

Engineering Management  
Field Project

**Water/Wastewater Treatment Plant Field Device  
Wiring Method Decision Analysis**

By

Scott C. Dicus

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Tom Bowlin  
Committee Chairperson

  
\_\_\_\_\_

John Brickley  
Committee Member

  
\_\_\_\_\_

Dewitt Smith  
Committee Member

Date accepted: 11/7/11

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## **Executive Summary**

The choice of field device wiring method for water and wastewater treatment plant design is extremely complex and contains many variables. The choice not only affects short-term startup and equipment costs, but also long-term operations and maintenance costs and attributes such as sustainability, water quality, and asset lifespan. The literature suggests several advantages and disadvantages to each available wiring method, though no industry standard wiring method exists since each client has their own unique situation and preferences. While it is true that the field device wiring method decision can many times be mandated by existing client standards or existing plant assets, new treatment plants or open-minded clients may benefit from an objective analysis, performed by subject matter experts, of the available wiring methods. This research report investigates the use of a dynamic decision analysis tool that utilizes the analytic hierarchy process. This process can utilize both objective data (like manufacturer quotes, bills of materials, or net present value calculations) and subjective data (like surveys) to weight alternative wiring methods based upon unique client preferences and engineering technical expertise. The resulting tool facilitates a standard process for making the complex field device wiring method decision.

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## Chapter 1 – Introduction

*Note: Critical data were redacted from this research report.*

Field device wiring in water and wastewater treatment plants has traditionally been hardwired. Though many other industries readily embrace new wiring technologies such as field device networking or wireless technologies, the water/wastewater industry has lagged other industries and tends to wait for new technologies to mature. While these new wiring method technologies have made some inroads in the water/wastewater industry, “standard” plant design typically uses the traditional hardwiring wiring methodology unless a client requests an alternative wiring method technology. It is important to note that a large percentage of engineering consulting workload involves “retrofits,” or upgrades to existing treatment plants. In these situations, many clients have standardized on a specific wiring method in their plants and it becomes economically and operationally infeasible to use an alternate wiring method technology. Therefore, the scope of this research report will investigate the use of alternate wiring methods for either new “green field” plants or for clients who are open to new technologies and are remodeling a significant portion of their existing plant.

There will never be a wiring method solution that is optimal for all clients, but it seems reasonable that a standard decision analysis tool for choosing the client’s preferred wiring method can be developed. The decision to use a particular wiring method is extremely complex and must account for numerous variables. Additionally, these

variables change based on client preferences, standards, and existing labor/equipment assets.

Currently, the wiring method decision tends to be highly subjective, and though this decision is based on both client and designer experiences and preferences, there is no guarantee that the chosen wiring method is optimal. Therefore, it is reasonable to wonder if there can be an objective way of comparing the myriad variables and then delivering the best wiring method solution to the client. This research report will develop an application of the analytic hierarchy process developed by Thomas Saaty to address the aforementioned “complex, multiperson, multiattribute, and multiperiod problem” (Canada, Sullivan et al. 1996).

## Chapter 2 – Literature Review

In performing a review of the existing literature relating to a field device wiring method decision analysis, the following areas were investigated:

- The historical emergence of process monitoring, control and automation
- Comparisons of the prevalent field device wiring architectures in the water/wastewater industry
- Case studies involving these wiring method comparisons
- The analytic hierarchy process for multi-attribute decision making

This literature review helped form the research procedure outlined in Chapter 3 of this research report.

### The Emergence of Process Monitoring, Control, and Automation

Modern water and wastewater treatment plants can be expansive, with some of the largest plants treating over one billion gallons of water per day. These plants may have thousands of field devices including valves, analyzers, instruments (such as flow meters, level transmitters, and pressure sensors), pumps, process equipment (such as centrifuges, filters, and ultraviolet reactors), and building systems equipment (such as security systems, fire alarms, and ventilation systems). It is simply impractical to monitor and control these field devices manually and expect to produce good quality water, or to maintain low operations and maintenance costs (and subsequently low

water rates for consumers). Therefore, it becomes necessary to wire each field device to a central control system that allows the entire plant to be monitored and controlled remotely. Control can even be automated using control logic embedded in microprocessor-based equipment, such as programmable logic controllers or distributed control systems.

Traditionally, water and wastewater treatment plants use a “hardwired” wiring method for field devices. However, despite the ubiquity of hardwiring in the water/wastewater industry, other process control industries such as oil, energy, and manufacturing have embraced a networked architecture for field device wiring. Since the mid-1990s when the first field device networks were pioneered, millions of networked devices have been sold (Fieldbus Foundation 2011). Among all process control industries, 55% of the installed devices (over 50 million devices) are networked devices, and that number has been growing by 30% per year since 2002 (Vincent 2008).

Field device networks have proven advantages, but “only if supporters convince reluctant colleagues and management of [their] usefulness” (Montague 2002). This trend of supporting process control with field device networks has led to a paradigm shift where process control workers are elevated from the production worker mindset (plant operator) to the knowledge worker mindset (process automation professional). In fact, Rockwell Automation has noted that in order “to support this network convergence, controls engineers and Information Technology professionals experience both organizational and cultural convergence as well as share best practices” (Rockwell

