Minimising the cost of noise control in the coal seam gas industry by selection of noise treatments for gas wells using engineering optimisation

David James DAVIS[1]

[1] URS, Australia

ABSTRACT

Reducing costs is an important consideration when designing gas field facilities. The cost of noise mitigation treatments to the power units and pumps at well-heads can be a significant proportion of capital expenditure, and opportunities to reduce these costs are usually welcomed. The assessment and management of environmental noise impact from land-based gas fields is somewhat unique because of the large number of noise sources distributed over a very large area, often with many noise receptors interspersed between the wells and with most receptors receiving noise simultaneously from many wells from different directions. With such complexity, it can be difficult to select and design noise control treatment for the noise sources located at the wells in a cost-effective manner. It would be advantageous to have a calculation tool that could select appropriate noise treatments for each noise source at each well so that the environmental noise targets are achieved at each receptor while simultaneously ensuring that the cost-effectiveness of the noise mitigation program is maximised. This paper demonstrates an example of using three different optimisation techniques to minimise the cost of the overall noise control treatment scheme for the major noise sources located at coal seam gas wells.

Keywords: Noise control, Cost, Optimisation I-INCE Classification of Subjects Number(s): 55

1. INTRODUCTION

The cost of noise control treatments can be a significant capital outlay for coal seam gas (CSG) projects. CSG projects are known for having many wells distributed over wide areas of land, as well as several compression stations more sparsely located throughout the gas field.

The large numbers of wells that are characteristic of CSG gas fields and their widespread spatial distribution means that noise receptors are often exposed to noise from many wells simultaneously. At every receptor there is a wide range of source noise level contributions from the wells depending on distance and other components of propagation attenuation between the sources and the receptors. In order to meet the required noise level targets at all of the receptors, each well needs to have an appropriate noise control treatment applied to it so that the combined cumulative total noise level from all wells meets the noise limit at each of the receptors.

The challenge is to achieve this overall noise mitigation goal while endeavouring to reduce the financial cost of the noise mitigation treatments. The operational reality of coal seam gas fields is that gas wells do not operate continuously and are often decommissioned and relocated across the life of the gas field, resulting in a constantly changing cumulative noise environment. However in Australia it is common practice to assume that all wells are operating simultaneously at full production for the purposes of obtaining environmental approval.

2. OPTIMISATION

A definition of mathematical optimisation is the process of attempting to find the best element from some set of available alternatives subject to a set of constraints.

[1] dave.davis@urs.com

In mathematical notation this is stated simply as:

$\max_{x\in X} f(x)$ to maximise some variable

or

$\min_{x\in X} f(x)$ to minimise a cost function, e.g. a cost function

$$f : R^n \to R$$

$$x \in R^n$$

Subject to:

$$h_i(x) = 0, i \in I = 1,\ldots, p$$

$$g_j(x) \le 0, j \in J = 1,\ldots, m$$

Many numerical techniques exist to seek the optimum result without evaluating all possible alternatives (Ravindran et al 2006). In practice, real optimisation problems are computationally too difficult to uncompromisingly seek only the absolute best possible outcome and instead must aim to achieve the best achievable result with the available computing power and time.

The theory and practice of optimisation exists with the deliberate purpose of achieving better overall outcomes than the much more common approach of satisficing, which seems to be prevalent among many engineering fields. Satisficing is the process by which the designer and customer only aim to achieve satisfactory results because the satisfactory position is familiar, hassle-free, and secure, whereas aiming for the best-achievable result would call for costs, effort, and incurring of risk (Simon H 1982).

However, in relatively large engineering projects the extra effort and associated labour costs involved in refining the design would usually reap large financial rewards because the capital cost savings typically far outweigh the extra design fees. This is particularly true if the design refinements are undertaken with the specific purpose of reducing costs and maximising the engineering design's overall value for money.

In this paper, three methods of optimisation are used and compared:

1. an advanced implementation of nonlinear programming (NLP) called the Generalised Reduced Gradient (GRG) technique (Lasdon et al., 1978);
2. an Evolutionary Algorithm (EA), which is a variant of the Genetic Algorithm (GA);
3. the proprietary optimisation algorithm called 'Expert System Industry' implemented by the environmental noise modelling software package SoundPLAN (version 7.3).

