allow the process to continue. If steam demand is specified and the convergence requirement is that steam supply should be within a certain percentage range of the steam demand and in excess of the steam demand before the process can stop, and the model encounters a minimum, it will become stuck. Identifying the fact that the program finds the same result after iterating without being satisfactorily close to the required steam production is critical to provide the program with a means to recognize the situation and act accordingly. Another cause for the program to become stuck is introduced when tracking and updating the best value seen so far for the objective function. This is typically done to be able to be able to make sure the cost function is improving. If an escape criterion is established for when there is no difference between the value for the current iteration and the best value seen so far, an issue can arise if an identical value for the cost function is reached even though steam output has improved. If continuing to iterate depends on improving the cost function, the iteration is terminated, wasting potential gains.

2.2 Algorithmic Results

The first method employed was a gradient based approach which uses steepest descent and shallowest ascent criteria to make a move. Random search is used to select starting load levels for the system and currently has been successfully employed only in basic form. Load levels for each system component, in this case a boiler, are all randomized at the beginning of iteration with feasibility constraints. The algorithm relies on a calculation of the first derivative of the boiler performance curve to determine which boiler load level to modify. A strong feature of this approach is the quick solution time. However, a weakness of relying on this approach alone is that it may reach a local minimum that is not the global minimum and currently cannot search elsewhere.

The approach uses a convergence criterion that terminates when it determines that a minimum has been reached. Thus it cannot inherently be expected to find the global minimum every time because it will get stuck in the first local minimum it comes across. To combat this nature, various techniques were attempted to induce perturbation to cause the algorithm to explore other areas of the solution space. Primarily, efforts were spent in employing the randomized start approach where the initial load percentage of each of the system components was assigned a random number between 0 and 100. Unfortunately this lead to the discovery of flaws and limitations within the VBA code in excel with using random number generators. The randomizing apparatus in the code relies on the system core clock of the computer on which it is operating and once one set of "random" numbers is generated from the "seed" data there is difficulty referencing those numbers. Additionally, after using the initial set there is a problem regenerating random numbers in a fashion that was compatible with the code of the gradient algorithm.

To provide reference of possible solutions as well as evaluate the effectiveness of the gradient based approach, an exhaustive search was also developed. This approach fully evaluates all possible solutions to the objective function and selects the best, or the global optimum. Fortunately this method does successfully determine the best possible solution. However it takes significantly more time. In a purely steam system limited to the four boilers referred to previously. It is possible that any one of them could be operating anywhere between 0 and 100 percent in the model. This means that there are 100^4 or 100,000,000 possible combinations and, therefore, solutions to be evaluated. Recall that this is the simplified case with steam only and the reality of the physical system includes electricity and chilled water production as well. Thus this approach is suitable only when long calculation times are acceptable or as a tool to measure the accuracy of faster solution methods and has only been used as such.

Ultimately, the best approach proved to be employing the gradient based method with intelligent starting points for the search. The starting points are set by looping through various combinations where individual generation components either completely off or at full power initially. If all five boilers are activated for analysis there are 2^5, or 32 possible combinations for starting values. The local search method from the gradient based approach with several convergence criteria easily finds minima. Depending on the characteristics of the load profiles for given generation components the global minimum should be in identifiable zones which then informs the selection of intelligent starting points for the local search. In a regime where unit efficiency is relatively poor in the middle operating zones the global optimum will be at a point in the solution space where demand is satisfied with each component either close to maximum power completely turned off due to energy conversion efficiency. Alternatively, in a regime where efficiency is purely linear with output, the global optimum will be at a point where the load is distributed across many units operating at a lower output level. In a boiler, sources of inefficiency can come from any number of areas which is why there are so many traditional means of improving by recycling waste heat to preheat fuel and water. It is also true that the hotter the boiler becomes as a physical structure, the more heat it gives off to its surroundings, reducing fuel efficiency for marginal steam output.

CHAPTER 3
PERFORMANCE AND CASE ANALYSIS

3.1 Evaluation of Methods

The primary gradient algorithm, the exhaustive search, and the gradient algorithm with intelligent starting points were developed in VBA for Microsoft Excel as previously mentioned. The code was executed on an Intel Core 2 Duo CPU with a clock speed of 2.00 GHz and 2 GB of RAM and the operating system was Windows XP. All methods were tested to compare optimal solutions for several target system outputs. Results were typical across the range of outputs tested and are characterized by the example provided below in Table 1.