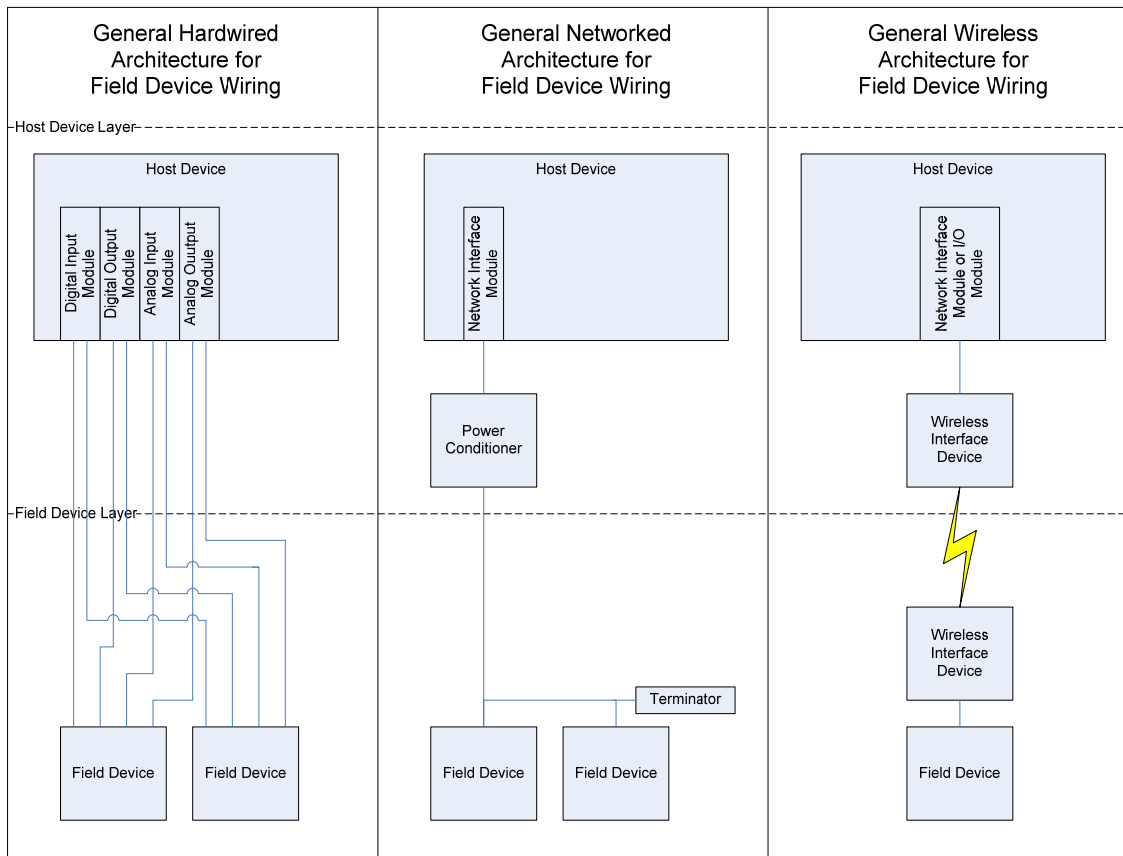


Automation and Cisco Systems 2008). Water utilities in particular have been reluctant to begin the transition to field device networks and have preferred to wait for product maturity.

### **Comparison of Field Device Wiring Architectures**

The prevalent hardwired wiring architecture involves communication from a host device interface module to a field device and typically uses a 4-20mA dc signal transmitted over a single pair of wires for analog inputs and outputs (I/O), and a 120V ac or 24V dc signal for discrete I/O. For example, a flow meter field device may have just a single analog input to the host device that is linearly-proportional to a process flow. However, a pump may have several analog I/O and several discrete I/O to monitor and control parameters such as pump speed, fault conditions, control panel switch statuses, and associated valve operations. See the “General Hardwired Architecture for Field Device Wiring” shown in Figure 2.1.

The “General Networked Architecture for Field Device Wiring” also shown in Figure 2.1 illustrates the use of a field device network. This architecture typically involves an interface module at the control system host device, one or more power conditioners, and the field devices themselves (Moore Hawke 2008). In fact, the field devices can even be device couplers (doubling as segment protectors) that have several segments, or “spurs,” that can aggregate traditional hardwired I/O from new or existing non-networked devices onto the trunk network (Parker, Schuessler, et al. 2011).



**Figure 2.1 – General Field Device Wiring Architectures**

Though there are fewer wires involved, field device networks are much more complex than a hardwired wiring method. During their infancy, field device networks were “comprised of specialized data links using various physical layer strategies, proprietary protocols, and varying degrees of conformity/compliance between communicating systems. Designing, implementing, and troubleshooting these networking interfaces was nearly always a ‘new adventure’ on every project” (Parker 2011).

As the technology matured, standards started to emerge. Typical nomenclature refers to these standard field device networks as “fieldbuses,” “digital networks,” or “device

networks,” and the terms are often used interchangeably. Fieldbus is “a generic term for a digital, two-way, multi-drop communication link between intelligent control devices” (Haken and White 2004). Fieldbuses can utilize “a variety of communications protocols using various media, but all are simply a means to an end” (Moore Hawke 2008).

Countless communication protocols for field device communication exist, though the water/wastewater industry has only seen wide adoption of a few protocols including: Foundation Fieldbus H1, Profibus DP, Profibus PA, DeviceNet, Modbus, Hart, OPC, and Ethernet. These protocols are now “open” standards, or standards that are supported by multiple vendors, though this was not always the case. Since many water and wastewater utilities are required to allow competition between hardware vendors, the use of proprietary protocols today is not typical unless a client has independently decided to standardize on that protocol. Further, treatment plants are not constrained to the use of a single protocol; in fact, “it is likely you will need to use multiple fieldbuses to accomplish the many tasks required. For example, you may use Foundation Fieldbus for process control, DeviceNet for discrete I/O, and Profibus DP for motor drives” (Moore Hawke 2008). Some protocols like Foundation Fieldbus H1 and Profibus PA both use “the same physical layer of individually shielded twisted pair cables wired in parallel” (Verhappen 2010). “You don’t even necessarily have to replace your existing wiring. Test kits are available to determine if existing wiring is compatible” with field device networking technology (Fieldbus Foundation 2011).

The choice of switching to a networked wiring architecture is not an arbitrary one, and can even be the wrong choice. Facility owners should not upgrade simply because everyone else is doing so, but should also not become complacent thinking that an upgrade is unnecessary since their current system works. The decision to utilize a networked wiring architecture is so complex, it is not unheard of for an instrumentation specialist to spend “six months researching available fieldbuses” (Montague 2002). There are several differences between the hardwired and networked architectures, and these differences can be either advantages or disadvantages depending upon unique client situations and preferences. The following is a discussion of the major differences between these two wiring architectures and the wireless wiring architecture.

### **Quantity of Wiring/Equipment**

Fieldbuses can reduce the quantity of field device wiring, and as a result, the quantity of conduit, the quantity of control cabinets, and the control cabinet footprint may also be reduced. Power provided over the fieldbus can even reduce the quantity of field-mounted power supplies (Vincent 2008). “The average cable run between automation hardware and final control element is 300 feet” (Parker, Schuessler, et al. 2011). Also, a “fieldbus theoretically allows up to 32 devices to be brought in over one twisted wire pair” (Moore Hawke 2008).