The practical application of these three methods is illustrated through a case study using simulated receptors, noise sources and noise treatments similar to real situations encountered in Australia in recent years.

2.1 Nonlinear Programming (Generalised Reduced Gradient)

NLP is the name given to optimisation problems where the aim is to maximise or minimise an objective function subject to some constraints, where either the objective function, the constraint(s) or both are non-linear with respect to the controllable variables. The GRG technique (Lasdon et al., 1978) is a special implementation of NLP which is quite robust because it is usually reliable at finding global maxima or minima for well-scaled problems. A basic software implementation of the GRG algorithm is provided with Microsoft Excel (2010) and a more powerful version is available from Frontline Systems Inc.

2.2 Evolutionary Algorithm

The Evolutionary Algorithm is an advanced variant of the Genetic Algorithm optimisation method. GAs are based on the principles of natural selection according to Darwin's theory of survival of the fittest. GAs or EAs can sometimes be useful for combinatorial optimisation problems in which the variables can only take discrete values because of the extremely large number of potential combinations of different variables. Genetic or evolutionary algorithms are usually very successful at finding good local minima/maxima, although there is no way of knowing if the procedure has found the global optimal solution. A basic software implementation of the EA method is provided with Microsoft Excel (2010) and a more powerful version is available from Frontline Systems Inc. Implementations of GA/EAs are also available in numerical computing software including MATLAB and Scilab.

2.3 SoundPLAN's Expert System Industry module

The proprietary environmental noise modelling software SoundPLAN features a numerical optimisation algorithm which can select noise control mitigation treatments from a predefined library with the express purpose of minimising the cost of the entire noise control scheme for all sources. The software documentation does not describe the mathematical algorithm that the software module follows; however, by inspection and experimentation its fundamental method can be deduced. After analysing and experimenting with several test models it appears that the algorithm incrementally applies noise control treatments in a forwards-only direction of progressive advancement. It seems that it discretely adds or replaces noise control treatments with the sole selection criteria of achieving the best incremental increase in the total noise reduction for the smallest increase in total cost. Furthermore, it seems that the algorithm is not recursive, that is it does not consider the viable option of downgrading the noise mitigation at a source in order to allow an improvement in the overall noise reduction per dollar by applying alternative noise mitigation to another source.

3. Noise sources and receptors

The CSG gas fields in Australia are characterised by large areas of land with many hundreds of gas wells interspersed between small rural communities and isolated residences. The distances between receptors can range between a few tens of metres to several kilometres in any direction. The distances between gas well heads depends on the underground well design but separation distances between 400m to 700m are not uncommon. In the case study described in this paper, a simulated total of 20 receptors and 373 wells have been located within an area of 10 km x 10 km, as shown in Figure 1. By legislative restriction, wells are generally prevented from placement within a certain buffer zone around residences, for example 500 m to 2 km. In this case study the buffer zone has been assumed to be a radius of 500 m.

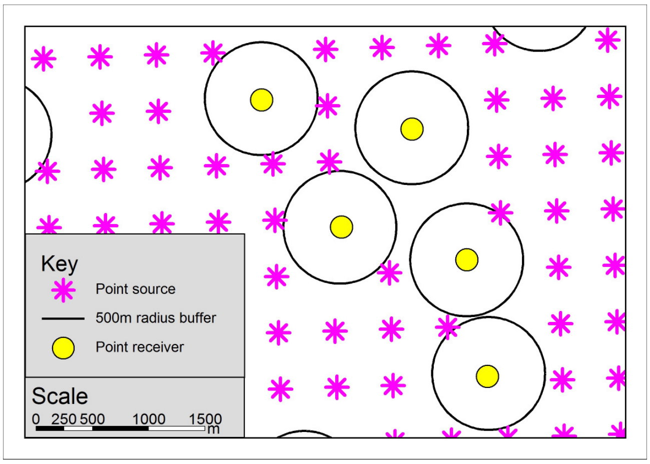

Figure 1 – Noise source buffer zones around receptors

3.1 Noise sources sound emissions

The noise sources used in this case study were the reciprocating gas engine power units that are used to drive well-head groundwater extraction pumps in some CSG projects because they are the dominant noise sources at the wells. The sound power levels of the simulated gas engines were similar to those that are currently being installed at the writing of this paper in some CSG fields in Australia. The noise mitigation treatments used in the case study were based approximately on the noise control treatments available for the gas engine power units that are currently being installed. The costs are fictitious and indicative only.