Table 1: Results for the 6 MW case

Method	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler 5	Cost Function	Calculation Time
Gradient Only	45%	Off	Off	100%	N/A	112.23	1 sec
Exhaustive Search	Off	Off	97%	Off	N/A	98.52	471 sec
Gradient with Intelligent Starts	Off	Off	97%	Off	N/A	98.52	1 sec

It is worth noting the significant differences between the optimized results from each algorithm. The gradient approach indicates that the first boiler should run at 45%

while the fourth boiler should run at 100%. This corresponds to a value for the cost function of approximately $112.23 per hour of operation. Solution time was less than 1 second. By comparison the exhaustive search shows the system is optimized when the first, second and fourth boilers are turned off while the third boiler is running at 97% capacity, this is the global optimum for the solution space. The value for the cost function from this method is approximately $98.52 per hour of operation. Solution time was 471 seconds. The exhaustive search solution provides an energy savings over the solution found by the current gradient method of approximately 13%. However it takes several minutes to compute. An interesting point is that if the gradient based approach alone is initially set to begin optimizing system load near the global optimum as determined by the exhaustive approach it properly finds the global optimum. Finally, using the gradient method with intelligent starts it is determined that the first, second and fourth boilers should be off while the third boiler runs at 97% at an hourly operational cost of $98.52 as in the exhaustive approach which is the global optimum. In this case the solution time was a fraction of a second. The approach provides the most accurate result with the most favorable timeframe.

3.2 Example Analysis

Applying the fully functional model to a realistic scenario provides highly useful information. Consider the following initial conditions to be input through the setup interface: steam demand of 25,000 lb/hr steam, enthalpy of 1,193 BTU/lb, Boiler 1 running on bio mass priced at $6/MMBTU, Boilers 2-4 running on natural gas at $4/MMBTU, and Boiler N not operating. Load profiles for all four boilers have already been stored in the model.

	A	B	C	D	E	F	G	H	I	J
1	This simulation will determine the approximate hourly cost of operation given different boilers, fuel types/costs.									
2										
3	Desired steam output? (lb/hr steam)				Enthalpy of Steam? (BTU/lb)					
4	25000				1193					
5										
6	Which boilers should be running? 1=On, 0=Off									
7	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N	Run Simulation				
8	1	1	1	1	0					
9										
10	Boiler Maximum Output (lb/hr steam)									
11	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N					
12	14246.34	17818.65	17818.65	10794.15	14246.34					
13										
14	Fuel Selection		Use this fuel in given boiler? What percentage share of total fuel value? (.25 = 25%, 1 = 100%)							
15	Fuel Type	Name	$/MMBtu	Boiler 1	Boiler 2	Boiler 3	Boiler 4	Boiler N		
16	Fuel1	Ngas	4	0	1	1	1	1		
17	Fuel2	Bio	6	1	0	0	0	0		
18	Fuel3	Coal	5	0	0	0	0	0		
19										
20	Boiler	Boiler 1	Boiler 2	Boiler 3	Boiler 4	BoilerN	(not used for calculation			
21	Efficiency	0.7	0.7	0.7	0.7	0.7	factored in through profiles)			
22										
23		Input Data								
24		x^6	x^5	x^4	x^3	x^2	x^1	x^0		
25	boiler1	-1.5E-08	5.43E-06	-0.00071	0.050384	-3.64650565	350.674786	-0.0620374		
26	dboiler1		-9E-08	2.72E-05	-0.00286	0.15115166	-7.293011304	350.674786		
27	boiler2	-1.9E-08	6.79E-06	-0.00089	0.063023	-4.56124342	438.6426932	-0.0775997		
28	dboiler2		-1.1E-07	3.4E-05	-0.00358	0.18906854	-9.122486838	438.642693		
29	boiler3	-1.9E-08	6.79E-06	-0.00089	0.063023	-4.56124342	438.6426932	-0.0775997		
30	dboiler3		-1.1E-07	3.4E-05	-0.00358	0.18906854	-9.122486838	438.642693		
31	boiler4	-1.1E-08	4.08E-06	-0.00054	0.037831	-2.73799059	263.3053002	-0.046581		
32	dboiler4		-6.8E-08	2.04E-05	-0.00215	0.11349271	-5.475981186	263.3053		
33	boilerN	-1.5E-08	5.43E-06	-0.00071	0.050384	-3.64650565	350.674786	-0.0620374		
34	dboilerN		-9E-08	2.72E-05	-0.00286	0.15115166	-7.293011304	350.674786		

Figure 3.1: Setup sheet for example case

Starting the numerical simulation, the window is automatically changed to the results page where the outcome of each iteration cycle is displayed with entries sorted by lowest value for the objective cost function. This information provides the cheapest operating configuration satisfying the demand as well as other arrangements that also satisfy demand and the associated cost trade-off. This gives the plant operator knowledge of the degree of flexibility in meeting generation needs.