Since multiple devices can communicate using the same pair of wires, the reduction of total plant wiring can be significant. However, the qualifier “theoretically” in the statement describing the quantity of field devices on a single network segment is

important. Though many networking protocols claim a theoretical 32 field devices (also known as slaves) per network segment, real-world implementation has shown that this statement is not quite true. A study conducted on the use of fieldbuses in power plants found that the increased information available over fieldbuses negatively impacted the control system response time.

To achieve network and control loop performance similar to a hardwired wiring architecture, fewer field devices than the theoretical limit should be installed on each network segment and the actual quantity of field devices that should be installed on each network segment is protocol-dependent. For example, one study recommends that when using Profibus DP as a communication protocol, a network segment containing a total of 16 slaves (12 field devices and four spare) is recommended – a number much less than the theoretical limit. Similarly, when using Profibus PA or Foundation Fieldbus H1 as a communication protocol, a network segment containing only eight slaves total (six field devices and two spare) is recommended (Parker 2011).

These recommendations are for typical applications, and longer cable runs may further decrease the maximum field device load (Schuessler 2011). Therefore, the reduction of field device wiring using fieldbuses can be less than equipment manufacturers' claims.

Furthermore, "there is a potential problem with losing communication with all devices if something happens to the power conditioners, [host] card or the trunk cable" (Moore Hawke 2008). To mitigate this problem, more equipment and field device wiring may need to be installed to allow for system redundancy, further reducing possible savings.

## Diagnostic Information

“Components degrade over time” and can “cause downtime for the plant, a costly proposition.” In fact, “unplanned shutdowns are the largest cost in the process industries” (Schuessler 2011). More than the field devices themselves, the physical layer (i.e. the wiring, signal conditioners, and host devices) can also degrade. “Usage and nature eventually take their toll wearing down parts, weakening weatherproof seals, and breaking down insulation...the list of possible problems with physical layer components is quite extensive” (Kelly 2005). Diagnosing faults and alarm conditions in traditional hardwired networks can be difficult. Maintenance on these networks is solely reactive; there is no warning that faults are about to occur. Additionally, the process is tedious, requiring a manual intervention using several pieces of test equipment on one field device at a time. Then, after diagnosing the problem, the diagnostic tools are disconnected and the process of waiting for another failure resumes (Schuessler 2011).

“The diagnostic information available from fieldbus instruments is a major reason that fieldbus is replacing the traditional 4-20mA systems.” Further, “collecting diagnostic information for the physical layer components of a fieldbus system – i.e. power supplies, connection blocks, terminators and cable” provides a wealth of real-time information that can lead to predictive/preventative maintenance or quick reactive maintenance (Kelly 2005). “Numerous end users have avoided unplanned shutdowns due to the diagnostics and function block capabilities” of fieldbuses (Fieldbus Foundation 2011).

Networking diagnostics that may be available include: bulk power health, segment voltage and current, ground fault or leakage, segment noise, device signal level, signal polarity, signal jitter, a selection of communication statistics, segment live list, cyclic redundancy check, frame error counter, and the number of received frames (Schuessler 2011). However, some of the additional diagnostics are needed simply to address the new problems that arise with field device networks that were not present with hardwired networks. “The list of possible problems with physical layer components is quite extensive” and can include: shield short, broken connection, noise, extra/missing terminator, and power conditioner fault (Kelly 2005).

“Several options exist for on-line diagnostic tools associated with the physical layer, including permanently attached and portable device diagnostic methods.” Benefits from these methods include “the ability to historize the data, and provide real-time alarming and trending of the data system.” However, it is noted that permanent diagnostic tools should only be installed with a well-integrated host system (Moore Hawke 2008). “It is important not to overload the users with unnecessary information, which is difficult to interpret,” and may lead to unnecessary maintenance labor and a reduction in network performance (Process Worldwide 2005).

Finally, diagnostics can assist during routine maintenance and equipment failures. Troubleshooting is faster because the enhanced available diagnostics simplify testing, capture intermittent problems, help pinpoint issues, guide to potential solutions, and allow consultation with offsite experts since they are accessible from a remote location

(Schuessler 2011). However, results cannot be guaranteed if maintenance staff is not properly trained. “Before they start using a fieldbus system, every user should be fully aware that this transition involves a change in planning and maintenance know-how” (Process Worldwide 2005). Since many utilities are not prepared for the cultural shift required to properly utilize field device networks, “approximately 80% of installed smart field devices are being underutilized,” and subsequently, even the most advanced plants still have opportunities for savings (Verhappen 2010).

### **Plant Installation and Startup**

“Up to 75 percent of all startup delays directly relate to instrumentation and controls” (Fieldbus Foundation 2011). One of the benefits touted by fieldbus manufacturers is a reduction in the quantity and duration of inevitable startup delays. However, despite assertions in manufacturers’ product literature, “fieldbus installations require some additional considerations over and above traditional 4-20mA projects” (Moore Hawke 2008) and are not simply “plug n’ play” (Parker 2011). Even with these required additional considerations, startup for fieldbuses can be shorter than startup for traditional hardwired networks. Depending on the protocol implemented, numerous factors can contribute to quicker plant startup (Susanto and Purwanto 2001), including:

- Reduction in termination and testing labor since there may be less wiring
- Capabilities of a device can be recognized instantly upon connection to the bus
- Time savings due to remote configuration capability from the control room



- Reduced wiring to control equipment due to advanced features
- Automated documentation

However, more training is required for construction personnel since installation for fieldbuses is completely different from hardwired systems (Susanto and Purwanto 2001). The plant owner may not have the choice of choosing an experienced fieldbus installer depending on local regulations since there may be a requirement to accept the low-bid contractor.

Hardwired systems also have the slight advantage of straightforward interoperability between various manufacturers because the “install base is also, simply put, cheap insurance for project execution” (Parker 2011), though fieldbus manufacturers are catching up and starting to provide standard communication drivers.

### **Plant Operations and Maintenance**

Utilizing fieldbuses can also reduce the plant operations and maintenance (O&M) costs. It has been estimated that 63% of field visits could be eliminated in a properly-implemented fieldbus system (Vincent 2008). Depending upon the protocol implemented, various factors can contribute to reduced O&M costs (Susanto and Purwanto 2001, Vincent 2008), including:

- Greater accuracy and precision due to digital floating point format and immunity from analog signal degradation
- More reliability and security due to error detection

- Higher process availability
- Enhanced diagnostics
- Remote calibration
- Aid in regulatory compliance

Again, more training may be required for operations and maintenance staff to realize the benefits mentioned herein.

