# A MANAGEMENT APPROACH FOR ASSESSING NUCLEAR SAFETY CULTURE HEALTH PERFORMANCE UTILIZING MULTIPLE-CRITERIA DECISION ANALYSIS

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*Nuclear power plants are among the most technologically complex of all energy facilities. Nuclear energy thus requires consistent, high levels of organizational performance by the highly skilled professionals who operate and maintain nuclear power plants. A key element for achieving consistent, high levels of performance in a nuclear organization is its safety culture. Maintaining a healthy Nuclear Safety Culture (NSC) is a leadership responsibility as it like most things rises and falls based on leadership. However, in order to facilitate a healthy NSC, which is the "sine qua non" of safe nuclear plant operation, the leadership team needs to understand its health. It is well understood that in order to manage risk one has first to comprehend it and equally true in order to manage the safety culture of an organization one must first comprehend it. This research provides an ongoing holistic, objective, transparent and safety-focused process to identify early indications of potential problems linked to safety culture. The process uses a cross-section of available data that is analyzed utilizing Multiple-criteria Decision Analysis (MCDA) methodology, that has incorporated belief degrees from a management team in its algorithm, resulting in insights about the data's meaning which may lead directly to corrective actions.*

## I. INTRODUCTION

Designed, built, and operated to produce electricity, commercial nuclear power plants consist of complex technologies operating in a complex regulatory environment. The technical challenges inherent in the design are confronted by economic demands, mainly due to changes in the circumstances of the energy industry.[1] The nuclear power industry has been challenged by changing circumstances, including governmental pressures to deregulate energy markets, increases in company mergers, organizational cost-saving strategies, and the replacement of aging technical components with newer and costlier technologies.[1] Competitive business pressures appear to have been compelling the nuclear power industry to improve delivered value and the processes that deliver value, which can affect the NSC through increased risk.[2] If an excellent NSC is not maintained, then another nuclear accident might occur at a nuclear power plant that is utilized for the commercial generation of electricity and this could result in the end of the commercial use of nuclear power to generate electricity.

### I.A. Background

The health of the NSC is a function of our belief and those beliefs can influence our understanding. In addition, our belief may not always agree with the results of our NSC assessments. Some assessments rely solely on belief in order to qualify or quantify the health of the NSC while others seek to exclude degrees of belief altogether by relying exclusively on objective data. Multiple assessments that seek to assess the health performance of a NSC in a specific organization could vary widely due to being based on tangible data or intangible data (e.g., belief). Rather than fault the subjectivity of our degrees of belief of the health performance of a NSC, or confuse our objective assessments with personal opinions, it is proposed that we integrate our belief as a unique component of NSC health assessments.

### I.B. Purpose

Consequently, the purpose of this research study was to evaluate NSC health as a function of belief, quantified as degrees of belief, and tangible inputs integrated with MCDA in order to reduce the subjectivity of NSC assessments. Some assessments rely on degrees of belief from subject matter experts (SME) in order to qualify or quantify. Others exclude degrees of belief altogether, relying on objective data, if available. Rather than fault the subjectivity of our belief, or dilute objective assessments with personal opinions, it is logical to embrace our belief of the health performance of a NSC, but isolate and include them as a unique component of the NSC health assessment. Again, a MCDA based NSC health assessment methodology is proposed to systematically collect and integrate tangible indicators of NSC health along with the intangible of our belief. Combined in a manner that each dimension can be explored uniquely, and such that both components (tangibles and intangibles) can be integrated into an overall Nuclear Safety Culture Health assessment in a consistent and reproducible manner. This NSC health assessment methodology draws from the fields of nuclear engineering, systems engineering, and psychology to develop a model that integrates the intangible of our belief with the various other tangible inputs using Multi-Criteria Decision Analysis (MCDA).

## II. METHODOLOGY

The NSC Assessment with MCDA Process consists of three phases. The first phase is the Deterministic Phase where the process inputs are evaluated and binned. The second phase consists of a Qualitative/Quantitative Survey where upper management's degrees of belief of the health of various NSC scenarios are assessed. The final phase is the assessment integration phase, where the binned process inputs and the assessment of degrees of belief are both assimilated.