The sound power level spectrum of the unattenuated gas engine noise sources is shown in Table 1.

Table 1 – Sound power level spectrum of unattenuated gas well noise sources, dB re 10^{-12}W

Octave band (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Sum dB(A)
SWL (dB re 10^{-12}W)	102.4	107.4	109.1	96.6	91.4	91.5	92.9	89.7	93	74	100

The attenuations of the available source noise control treatments are shown in Table 2.

Table 2 – Available noise mitigation treatments, dB

Treatment Type	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	Unit Cost ($)
Type A	1	2.8	7.9	3.9	1.7	6.2	5.3	8.5	11.2	2,000
Type B	2	7	11	7	8	11	9	12	15	3,000
Type C	3	10	14	12	10	12	12	15	18	4,500

The noise mitigation treatments shown in Table 2 are mutually exclusive and cannot be combined additively. The available options are therefore only (i) nil, or (ii) Type A, or (iii) Type B, or (iv) Type C.

3.2 Noise receptors and criteria

The noise receptors simulated in the case study were isolated residences separated by various distances ranging from a few hundred metres to several kilometres apart, representing mostly farmhouses. The ambient noise levels in this type of area are typically quite low (often less than 25 dB(A)). The legislated noise limits in Australia vary in different jurisdictions, but in this paper all receptors have been given a common threshold noise limit of either 28 dB(A) or 30 dB(A).

4. Methodology

4.1 Nonlinear programming

To reduce the complexity of the sound propagation attenuation for the purposes of demonstration, the NLP optimisation procedure was simplified by working only within a single octave band. In practice there is no reason why the calculations cannot be performed in all relevant frequency bands, but for the purpose of demonstration this case study has been undertaken in the 125 Hz octave band for the reasons explained below.

In order to calculate the required amount of noise attenuation required for each gas well that will result in the minimal overall cost of noise mitigation for all combined wells, it is necessary to derive an equation that represents the noise reduction as a function of cost for each well. Note that the quantum of noise reduction achieved at a receptor in dB(A) is not the same as the noise reduction at the source in dB(A), and this is true at every receptor receiving noise from each source. Consequently, it was necessary to select only one frequency band that gave the best representative corresponding reduction at the receiver as at the source. In identifying this dominant band, it is important to realise that the high frequencies will be significantly attenuated by distance and air and ground absorption; therefore, the impact at receivers will typically be controlled by the lower frequency bands. By visually averaging the source contribution spectra, it was observed that the 125 Hz band is usually the dominant low- to mid-frequency contributor at receivers from the most dominant unattenuated sources. Also, it was confirmed that there was good correlation between the noise treatments' insertion loss (IL) at 125 Hz and the corresponding dB(A) reduction at the receiver. An extract from the list of unattenuated source contributions at one of the receivers is shown in Table 2, in which the darker red shading indicates dominant frequency bands in dB(A). The dominant noise sources in terms of overall dB(A) are highlighted in darker blue.

In order to undertake NLP for the design of noise treatments, it was necessary to convert the available noise mitigation and associated cost data into a continuous function that describes the cost-effectiveness of the available noise mitigation treatments. In this case, since the attenuations at 125 Hz and the associated costs of the different noise mitigation treatments form a monotonically increasing function, a suitable continuous function can be developed by polynomial interpolation. The four co-ordinates of the 125 Hz band cost-effectiveness relationship are shown in Table 4.