	A	B	C	D	E	F	G
1	bLoad1	bLoad2	bLoad3	bLoad4	bLoadN	costFunction	steamSupply
2	0	0	98	70	0	149.7426453	25018.17969
3	0	0	98	70	0	149.7426453	25018.17969
4	0	98	0	70	0	149.7426453	25018.17969
5	0	98	0	70	0	149.7426453	25018.17969
6	0	0	80	100	0	150.0897064	25049.07031
7	0	0	80	100	0	150.0897064	25049.07031
8	0	80	0	100	0	150.0897064	25049.07031
9	0	80	0	100	0	150.0897064	25049.07031
10	0	0	80	100	0	150.0897064	25049.07031
11	0	0	80	100	0	150.0897064	25049.07031
12	0	41	100	0	0	161.2725525	25124.29102
13	0	41	100	0	0	161.2725525	25124.29102
14	100	0	0	100	0	180.0193787	25040.48828
15	100	0	0	100	0	180.0193787	25040.48828
16	100	0	0	100	0	180.0193787	25040.48828
17	100	0	0	100	0	180.0193787	25040.48828
18	100	0	0	100	0	180.0193787	25040.48828
19	100	0	0	100	0	180.0193787	25040.48828
20	100	0	0	100	0	180.0193787	25040.48828
21	100	0	0	100	0	180.0193787	25040.48828
22	100	0	0	100	0	180.0193787	25040.48828
23	100	0	0	100	0	180.0193787	25040.48828
24	100	0	0	100	0	180.0193787	25040.48828
25	100	0	0	100	0	180.0193787	25040.48828
26	100	0	0	100	0	180.0193787	25040.48828
27	100	0	0	100	0	180.0193787	25040.48828
28	100	0	61	0	0	198.5975952	25115.71094
29	100	0	61	0	0	198.5975952	25115.71094
30	100	61	0	0	0	198.5975952	25115.71094
31	100	61	0	0	0	198.5975952	25115.71094
32	100	0	61	0	0	198.5975952	25115.71094
33	100	0	61	0	0	198.5975952	25115.71094

Figure 3.2: Results sheet from example case

The process was extremely brief, demonstrating the effectiveness of the nimble model. Immediately, the simulation can also be used to reevaluate based on an expected 10% decrease in natural gas prices as well as a 5% increase in steam demand for the next year. This is well suited to a board room or meeting environment where hypothetical circumstances are often explored.

CHAPTER 4

CONCLUSIONS

In response to a need identified by Facilities Management at the University of Iowa, a simulation tool was developed. The model was requested to allow a degree of formal analysis on a very nimble platform that could be used in Excel software. The utility provided by the simulation tool for use in strategic planning is significant. It easily and quickly provides information about operating cost and flexibility of operation. It also allows for predictive analysis in light of expected changes to fuel costs, steam demand, new boilers, co-firing, and optional removal of existing boilers for maintenance. The model will be provided to Facilities management for use in ongoing analysis and strategic planning.

APPENDIX

Pseudo Code for Methods Attempted

```
Gradient Pseudo Code
Do Until convergence
gradient performance curve {boiler1...boiler4}
        If steam supply < demand
                most efficient boiler, increase 1%
        If steam supply > demand
                least efficient boiler, decrease 1%
        Evaluate cost function

Exhaustive Search Pseudo Code
For boiler1 = 0 To 100
For boiler2 = 0 To 100
For boiler3 = 0 To 100
For boiler4 = 0 To 100
        Evaluate Cost function
Keep lowest seen

Gradient Pseudo Code with Intelligent Start
For boiler1 = 0 To 100 Step 100
For boiler2 = 0 To 100 Step 100
For boiler3 = 0 To 100 Step 100
For boiler4 = 0 To 100 Step 100
For boiler5 = 0 To 100 Step 100

Do Until convergence
gradient performance curve {boiler1...boiler5}
        If steam supply < demand
                most efficient boiler, increase 1%
        If steam supply > demand
                least efficient boiler, decrease 1%
        Evaluate cost function
```

REFERENCES

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