### II.A. NSC MCDA Process Phase I

The first phase of this research reviewed and selected the existing Safety Culture Monitoring Panel binning of Process Inputs.

#### *I.A.1. Process Input Binning Methodology*

This process is conducted in accordance with the Nuclear Energy Institute (NEI) document NEI 09-07, Fostering a Strong Nuclear Safety Culture.[3] Also in accordance with the Institute for Nuclear Power Operation (INPO) document INPO 12-012, Traits of a Healthy Nuclear Safety Culture.[4] The traits described in the later document are divided into three categories that are similar to the three categories of safety culture found in International Nuclear Safety Advisory Group, *Safety Culture*, (International Nuclear Safety Advisory Group.[5] The categories and their primary traits are as follows:

*Individual Commitment to Safety* with primary traits of: personal accountability, questioning attitude and effective Safety Communication.

*Management Commitment to Safety* with primary traits of: leadership safety values and actions, decision-making and respectful work environment.

*Management Systems* with primary traits of: continuous learning, problem identification and resolution, environment for raising concerns and work processes.

#### *I.A.1. Process Input Binning Data Collection*

Process Input binning data was obtained with approval for the previous three years from Surry Power Station (SPS) located in Surry, VA, USA. Based on the common codes for each of the ten indicators for a nuclear safety culture appropriate plant incident reports from plant were identified and subsequently evaluated to validate the coding and related trends.

### II.B. NSC MCDA Process Phase II

The survey was developed to obtain the degrees of belief, by leadership at a nuclear power station, between binned process input magnitude and NSC health performance. The survey was then piloted to a group of subject matter experts. Participation in the survey was voluntary and the participants were informed they could decline to participate in the survey at any point in the process without risk of any adverse implications or effects. The participants of the pilot remained anonymous in the final documentation of results. The results of the pilot were quantitatively and qualitatively analyzed. Qualitative analysis was conducted by reviewing the comments section for each question and the comment section for the survey as a whole. The survey instrument was modified using information gained from the quantitative and qualitative analysis. These selected individuals had a mean value of 31.5 years of commercial nuclear power experience and with a mean value of 4.13 years of experience on a NSC monitoring panel. The survey was administered to members of the Nuclear Safety Culture

(NSC) Monitoring Team and Panel at SPS in order to obtain degrees of belief information with respect to NSC Health Performance. SPS nuclear power plant was selected because the plant leadership had a desire to improve their methodology for NSC health performance assessment. Access to the populations and the plants' corrective action systems were obtained through the plant's leadership team. The researcher had made previous inquiries with the subject nuclear power plant and experienced no difficulties in gaining access to study the plant's systems.