### Advanced Features

One disadvantage of utilizing fieldbuses can be slower process value update times when compared to hardwired networks. The update times can suffer when control functions are distributed to remote controllers and the control network becomes clogged. To mitigate this problem, Foundation Fieldbus created an advanced feature called “Control in the Field,” or CIF (Susanto and Purwanto 2001). CIF creates “single loop integrity” and can add another layer of redundancy (Fieldbus Foundation 2011). Additionally, Foundation Fieldbus “devices manage all communication in the network, and therefore do not require a dedicated [processor]. Thus, it is possible to increase the Foundation [Fieldbus] network without increasing [processor] hardware” (Bonadio and Argolo 1999). However, if inter-dependent, remote processes exist at a plant, “one of the drawbacks to CIF is that it extends the amount of information that must be communicated across the network, in turn, slowing the network cycle time” (Schuessler 2011). Since water/wastewater treatment plants often contain many inter-dependent

processes that may not be collocated, network performance can actually suffer using CIF. Additionally, since CIF is protocol-specific, interoperability between components may become an issue. Therefore, the use of CIF is not typically recommended for water/wastewater treatment plants and should not play a significant role in a wiring method decision analysis. Additionally, other minor advanced features may be offered by various protocols and also lack wide adoption in the Water/Wastewater industry.

### **Wireless Wiring Architecture**

The “General Wireless Architecture for Field Device Wiring” shown in Figure 2.1 illustrates the use of a wireless network architecture. This network architecture just replaces the physical layer between the host and field devices, but the information travelling over the wireless link can be either analog or digital. For example, if only non-networked field devices are available, Wireless I/O can be used as a wireless interface device to transmit these signals and repeat them to the host device in the same format. If networked, or “intelligent,” field devices are available, data radios can encapsulate and transmit these digital signals (including a wide array of communication protocols) in a serial or Ethernet “envelope.” These radios can be unlicensed or licensed and can transmit over great distances. Some intelligent field devices may even have wireless built-in, eliminating the need for a field-mounted wireless interface device.

Using a wireless network architecture, “the number of cables and total length of cable [and conduit] used in the system is minimized.” In addition, “the radio’s mean time between failure is high, and is mostly exempt from frequent maintenance.” Even

though the technology promises low installation and maintenance costs since wiring is minimized, the “cost of this system mainly resides with the purchase of transmitters, cables, and structure to support the [transmission] cables.” Additionally, the cost “depends on the distance between” devices and “the amount of information that is necessary to be acquired” (Bonadio and Argolo 1999). Data-intensive applications present in water/wastewater treatment plants will naturally cost more when utilizing wireless, especially in plants with compressed site plans where inexpensive, short cable runs are possible. Therefore, wireless is typically used for remote, individual field devices or groups of collocated devices, not entire plants. Wireless technology is not typically considered for an application unless it involves remote data acquisition or infeasible wiring. Additionally, utilities are very apprehensive about using wireless technology for intelligent field device control applications because of the relative product immaturity. In fact, a recent article from the Fieldbus Foundation notes that, in reference to fieldbus technologies, “wireless in control applications is a long way off” (Fieldbus Foundation 2011).

## Case Studies

Several case studies are available from various process control industries about the successes of fieldbus technology. One success story involves an Indonesian oil company that was able to replace 27,720 feet of analog hardwired cable with just 6,950 feet of fieldbus wiring at one of their plants. Additionally, the number of cable terminations was cut in half, from 324 to 148, the maintenance schedule was reduced from once a

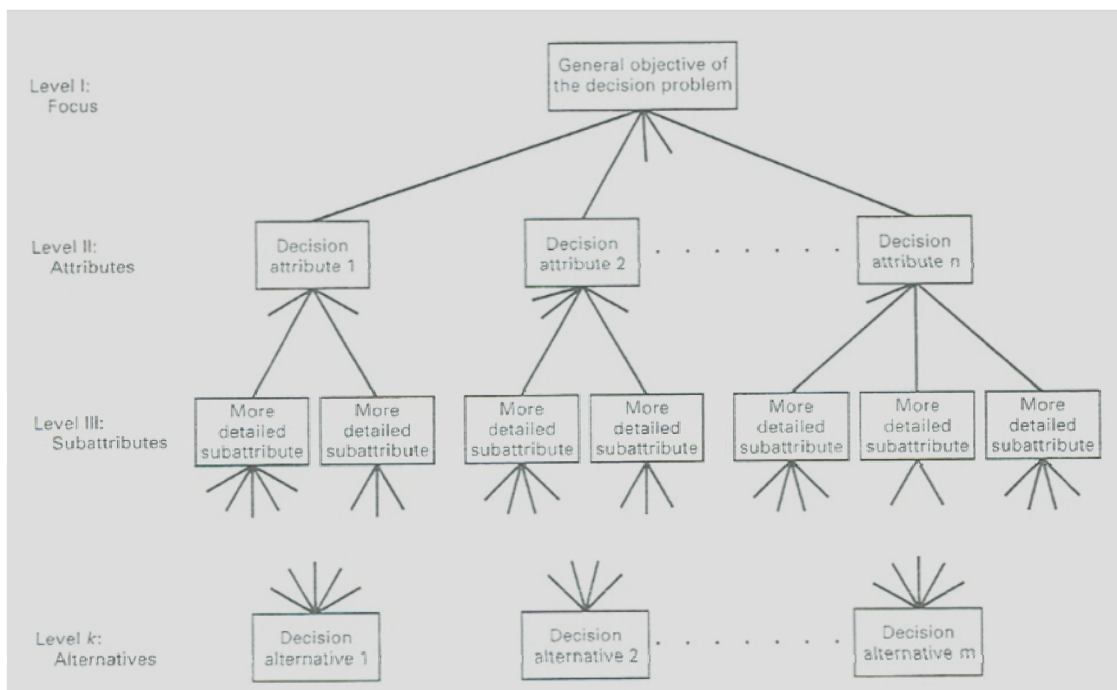
month to once a year, and the plant startup time met an accelerated schedule. In total, the installation costs were reduced from \$87,914 to \$55,541. Despite the obvious success, the company was “careful not to go too far in implementing all the [Foundation Fieldbus] functions,” since the benefits of some of the niche features (like CIF) were still unproven. Also, there were installation issues during this plant’s startup phase that included: improper grounding of cable shielding, interoperability issues between products from different manufacturers, outdated device firmware, and terminator problems (Susanto and Purwanto 2001). It was suggested that contractor experience could have corrected some of these issues.