Table 3 – Example noise source contributions from wells at a receiver (dB(A))

Receiver Number	Source Number	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	Sum
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2	336	-12.5	5.9	5.4	-3.9	-2.5	3.8	-1.7	-35	-100	10.6
2	337	-9.86	8.6	8.4	-0.7	1.1	8.3	4.7	-21.8	-91.1	14.2
2	338	-6.25	12.3	13.4	3.5	5.7	13.7	12.2	-7.4	-52.1	19.3
2	339	-6.23	12.3	13.4	3.5	5.7	13.7	12.2	-7.4	-52.1	19.3
2	340	-9.86	8.6	8.4	-0.7	1.1	8.4	4.9	-21.4	-90.4	14.2
2	341	-26.4	-8.8	-11.1	-24.3	-29.6	-32.6	-64.1	-100	-100	-6.7
2	342	-25.3	-7.6	-9.7	-22.3	-26.8	-28.5	-56.2	-100	-100	-5.3
⋮ etc.	⋮.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 4 – Cost-effectiveness of mitigation treatments at 125 Hz

Point i	Insertion Loss x_i, dB	Cost C_i, $
1	0	0
2	7.9	2,000
3	11	3,000
4	14	4,500

The 3rd order polynomial that passes through all of these points is as follows:

$$C(x) = 1.627x^3 - 24.44x^2 + 344.7x + 0 \quad (1)$$

The cost-effectiveness curve of the available attenuation treatments in the 125 Hz band is shown in Figure 2.

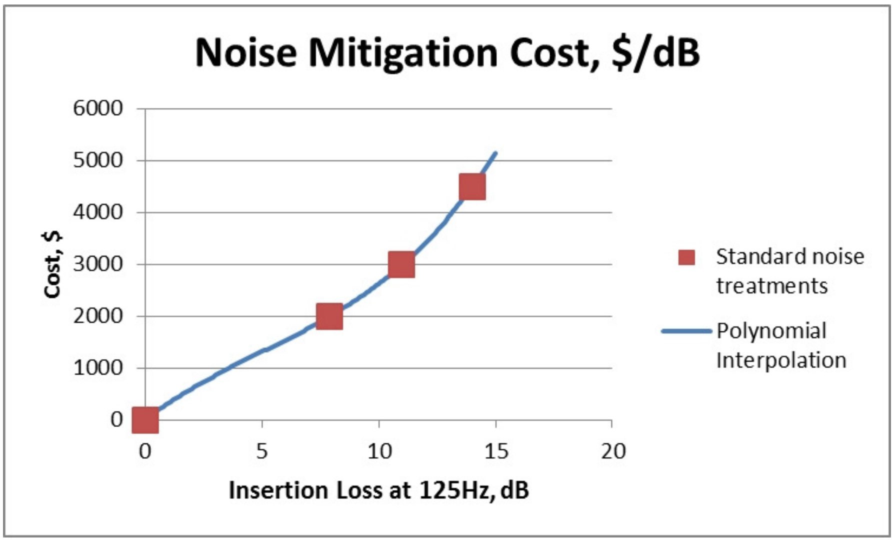

Figure 2 – Noise mitigation cost effectiveness and polynomial interpolation

With this continuous function representing the cost-effectiveness of the available noise control treatments for each well, it is now possible to define the optimisation problem using total cost as a non-linear objective function and the predicted noise levels at receivers being less than or equal to the noise limits defined as the set of constraints. That is:

Minimise the total cost C_{total}:

$$C_{total} = \sum_{i=1}^{n} C_i(x_i) \tag{2}$$

subject to

$$L_{\text{receptors}\ j}(\overline{X}) \leq L_{\text{limit}\ j} \tag{3}$$

(i.e. the noise levels at all receptors must be less than or equal to the noise limit)

where

$\overline{X} = [x_1, \ldots, x_n]$, the insertion loss of noise attenuation of treatments applied at the wells (in dB)

and

$C_{1 \ldots n}$ are the costs of noise treatments at each well

4.2 Evolutionary Algorithm

The EA method of optimisation was implemented with a similar methodology as the NLP method except that the noise attenuation treatments were applied discretely and separately, across the entire frequency spectrum exactly as shown in Table 2.

4.3 SoundPLAN - Expert System Industry

The noise mitigation scheme devised using the optimisation module in SoundPLAN was implemented using the same attenuation values and costs as shown in Table 2.

5. Results

Each of the optimisation methods were run for design target noise levels of 28 dB(A) and 30 dB(A) at all receptors and the results are compared in section 5.4. The results for the design target noise level of 30 dB(A) are discussed in detail below.