## II.C. NSC MCDA Process Phase III

The third phase of this research was used to determine a methodology for integrating degrees of belief assessments with the process inputs in a MCDA model. Four MCDA models: Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Multi Attribute Utility Theory (MAUT) and Evidential Reasoning (ER) were evaluated for their utility in integrating the binned process inputs and degrees of belief information with the best candidate to be selected for implementation. This final phase (assessment integration) is the most crucial. Many approaches exist that could integrate the Process Input binning and degrees of belief assessments. Furthermore, based on the goal of this research, the result of this phase of the MCDA methodology must characterize the health of the NSC. The most effective model for a MCDA NSC integrated assessment methodology was determined to be Evidential Reasoning (ER), which deals with problems having both quantitative and qualitative criteria under uncertainty, such as ignorance or randomness.[6] It is used to support decision analyses, assessments, or evaluation activities. It addresses the decision problem using a belief structure to model an assessment with uncertainty, a belief decision matrix to represent a problem under uncertainty, ER algorithms to aggregate criteria for generating distributed assessments, and belief and plausibility functions to generate a utility interval which measures the degree of ignorance. Both ER and AHP use a hierarchy to model a MCDA problem; however, ER differs from AHP in a several ways. With AHP all of the alternatives comprise the lowest level of the hierarchy, but with ER the alternatives are not included in the hierarchy at all.[7]. Further, ER uses a generalized decision matrix where each element of the matrix is an assessment of a given attribute using belief degrees. The decision matrix in AHP merely describes the relative importance of one attribute over another; therefore, “ER can be used to assess an alternative against a set of standards, while AHP can only compare the relative importance between attributes”.[7] Finally, ER aggregates the belief degrees of lower level attributes to higher level attributes gradually, until it achieves an overall score, whereas AHP aggregates average scores based on pairwise comparison.[7] One implication of these differences is that ER can tackle large-scale MCDA problems (without limits on the number of alternatives or attributes). In addition, as new attributes are added, an ER model does not need to be re-evaluated since each attribute is scored for each alternative separately. ER also does not suffer from a common AHP problem known as rank reversal, which can occur when new attributes are added to an AHP model. Perhaps most importantly, ER can handle mixed data, including random and deterministic, qualitative and quantitative, as well as incomplete data for some attributes. Furthermore, ER can incorporate AHP procedures into certain aspects of a model, such as using pairwise comparisons to weight attributes against each other.[7]

### *II.C.1. MCDA Software Selection Results*

While most conventional MCDM methods use a decision matrix for problem modeling, the ER approach uses a belief decision matrix, of which the conventional decision matrix is a special case. In a belief decision matrix, a distribution instead of a single value is used to represent an alternative’s performance on an attribute. For example, if a company is assessed to be Excellent on short-term planning and Poor on long-term planning, it would then be described as Average on Planning in a decision matrix, while in a belief decision matrix, this would be a distribution of {[Excellent 50%], [Average, 0], [Poor, 50%]}. ER utilizes a modified Dempster’s evidence combination algorithm is used for aggregating the information in the belief decision matrix. The aggregation process is nonlinear, and in essence a probabilistic approach. The outcome of the aggregation is also a distribution, not a single score, of an alternative’s performance on the top attribute. However, a score can be calculated from the distribution by adding each assessment grade value weighted by the associated belief degree in the distribution. However, the score will normally be different from weighted sum method because the distribution is generated through a nonlinear aggregation process.[8]

### *II.C.2. ER MCDA Software Advantages*

There are two general advantages in employing the ER approach for MCDM. Firstly, it provides a novel belief framework to model and synthesize subjective information. Secondly the ER approach can make full use of different types of data, including subjective judgments, probabilistic data, and incomplete data under weaker assumptions that may undermine other methods such as MAVT. For example, it requires only the satisfaction of value independence condition, which is easy to check and satisfy, in order to apply the ER approach for attribute aggregation, not the stringent preferential independence condition required by the multiple value function theory (MAVT). When there are only a few attributes, it may be manageable to check the satisfaction of the preferential independence conditions. It becomes much more difficult when attribute number increases beyond a handful. Therefore, decision scientists normally recommend carefully selecting only a small number of attributes, such as nine or up to a few tens, when structuring a MCDM problem. In self-assessment, the above general advantages of the ER approach can be transformed into the following three practical advantages. Firstly, the belief decision matrix provides flexibilities in question presentation and data collection. Secondly, the ER aggregation process generates more insight information on performance diversities and supports the identification of strengths and weaknesses. Thirdly, the number of attribute (or questions) in the assessment model is much less a concern to the ER approach than to other conventional approaches.[8]

#### *II.C.3. ER MCDA Software Conclusion*

In conclusion, software for AHP is widely available but can be very expensive. Software for ANP and MAUT are not as common. Consequently, ER is the prudent choice for the NSC MCDA Health Performance research and conveniently, there is free ER software available with limited but sufficient attributes for the research. Furthermore, the ER software can communicate health performance and decisions through graphical data visualizations, making it a logical choice for this research.