Though several success stories exist, little was found in the literature about decision analysis tools for wiring methods. One SixSigma project for power plants investigated a way to “develop and deploy an electronic tool to generate a comparative cost/benefit between control interface technologies.” While this project was successful, it was specific for power plants and looked at only the cost variable, not subjective client preferences such as security, sustainability, and network performance (Parker, Butcher, et al. 2011). It is obvious that “there is no one correct answer for what [wiring method] to select,” (Parker 2011) so the goal of this research report is to construct a tool to allow a choice to be made objectively, but with the possible input of both objective and subjective data. Fortunately, a process exists that allows both of these types of data to serve as inputs and is simple enough to be performed using a standard spreadsheet program.

## The Analytic Hierarchy Process

The analytic hierarchy process (AHP) developed by Thomas Saaty is a method that can be used for computing a decision regarding a client's preferred wiring method solution. "The strength of the AHP method lies in its ability to structure a complex, multiperson, multiattribute, and multiperiod problem hierarchically" (Canada, Sullivan, et al. 1996). Additionally, the determination of the overall alternative priority weights can be made using pairwise comparisons consisting of either objective or subjective data. The AHP consists of five stages (Canada, Sullivan, et al. 1996):

1. Construction of a decision hierarchy by breaking down the decision problem into a hierarchy of decision elements and identifying decision alternatives. A general decision hierarchy is depicted in Figure 2.2.



**Figure 2.2 – General AHP Hierarchy (Canada, Sullivan, et al. 1996; Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ)**

2. Determination of the relative importance of attributes, sub-attributes, and alternatives.
3. Determination of the relative standing (weight) of each alternative or attribute with respect to each next higher level attribute or sub-attribute.
4. Determination of indicator(s) of consistency in making pairwise comparisons.
5. Determination of the overall priority weight (score) of each alternative.

During stage one of the AHP, the following guidelines should be considered when constructing hierarchies (Canada, Sullivan, et al. 1996):

1. The number of levels used should be chosen to represent effectively the problem at hand.
2. The order of the levels should reflect a logical causal relationship between adjacent levels.
3. The number of members in a particular level should be chosen to describe the level in adequate detail, but should not cause unnecessary complexity.

“It is important to note that the selected attributes and sub-attributes should be independent.” If the attributes are not completely independent, rank reversal can occur. “Rank reversal is when the introduction of a new alternative reverses the rankings of previously evaluated alternatives” (Canada, Sullivan, et al. 1996). Therefore, a carefully-constructed hierarchy is of paramount importance.

The vagueness of the questioning procedure often used in the AHP has also received criticism. “The decision maker is asked questions such as, ‘which is more important, good gas mileage or low maintenance, and by how much?’ The crucial observation is that such questions are meaningless...unless average quantity interpretation is assumed.” It is suggested that objective data is preferred, but subjective data is acceptable if the decision maker is aware of how the results were computed (Canada, Sullivan, et al. 1996).

Another criticism of AHP to be aware of is aggregation of benefits and costs. “In many applications of the AHP, two hierarchies are used to evaluate alternatives, a benefits hierarchy and a cost hierarchy.” The two hierarchies can be combined using a cost-benefit ratio. However this method has been criticized “for failing to yield optimal results for the general case,” and for “the general arbitrariness inherent in any labeling procedure” (Canada, Sullivan, et al. 1996).

During stage two of the AHP, decision makers must establish a priority for each set of elements at every level of the hierarchy. The decision maker responds to questions of the form: “With respect to [attribute], how strongly do you prefer [alternative one] to [alternative two].” “The response to each question takes the form of a value from one to nine and its reciprocal.” The scale shown in Table 2.1 is used when collecting data to express degrees of preference.



**Table 2.1 – Scale Legend**

1/9 = Absolutely less preferred
1/7 = Very strongly less preferred
1/5 = Strongly less preferred
1/3 = Weakly less preferred
1 = Equally preferred
3 = Weakly more preferred
5 = Strongly more preferred
7 = Very strongly more preferred
9 = Absolutely more preferred

“The magnitude of the response indicates the strength of preference of one decision element to another” (Canada, Sullivan, et al. 1996). The major assumptions of the comparison procedure are:

1. The relative weights of attributes within a level, conditional on each attribute in the immediately preceding level, are unidimensional.
2. Pairwise judgments of attributes encompass all relevant aspects of importance.
3. Decision makers can evaluate subproblems in an accurate and relatively consistent manner (Canada, Sullivan, et al. 1996).

The element priority may also be determined using objective (performance) data instead of the pairwise comparison process. However, this performance data must have a linear relationship to each attribute, otherwise subjective data must be used.

The remainder of the five stages of the AHP involves calculations on the inputs to determine overall priority weights for each alternative with respect to the AHP focus

and determining the consistency of the subjective judgments. “Judgmental consistency is concerned with the transitivity of preference in the pairwise comparison matrices. Consider the case in which attribute A is judged to be twice as important as attribute B and attribute B is judged to be twice as important as attribute C. Perfect cardinal consistency would then require that attribute A be judged four times as important as attribute C.” Both local and global consistency ratios exist to approximate the consistency of the pair-wise judgments. “If the consistency ratio is found to be unacceptable, the decision maker should review the judgments made and look for intransitivity...If the source of inconsistency is not apparent or cannot be resolved satisfactorily through the reestimation of preferences, it is possible that there is a problem with the hierarchical formulation of the problem.” Saaty posits that a consistency ratio no greater than 0.1 is acceptable (Canada, Sullivan, et al. 1996). Since the consistency ratio is calculated by taking the ratio of a calculated consistency index to a standard random index, a consistency ratio of less than 0.1 indicates that the subjective judgments contain less than ten percent of the randomness of a completely random sample.

## Chapter 3 – Research Procedure

The research procedure and computational method used for development of the water/wastewater treatment plant field device wiring method decision analysis tool supports potential implementation of the AHP method.