5.1 Nonlinear Optimisation Results

With a noise limit of 30 dB(A) at all receivers, the nonlinear optimisation procedure successfully applied noise mitigation so that the noise limits were met at all receivers, as shown in Table 5.

An extract from the calculated table of IL values and associated costs is shown in Table 6.

Table 5 – Nonlinear optimisation results - receivers

Receiver number	L (unattenuated) dB(A)	Target noise level dB(A)	L (attenuated) dB(A)
1	33.4	30	29.4
2	32.9	30	29
3	33.5	30	29.3
4	34.1	30	29.5
5	34.5	30	29.7
⋮	⋮	⋮	⋮
20	30.9	30	27.4

Table 6 – Extract from table of attenuation and associated cost of noise control at wells

Source Number	Insertion Loss (dB)	Cost ($)
⋮	⋮	⋮
10	5.5	1,420.64
11	8.1	2,062.28
12	3.9	1,061.13
13	1.6	493.19
14	0.7	216.00
⋮ etc.	⋮	⋮
	Total costs	332,626

5.2 Evolutionary Algorithm Optimisation Results

The Evolutionary Algorithm was run many times to try and find results at or close to the global optimum (minimum) cost. The results of seven of the most successful runs are shown in Table 7. Due to the inherent randomness of the GA/EA, the procedure often failed to start, as the initial set-up runs could not find any feasible solutions. Consequently, the solution space had to be manually restricted in order for the algorithm to work. The simplest restriction that gave the algorithm the necessary starting points was to assign a minimum of treatment Type A to all noise sources. Other types of restrictions on the size of the solution space were also tried with varying degrees of success. The types of restrictions that worked well are discussed in section 6.1.2.

5.3 SoundPLAN Expert System Industry

SoundPLAN's Expert System Industry module also produced a noise mitigation scheme that achieved the noise limit of 30 dB(A) at all receivers. A summary of the noise mitigation treatments applied at the sources and the total costs is shown in Table 8.

Table 7 – Evolutionary algorithm results: predicted noise levels at receptors dB(A)

Receptor	Noise limit	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
1	30	26.8	26.8	27.9	26.6	28.0	27.7	27.3
2	30	25.6	26.2	26.5	26.9	25.8	27.0	25.8
3	30	27.2	26.7	27.9	27.6	26.9	27.6	28.0
4	30	27.3	26.9	27.2	28.4	27.4	27.9	27.1
5	30	28.3	27.8	28.6	28.5	28.5	29.0	28.3
⋮ etc.	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Cost ($)		894,500	984,500	734,500	805,000	809,500	764,500	770,500

Table 8 – Summary of SoundPLAN's Expert System Industry optimisation results

Type 1 mitigation:	143 wells	×	$2,000	=	$286,000
Type 2 mitigation:	80 wells	×	$3,000	=	$240,000
Type 3 mitigation:	49 wells	×	$4,500	=	$220,500
			Total Cost	**=**	**$746,500**

5.4 Comparison and Summary

A comparison of the results from each of the three optimisation methods is shown in Table 9.

Table 9 – Comparison of all three methods' optimisation results

Optimisation Method	Cost ($)	
	Target 28 dB(A)	Target 30 dB(A)
Nonlinear Programming	524,286	332,626
Evolutionary Algorithm	1,013,000	764,500
SoundPLAN: Expert System Industry	746,500	457,500

6. Discussion

6.1 Comparison of algorithms

6.1.1 Nonlinear programming – advantages and disadvantages

The NLP optimisation method was found to be very robust, since it always found a solution very quickly (within a few minutes) and often found the same solution from a number of different starting points. This solution was the lowest cost of all other minima that the algorithm converged to, which implies that this point may have been the global optimum.

The biggest disadvantage of the method is that it needed the insertion loss of the available noise mitigation treatments to be modelled as a continuous function, meaning that the resultant required IL at each well is not constrained to correspond to one of the available noise mitigation treatment types. In practice, either the noise control manufacturer would have to be able to custom-make the treatment for every single well, or the treatments would need to be selected on a 'just-sufficient' basis which would result in a somewhat higher total cost than the algorithm predicted.