## III. RESULTS

This research investigated the ability to integrate survey instrument degrees of belief results and MCDA into a comprehensive methodology to measure NSC Health Performance. The basis of this research was a detailed literature review showing that there is strong interest in maintaining a healthy NSC and that there was a wide gap in the body of knowledge in this area. The literature review went further to identify a specific gap in the body of knowledge for accurately measuring the health performance of a NSC. From the literature review, a conceptual model was formed and research questions were built. A survey was developed, vetted through peer review and distributed. Solicitations for participation were made via the Internet and data were collected. A quantitative data analysis was performed followed by a qualitative interpretation. This degrees of belief data were then utilized in Evidential Reasoning Software. The results of this analysis follow.

### III.A. Phase I: Binned NSC Process Inputs Results

Nuclear safety culture evolves over time; therefore, it is also appropriate to review any evidence of problems on a frequent, ongoing basis. Personnel and organizational changes, budget challenges, handling of emergent issues, and day-to-day organizational dynamics can have a profound impact on what is viewed as important and hence can influence the behaviors and nuclear safety culture at the plant and across the organization. Many sources of data may indicate a potential nuclear safety culture issue.

#### *III.A.1. Corrective Action Program High Yield Data Source*

The CAP is the largest single source of potential input to the culture monitoring process. Important causal investigations are considered for inclusion in the culture monitoring process. The causes and contributors or other latent weaknesses identified are examined for possible safety cultural implications. “Good catches”, CAP trends, anonymous reports, and other CAP feedback are considered for additional insights. In addition, at Surry Power Station (SPS) the CAP process also captures issues that are not adverse to quality. These lower-tier issues are examined for safety culture insights. In general, special consideration is given to CAP entries that appear to be emotionally charged, carry negative tones, or indicate current frustration or dissatisfaction with procedures, processes, resources, or other organizational deficiencies. Special consideration is also given to entries expressing concerns about the ability of the management team to address repetitive or longstanding issues or expressing lack of respect or trust.[9]

#### *III.A.2. Other High Yield Data Sources*

In addition to CAP data, the following data types are considered high yield inputs important for consideration of cultural implications.

Regulatory Communications – This category includes items that arise from communications with regulatory agencies and are not already in CAP. "Regulatory agencies" include the NRC, other federal regulators (e.g., NERC, EPA), and state and local agencies. The regulatory communications items to capture are those appearing to have safety culture implications.

Assessments – This category includes periodic and ad hoc assessments directly focused on nuclear safety culture behaviors, such as nuclear safety culture assessments (NSCAs). Other assessments may also be included if they address safety culture behaviors or appear to have other safety culture implications.

Industry Evaluations – This includes evaluations conducted by outside organizations (e.g., INPO, American Nuclear Insurers (ANI), Nuclear Electric Insurance Limited (NEIL)). For example, INPO evaluations are conducted approximately every other year, ideally in the alternate year from the nuclear safety culture assessment. Included in the INPO evaluation is an assessment of nuclear safety culture, resulting in a nuclear safety culture assessment of a site almost every year. These industry evaluations are available to NRC on site and are checked for safety culture implications.[9]

*III.A.3. Lower Yield Data Sources*

The following lower yield data types, that may be less rich in signs of cultural health, are considered on a case-by-case basis: Operating Experience, Quality Assurance Items, Self-Assessments, Benchmarking/Observations, Site Performance Trends, Allegations, Workforce Issues, Employee Concerns Program (ECP).

*III.A.4. Process Input Binning*

These process inputs are then collegiately vetted and binned by the Nuclear Safety Culture Monitoring Panel members into the following ten traits divided into three categories.

Individual Commitment to Safety, which includes the following traits:

PA. Personal Accountability - All individuals take personal responsibility for safety. Responsibility and authority for nuclear safety are well defined and clearly understood. Reporting relationships, positional authority, and team responsibilities emphasize the overriding importance of nuclear safety.

QA. Questioning Attitude - Individuals avoid complacency and continuously challenge existing conditions, assumptions, anomalies, and activities in order to identify discrepancies that might result in error or inappropriate action. All employees are watchful for assumptions, values, conditions, or activities that can have an undesirable effect on plant safety.