Stage one of the AHP process, creation of the AHP hierarchy, was pursued using the hierarchy guidelines and general AHP hierarchy shown in Chapter 2 of this research report. Stage two of the AHP process, determination of the relative importance of attributes and alternatives, was accomplished using an online survey tool comprised of pair-wise comparison questions. One survey for pair-wise comparisons of the AHP alternatives to the next-level attributes or sub-attributes was administered to subject matter experts. These comparisons are based on knowledge of the different wiring method architecture alternatives and are intended to be independent of client preferences. Note that, though these comparisons do not need to be updated for each client since the results do not change quickly with respect to time, the decision analysis tool has been designed to be dynamic since industry technologies mature and change gradually over time. Additionally, the tool may need to be updated as new technologies emerge and as designers gain more experience in using each available technology.

A second survey was developed for pair-wise comparisons of the attributes to the overall hierarchy focus. These comparisons are based on client preferences, so they must be completed for each project by the client or a client representative (such as a

project manager who is intimately familiar with the client preferences). Appendix A provides complete copies of the two surveys that were developed.

Stages three through five of the AHP process, determination of the alternative and attribute priority weights and the judgment consistency ratios, was accomplished using dynamic calculations built in to a standard spreadsheet tool. As inputs to the tool change, the outputs update in real time. This feature allows designers with little understanding of the AHP calculations and procedures to be able to use the tool with little training.

## **Chapter 4 – Results**

The development of the water/wastewater treatment plant field device wiring method decision analysis tool utilized the five-stage AHP process discussed in detail in Chapter 2 of this research report.

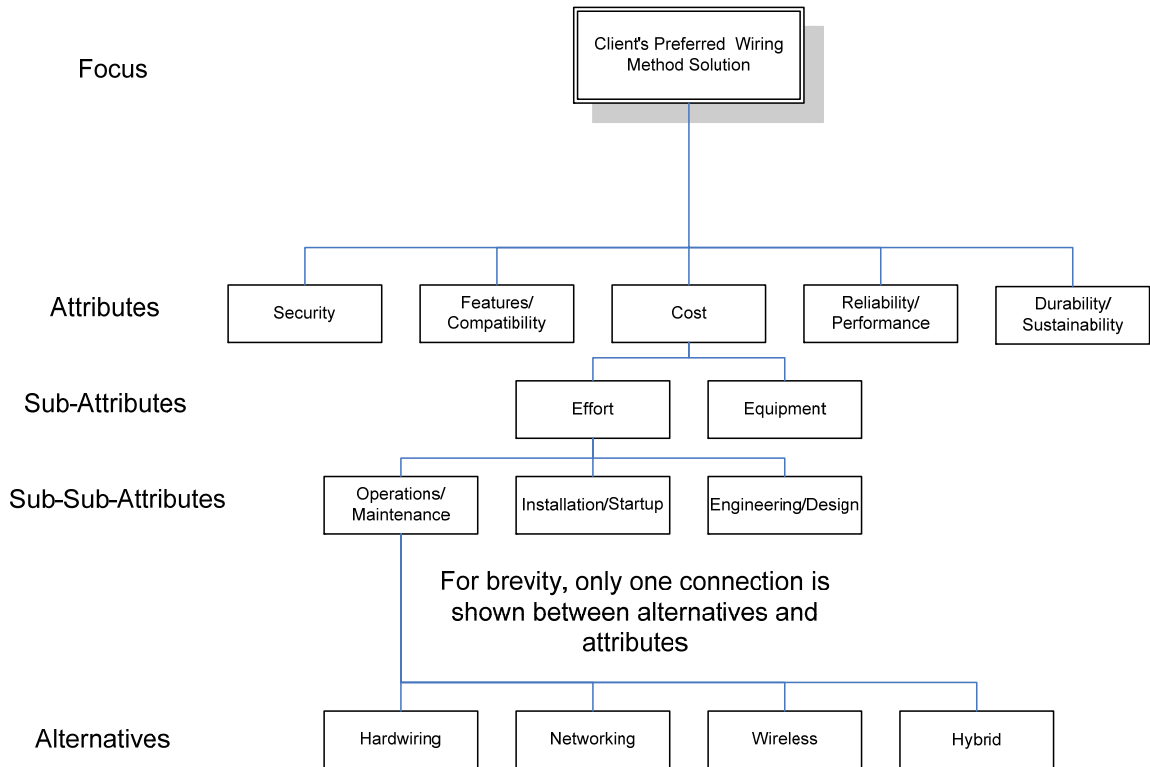
### **AHP Stage One: Construction of the Decision Hierarchy**

Five attributes were selected to provide an adequate level of detail for obtaining meaningful results while keeping complexity and computation time to a minimum. Further, it was decided to use one hierarchy instead of two separate cost and benefit hierarchies to reduce complexity. The cost attribute was refined into a three-level hierarchy with sub-attributes and sub-sub attributes to cover the many types of costs involved in this type of construction project. Figure 4.1 illustrates the final hierarchy to be used in the decision analysis tool. Alternate hierarchies are discussed in Chapter 5 of this research report.

### **AHP Stage Two: Determination of the Relative Importance of Alternatives/Attributes**

Following the research procedure outlined in Chapter 3, two surveys were developed. An alternative comparison survey was developed to determine the relative importance of the alternatives with respect to the attributes and sub-attributes. Specifically, this survey determines the attribute advantages and disadvantages of each wiring method. This survey was administered to field device wiring method subject matter experts so sample data could be obtained. A total of 29 responses to this survey were recorded

and each question's response was averaged, rounded, scale-shifted (to conform to the AHP standards – shown in Table 2.1 – since the online survey tool had limited scale options), and evaluated for standard deviation.



**Figure 4.1 – Proposed AHP Hierarchy**

An attribute comparison survey was also developed to determine the relative importance of the attributes with respect to the client's preferences. For example, this survey determines if a client values low cost more than sustainability, or vice versa. To test the decision analysis tool validity, this survey was administered to an individual playing the role of a client interested in building a new water treatment plant so sample data could be obtained. One response was recorded, and each question's response was

scale-shifted to conform to AHP standards. See Appendix B for the scale-shift legend and the complete log of survey responses.