6.1.2 Evolutionary Algorithm – advantages and disadvantages

The advantage of the EA is that it applies the IL of the available noise control treatments exactly as provided, across the entire noise source spectrum. The propagation attenuations can be properly incorporated in all frequency bands and more complicated criteria can be incorporated if necessary, such as low frequency noise content and/or impact of tonality. Also, every noise receptor can be assigned a different noise level limit target to be achieved.

The main disadvantage of the EA is that due to its inherent randomness when setting up the initial population of draft solutions for refinement and improvement, it can be prone to not finding any feasible solutions at all, in which case it simply terminates after a preselected time period. In order to overcome this disadvantage and to 'force' the algorithm to find some initial feasible solutions to begin the population, it was necessary to manually impose some constraints to narrow the search space. The additional constraints that successfully narrowed the search field and allowed the EA to find a solution were:

- All sources were assigned a minimum noise mitigation treatment of Type A.
- For the target of 30 dB(A): all sources that contributed more than 10 dB(A) below the loudest source at any receptor were automatically assigned a minimum noise mitigation treatment of Type A.
- For the target of 28 dB(A): all sources that contributed more than 13 dB(A) below the loudest source at any receiver were automatically assigned a minimum noise mitigation treatment of Type A. Also, all sources that contributed more than 10 dB(A) below the loudest source at any receptor were automatically assigned a minimum noise mitigation treatment of Type B.

It is strongly suspected that without the manual application of treatments to wells, the EA method would have found lower cost solutions than the SoundPLAN software if it had found enough feasible solutions to start the algorithm.

6.1.3 SoundPLAN Expert System Industry – advantages and disadvantages

The main advantages of the optimisation routine in SoundPLAN's Expert System Industry module are that it is extremely fast to run and that it applies the IL of the available noise control treatments exactly as provided, across the entire noise source spectrum.

The disadvantages are that it is slow and cumbersome to set up the optimisation calculation run; the data files are locked so the calculation details are inaccessible; and the receptors can only be allocated a very limited selection of noise level limit design targets.

7. CONCLUSIONS

The NLP optimisation method was able to develop a noise mitigation scheme that determined the required IL at all wells in order to achieve the noise limits at all receptors for lower total costs than the other two optimisation methods. However, the required IL at each gas well would need to be achieved with custom-made noise treatments for each well. In comparison, both the EA and the Expert System Industry module of SoundPLAN were able to devise noise mitigation schemes for all of the noise sources across the entire gas field, using the available noise mitigation types. Although the SoundPLAN module was able to develop a lower cost noise mitigation scheme than the EA, it is not able to develop a scheme considering different noise level targets for each receiver. In comparison, the

EA is able to design a noise mitigation scheme even if every receptor has a different noise level limit. The major disadvantage of the EA method was that it required some manual intervention to narrow down the search space, which in practical terms means that noise control treatments were unnecessarily applied to some noise sources solely to make the optimisation routine function correctly. It is conceivable that in different circumstances the evolutionary algorithm might yield substantially lower total costs than the SoundPLAN software would, especially if it was not necessary to narrow the search space by manually applying a minimum grade of noise control to all sources.

8. REFERENCES

1. Ravindran A., Ragsdell K.M., Reklaitis G.V. Engineering Optimisation: Methods and Applications, 2nd ed. Hoboken, New Jersey, John Wiley & Sons, 2006
2. Lasdon LS, Waren AD, Jain A & Ratner M. Design and Testing of a Generalized Reduced Gradient Code for Nonlinear Programming. Association for Computing Machinery ACM Transactions on Mathematical Software, Volume 4, Issue 1 March 1978, pp. 34-50
3. Simon H.A. Models of Bounded Rationality and Other Topics in Economics. Cambridge, Massachusetts, MIT Press, 1982
4. SoundPLAN (version 7.3) [software] (2014) Braunstein & Berndt GMBH. Computer Software.
5. Scilab Enterprises (2012). Scilab. Free and Open Source software for numerical computation (Version 5.5.0) [Software]. Computer Software.
6. MATLAB and Optimization Toolbox Release 2014a, The MathWorks, Inc., Natick, Massachusetts, United States. Computer Software.
7. Microsoft Excel. Redmond, Washington: Microsoft, 2010. Computer Software.