CO. Safety Communication - Communications maintain a focus on safety. Safety communication is broad and includes plant-level communication, job-related communication, worker-level communication, equipment labeling, operating experience, and documentation. Leaders use formal and informal communication to convey the importance of safety. The flow of information up the organization is seen as important as the flow of information down the organization.[4]

Management Commitment to Safety, which includes the following traits:

LA. Leadership Accountability -Leaders demonstrate a commitment to safety in their decisions and behaviors. Executive and senior managers are the leading advocates of nuclear safety and demonstrate their commitment both in word and action. The nuclear safety message is communicated frequently and consistently, occasionally as a stand-alone theme. Leaders throughout the nuclear organization set an example for safety. Corporate policies emphasize overriding importance of nuclear safety.

DM. Decision-Making - Decisions that support or affect nuclear safety are systematic, rigorous, and thorough. Operators are vested with the authority and understand the expectation, when faced with unexpected or uncertain conditions, to place the plant in a safe condition. Senior leaders support and reinforce conservative decisions.

WE. Respectful Work Environment - Trust and respect permeate the organization, creating a respectful work environment. A high level of trust is established in the organization, fostered, in part, through timely and accurate communication. Differing professional opinions are encouraged, discussed, and resolved in a timely manner. Employees are informed of steps taken in response to their concerns.[4]

Management Systems, which includes the following traits:

CL. Continuous Learning -Opportunities to continuously learn are valued, sought out, and implemented. Operating experience is highly valued, and the capacity to learn from experience is well developed. Training, self-assessments, and benchmarking are used to stimulate learning and improve performance. Nuclear safety is kept under constant scrutiny through a variety of monitoring techniques, some of which provide an independent "fresh look."

PI. Problem Identification and Resolution - Issues potentially impacting safety are promptly identified, fully evaluated, and promptly addressed and corrected commensurate with their significance. Identification and resolution of a broad spectrum of problems, including organizational issues, are used to strengthen safety and improve performance.

RC. Environment for Raising Concerns - A safety-conscious work environment (SCWE) is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination. The station creates, maintains, and evaluates policies and processes that allow personnel to freely raise concerns.

WP. Work Processes - The process of planning and controlling work activities is implemented so that safety is maintained. Work management is a deliberate process in which work is identified, selected, planned, scheduled, executed, closed, and critiqued. The entire organization is involved in and fully supports the process.[4]

### III.B. Phase II: Degrees of Belief Survey Results

The survey was an instrument to obtain belief degrees from Subject Matter Experts in NSC at an operating commercial nuclear power station to accomplish the goal of producing a MCDA model for NSC Performance health ranking (i.e., inductive research). It was known how many individuals were contacted and how many responses were received for a response rate of 66.6%. Additionally, by using a built-in function selection in "Survey Monkey" the respondents were not allowed to partially fill out a survey. All questions for the Independent and Dependent variables had to be answered in order to submit the survey. To help ensure internal validity was maintained it was determined that all questions on each variable be answered in order to complete the survey. In addition, basic statistical analysis being conducted.