### AHP Stage Three: Determination of Alternative/Attribute Weights

The third stage in the AHP method is the determination of the relative standing (weight) of each alternative or attribute with respect to each next-higher-level attribute or sub-attribute using the collected sample data. The results of the pairwise comparisons – in this case the averaged, rounded, and scale-shifted survey responses – are placed in a matrix. This matrix is used to evaluate the alternatives (i.e. determine their normalized weights) with respect to each attribute or sub-attribute above it (Canada, Sullivan, et al. 1996). For example, Table 4.1 shows the matrix used for evaluating the wiring method alternatives with respect to the Security attribute.

**Table 4.1 – Preference Matrix for Alternatives with Respect to the Security Attribute**

Alternative	Hardwiring	Networking	Wireless	Hybrid
Hardwiring	1	5	7	5
Networking	1/5	1	3	1
Wireless	1/7	1/3	1	1/5
Hybrid	1/5	1	5	1
<b>Column Sum (<math>\Sigma</math>)</b>	1.543	7.333	16	7.2

The next step is a computation of a vector of priorities (the normalized alternative weights). This process consists of calculating the eigenvector of the matrix and then normalizing it. Several methods were tested for calculating the eigenvector, but the complexity of the calculation using a standard spreadsheet tool merited the use of an

approximation method. This approximation method consists of dividing “the elements of each column by the sum of the column (i.e., normalize the column), then [adding] the elements in each resulting row, and [dividing] this sum by the number of elements in the row” (Canada, Sullivan, et al. 1996). This process is illustrated in Table 4.2 using the matrix shown in Table 4.1.

**Table 4.2 – Normalized Preference Matrix and Calculations of Priority Weights of Alternative with Respect to the Security Attribute**

Alternative	Hardwiring	Networking	Wireless	Hybrid	Row $\Sigma$	Average = $\Sigma/4$
Hardwiring	0.648	0.682	0.438	0.694	2.462	0.615
Networking	0.130	0.136	0.188	0.139	0.592	0.148
Wireless	0.093	0.045	0.063	0.028	0.228	0.057
Hybrid	0.130	0.136	0.313	0.139	0.717	0.179

#### AHP Stage Four: Determination of Comparison Consistency

Next, the consistency of the sample subjective judgments is calculated. The local consistency ratio for each matrix is a function of its maximum eigenvalue, the matrix size, and its associated random index (shown in Appendix C) (Canada, Sullivan, et al. 1996). The first step is to multiply the preference matrix by a matrix consisting of the alternative weights.

$$\begin{bmatrix} 1 & 5 & 7 & 5 \\ 1/5 & 1 & 3 & 1 \\ 1/7 & 1/3 & 1 & 1/5 \\ 1/5 & 1 & 5 & 1 \end{bmatrix} \times \begin{bmatrix} 0.615 \\ 0.148 \\ 0.057 \\ 0.179 \end{bmatrix} = \begin{bmatrix} 2.652 \\ 0.622 \\ 0.230 \\ 0.736 \end{bmatrix}$$

Next, each element in the resulting matrix is divided by its corresponding element in the alternative weights matrix.



$$\begin{bmatrix} \frac{2.652}{0.615} & \frac{0.622}{0.148} & \frac{0.230}{0.057} & \frac{0.736}{0.179} \end{bmatrix} = [4.309 \quad 4.199 \quad 4.034 \quad 4.103]$$

Then, the maximum eigenvalue, denoted by  $\lambda_{max}$ , is obtained by averaging the elements in the resulting matrix.

$$\lambda_{max} = \frac{4.309 + 4.199 + 4.034 + 4.103}{4} = 4.161$$

The consistency index is then calculated for a matrix of size N.

$$CI = \frac{\lambda_{max} - N}{N - 1} = \frac{4.161 - 4}{4 - 1} = 0.054$$

Finally, the consistency ratio is calculated by dividing the consistency index by its associated random index.

$$CR = \frac{CI}{RI} = \frac{0.054}{0.9} = 0.06$$

The resulting consistency ratio of 0.06 is less than 0.1, and therefore is deemed acceptable by the criterion of the AHP method used (Canada, Sullivan, et al. 1996).

The same process is used for the remainder of the preference matrices at each level of the hierarchy. See Appendix C for computations and results. Note that a spreadsheet tool was developed to perform many of the required computations automatically, so the entire computational method illustrated herein can be performed efficiently and dynamically. Therefore, many intermediate calculations are not shown in Appendix C.

## AHP Stage Five: Determination of the Overall Priority Weight of Each Alternative

After development of the alternative and attribute weighting with respect to the next higher elements in the AHP hierarchy, the overall priority weights of the alternatives and the overall consistency ratio of the judgments are calculated.

First, using the results shown in Appendix C of the individual alternative and attribute weights, the overall alternative weights can be calculated “by summing the product of weights for all branches that include the alternative” (Canada, Sullivan, et al. 1996). For example, to find the overall weight of the hardwiring alternative, the calculation is:

$$\begin{aligned} & (0.615)(0.380) + (0.079)(0.040) + (0.250)(0.669)(0.875)(0.063) \\ & + (0.100)(0.243)(0.875)(0.063) + (0.244)(0.088)(0.875)(0.063) \\ & + (0.250)(0.125)(0.063) + (0.590)(0.363) + (0.525)(0.153) = 0.545 \end{aligned}$$

The overall priority weight for the remaining alternatives is calculated similarly using the spreadsheet tool. See Chapter 4 for these results.

Finally, the global consistency ratio of the hierarchy (abbreviated CRH) can be calculated. This quantity is “obtained by taking the ratio of an aggregate consistency index,  $M$ , for the entire three-level hierarchy to an aggregate random index,  $\bar{M}$ . These quantities are computed in the following manner” (Canada, Sullivan, et al. 1996).

$$M = \text{second level consistency index} + \begin{bmatrix} \text{Vector of} \\ \text{second level} \\ \text{priority weights} \end{bmatrix} \times \begin{bmatrix} \text{Vector of} \\ \text{third level} \\ \text{consistency} \\ \text{indices} \end{bmatrix}$$

$$\bar{M} = \text{second level random index} + \begin{bmatrix} \text{Vector of} \\ \text{second level} \\ \text{priority weights} \end{bmatrix} \times \begin{bmatrix} \text{Vector of} \\ \text{third level} \\ \text{random} \\ \text{indices} \end{bmatrix}$$

For example, when calculating the CRH of the Effort/Complexity Cost sub-hierarchy, the aggregate consistency indices become:

$$M = 0.004 + [0.669 \quad 0.243 \quad 0.088] \times \begin{bmatrix} 0.000 \\ 0.000 \\ 0.052 \end{bmatrix} = 0.0086$$

$$\bar{M} = 0.580 + [0.669 \quad 0.243 \quad 0.088] \times \begin{bmatrix} 0.900 \\ 0.900 \\ 0.900 \end{bmatrix} = 1.48$$

Finally, the CRH can be computed by taking the ratio of the aggregate consistency indices.

$$CRH = \frac{M}{\bar{M}} = \frac{0.0086}{1.48} = 0.005$$

The resulting CRH of 0.005 is less than 0.1, and therefore is deemed acceptable by the criterion of the AHP method used.