### III.C. Phase III: MCDA (Evidential Reasoning) Model Results

An Evidential Reasoning Model was developed, with Intelligent Decision System (IDS) software (Intelligent Decision System Version 1.2), for the determination of NSC Health utilizing the binned process input data obtained from SPS and the degrees of belief data obtained from the survey conducted at SPS. This model consists of twelve NSC Health *Alternatives*, which are the past twelve quarters of NSC Process Data Binning results for SPS (i.e., SPS 2012 Q2 through SPS 2015 Q1). In order to determine the value of the Level 1 NSC Performance *Attribute* for each Quarter of a year *Alternative* there are three Level 2 *Attributes* (Individual Commitment to Safety, Management Commitment to Safety and Management Systems) that receive the binned process input data via ten Level 3 *Attributes* (PA, QA, CO, LA, DM, WE, CL, PI, RC, WP). The model also utilizes weighting to determine the contribution of the Level 2 and 3 Attributes to the Level 1 Attribute, utilities to determine the relationship between the binned process input data and the *Child Attributes* and two sets of belief degrees. One is used to relate the grades of *Child* and *Father Attributes*, the other to determine the beliefs held for the process input data selected within each *Child Attribute* for each *Alternative*. While this model is relatively simple, it is extensible and could easily address additional layers of complexity from an increase in the number of *Alternatives* under study, to a more complex description of the father and child *Attributes* (e.g., adding additional sub-categories or *Child Attributes* to each of the ten NSC Traits). The utility of ER, and the IDS software for implementing ER, is its simple structure, which can be organized into many combinations of *Attributes* and *Alternatives* making it easy to implement, but capable of handling complex problems without overcomplicating them. An example output from this model is show in Figure 1 and Figure 2.

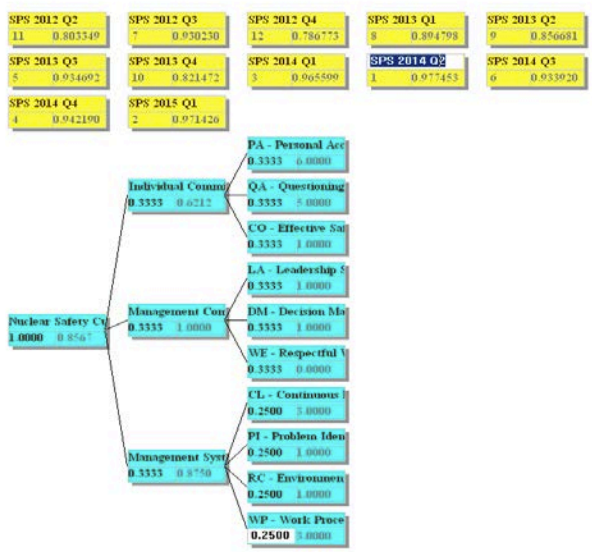


Fig. 1. IDS NSC Model (Dialog Box View)

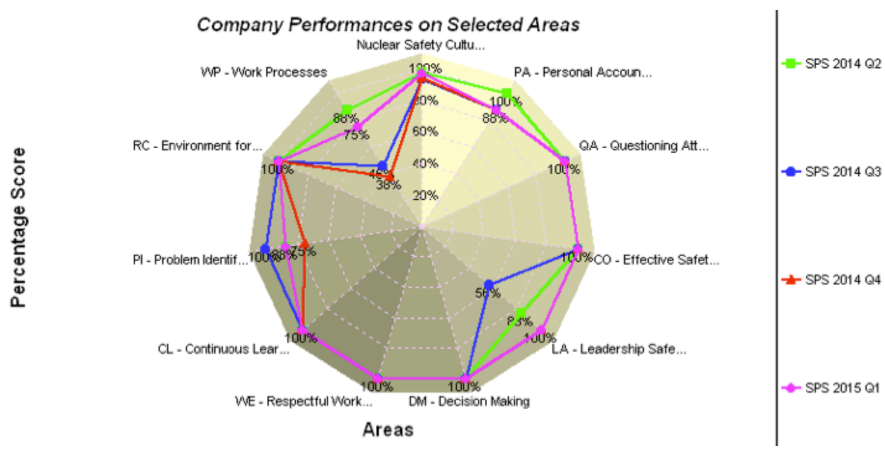


Fig. 2. Example NSC Health Performance and Traits Radar Plot 4 Qtr's

## IV. CONCLUSIONS

This section discusses the summary of the findings, limitations and recommendations for future research. This section will also explain the relevance of this research to academia and the implications to engineering managers.

### IV.A. Implications

The implications to academia are to expand the current body of knowledge in the area of nuclear safety culture health evaluation. The literature review conducted along with this research has expanded the body of knowledge by highlighting relevant research literature, and exploring common themes, and identifying new conceptual models. In addition, the literature review also exposed the considerable gap in the current body of knowledge. The research presented in this paper furthers our understanding on the causal relationship between the process inputs and NSC health utilizing MCDA. This research provides several avenues to expand and bolster this area of study. The implication to the engineering and project managers is to provide a better functional understanding of the relationship between process inputs and NSC utilizing MCDA in an operating commercial nuclear power station. This research also identified areas of the NSC that had higher significant correlations. This information better equips the manager when deciding on what areas to focus on and perhaps most of all allows the manager to have a better actionable insight on the relationships and interactions between the process inputs and the NSC Health.

### IV.B. Recommendations

There are several important limitations that will be discussed in this section. The sample size, while technically acceptable, was low. Eight respondents answered the survey. A larger sample size in the range of hundreds would make the results more generalizable. The sample size included only one nuclear power station. It is possible that there is bias in the study to one particular industry (i.e., US commercial nuclear power stations). Future research should account for other industrial safety cultures. The survey was self-administered and while self-administered surveys are accepted as a standard measurement tool, self-assessment raises concerns of source biases. Other important areas for future research are the correlations established between aspects of the process inputs and NSC Health. Research in the specific area of how best practices in NSC Health are documented, socialized, and disseminated both within and without a nuclear power station would bolster the research presented here.

### IV.C. Summary

A literature review on the performance of a nuclear safety culture in an operating commercial nuclear power station environment was conducted. From the review it was established that there was a large gap in the body of knowledge. A conceptual model was built, research explored and research questions posed. It has been established that quantitative data in the form of Process Inputs, that have causality with NSC health, at a nuclear power station can be obtained (Question 1). That the degrees of belief of NSC health by leadership at a nuclear power station can be quantified for NSC health via a survey (Question 2). That MCDA can be utilized to integrate the degrees of belief of NSC health and the process inputs into a comprehensive methodology to dynamically evaluate NSC Health Performance (Figure 3). This research has provided a more objective living NSC management tool that provides a management team with NSC health changes dynamically. This can lead to thoughtful discussion and cognitive analysis by the site leadership team as to the reason for any changes in the health the NSC.

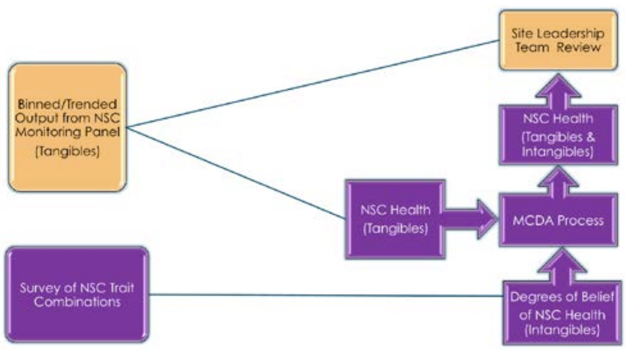


Fig. 3. NSC Assessment Model with MCDA (Simplified View)

## REFERENCES

1. N. Itoigawa, B. Wilpert and B. Fahlbruch, *Emerging demands for the safety of nuclear power operations : challenge and response*. (CRC Press, Boca Raton, 2005).

2. A. V. Gheorghe, *Critical infrastructures at risk : securing the European electric power system*. (Springer, Dordrecht, 2006).

3. N. E. Institute, in *NEI 09-07, Rev. 0* (2010).

4. I. f. N. P. Operation, *Traits of a Healthy Nuclear Safety Culture*, Revision 1 ed. (2012).

5. I. N. S. A. Group, *Safety Culture*. (1991).

6. Y. N. V. N. Huynh, Tu-Bao Ho and T. Murai, IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans **36** (4), 804-822 (2006).

7. L. Xu and J.-B. Yang, *Introduction to multi-criteria decision making and the evidential reasoning approach*. (Manchester School of Management, 2001).

8. D.-L. Xu, McCarthy and J.-B. Yang, Decision Support Systems **42** (2), 664-673 (2006).

9. N. E. Institute, in *NEI 09-07, Rev. 1* (2014).