The same process is used for the remainder of the individual three-tier hierarchies (Canada, Sullivan, et al. 1996). See Appendix D for results.

### Overall Calculation Results

Based on the sample survey response inputs to the decision analysis tool, the overall priority weight for each alternative was computed and the results are shown in

Table 4.3. Note that the results have been normalized and the overall priority weights add to unity.

**Table 4.3 – Overall Alternative Priority Weights**

<b>Alternative</b>	<b>Priority Weight</b>
Hardwiring	0.545
Networking	0.195
Hybrid	0.172
Wireless	0.088

Based on the computations, the best wiring method for this sample client would be hardwiring. Additionally, the overall consistency ratio for the hierarchy was computed. The resulting CRH of 0.063 is less than 0.1, and therefore is deemed acceptable by the criterion of the AHP method used.

Finally, it is notable that the priority weight magnitude of the hardwiring alternative is more than twice the priority weight magnitude of the next preferred alternative. In this set of circumstances provided by the sample data, hardwiring is by far the wiring method that most closely aligns with the sample client preferences. Had the two best alternatives been close in priority weight magnitude, the decision analysis results would be much more open to interpretation and input sensitivity would become critical.

## Summary

The choice of field device wiring method for water and wastewater treatment plants is extremely complex and contains many objective and subjective variables. A hierarchy

was constructed using the AHP guidelines with the intention of simultaneously providing useful results and keeping complexity to a minimum. Two surveys were constructed following AHP guidelines. One survey for the comparison of wiring method alternatives to wiring method attributes was administered to subject matter experts and, while dynamic, its inputs will only change as technologies mature or as designers gain more experience. A second survey for the gathering of client preferences was created with the intention that it would be updated for each project. A software tool using a standard spreadsheet program was then developed to automate the aggregation of survey responses, the AHP calculations, and the presentation of the final results.

## Conclusions

The decision analysis tool has been verified for computational accuracy using manual calculations. Though the tool performs the AHP method accurately, the usefulness of the results still needs to be validated. This step would involve a “sanity check” after using the tool in a real-world application requiring the designer, project manager, and client to use common sense to make sure the resulting decision (tool output) makes sense. Given the unfavorable wireless wiring method review presented in the literature review, one would expect this method to be the lowest-rated decision, and indeed it is. However, despite the many advantages and benefits that a networked wiring method may present, the example developed in Chapter 4 recommends a hardwired wiring method for the client. Therefore, it is clear that no single wiring method is the best

solution for all clients, but the decision is based upon their unique situation and preferences.

## Chapter 5 – Suggestions for Additional Work

Even though a functional tool was developed using the AHP method, further benefit may be gained with additional work. One suggestion would be to perform a sensitivity analysis of the tool. This analysis may involve determining the range of inputs that always yields the same wiring method decision. For example, if it is found that no matter what inputs are used for the Sustainability/Durability attribute the tool output remains unchanged, the tool could be trimmed to ignore that attribute. Additionally, it may be possible to work backwards from the wiring method output to determine what range of survey responses is possible for each wiring method alternative. In other words, it may be possible to determine the general characteristics of clients that would prefer each alternative, in turn making the use of the tool unnecessary for each project.

Another suggestion for additional work would involve changing the alternatives that are considered. For example, since several protocols are available within the networked wiring method alternative, one could narrow down the wiring method decision to the use of a specific communication protocol. This step would be beneficial since each protocol has unique advantages and disadvantages. For example, Modbus cannot be used in areas requiring intrinsically safe devices, so if the client was known to have these areas, additional consideration would be given to other protocols. Similarly, since Foundation Fieldbus has the ability to do “Control in the Field,” but requires more host modules, cabinet space, and terminations than Profibus DP, additional considerations could allow a client with a specific control philosophy to be matched with Foundation

Fieldbus, while another client with an identical plant but a different control philosophy to be matched with Profibus DP. Additional considerations may even allow multiple protocols to be used for the same client within the same treatment plant depending on the process type.

A third suggestion for additional work would involve the modification of how the subject matter expert survey responses are recorded. For example, the survey responses could be weighted based on the experience level of a particular responder. If, for instance, a responder had little experience with fieldbuses, but extensive experience with hardwiring, their responses may give additional weight to the areas of their expertise. Also, the tool could be updated for a specific project if, for example, a client has a known contract type allowing for the sole sourcing of a contractor with fieldbus experience, some of the survey responses regarding startup cost would change. In fact, many survey responses would likely change if specific client data was provided before administration of the survey. One of the prevalent complaints offered by survey responders was the fact that many of the questions were too general for a specific response.

A final suggestion for additional work would involve the use of actual performance data for inputs to decision analysis tool. For example, if a client has historical data for their operating costs or updated budgets for expected engineering design time, the tool could use that data instead of the survey response data. Additionally, since the standard deviation of the survey responses for particular questions was very high, a suggestion



would be to investigate the use of performance data for these measures since no subjective consensus for those questions seems to exist.

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## Appendix A – Survey Forms

*Critical data were redacted.*

## Appendix B – Survey Responses

### Scale Shift Legend

Survey Response Value	AHP Exact Value	AHP Approximate Value
1	1/9	0.11
2	1/7	0.14
3	1/5	0.2
4	1/3	0.33
5	1	1
6	3	3
7	5	5
8	7	7
9	9	9

*Critical data were redacted.*

## Appendix C – AHP Weighting Calculations

### Matrix of Random Indices

N	1	2	3	4	5	6	7	8	9	10	11	...
R1	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	...

*Critical data were redacted.*

## Appendix D – Overall Results Output from Decision Analysis Tool

*Critical data were redacted.*