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Department of Electrical Engineering and Computer Science

Technical Report

SYR-EECS-2010-05 Nov. 15, 2010

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ABSTRACT: This paper presents a software tool (the Investment Comparison Tool), a methodology (the Investment Comparison Methodology), and a decision support system (the Investment Comparison System) to aid decision makers with Research and Development Investment allocations. The Investment Comparison System (ICS) can be used vertically within an organization and horizontally across organizations at multiple portfolio investment levels. The ICS is applicable to any R&D environment ranging from Industry Research Environments to Federal Agencies. The ICS described in this paper is comprised of a system architecture, databases, Group Decision Making (GDM) methods, an Investment Comparison Tool (ICT) that includes various algorithms, and reporting tools. To aid in the usage of the ICS, an Assessment and Evaluation Framework, a detailed methodology with its technical foundation, and a corresponding example are also presented. The decision making process used in the methodology is the Analytical Hierarchy Process combined with methods for GDM. ICS is unique because of how it uses a combination of algorithms for assessing R&D Investments and the wide flexibility of its use.

KEYWORDS: Assessment and Evaluation, Assessment Framework, Portfolio Analysis, R & D Assessment, Analytic Hierarchy Process

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[1] The views expressed in this paper are those of the authors and not of any organization.

The Investment Comparison Tool (ICT): A Method to Assess Research and Development Investments[1]

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Abstract

This paper presents a software tool (the Investment Comparison Tool), a methodology (the Investment Comparison Methodology), and a decision support system (the Investment Comparison System) to aid decision makers with Research and Development Investment allocations. The Investment Comparison System (ICS) can be used vertically within an organization and horizontally across organizations at multiple portfolio investment levels. The ICS is applicable to any R&D environment ranging from Industry Research Environments to Federal Agencies. The ICS described in this paper is comprised of a system architecture, databases, Group Decision Making (GDM) methods, an Investment Comparison Tool (ICT) that includes various algorithms, and reporting tools. To aid in the usage of the ICS, an Assessment and Evaluation Framework, a detailed methodology with its technical foundation, and a corresponding example are also presented. The decision making process used in the methodology is the Analytical Hierarchy Process combined with methods for GDM. ICS is unique because of how it uses a combination of algorithms for assessing R&D Investments and the wide flexibility of its use.

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1. Introduction

A difficult challenge exists for decision makers responsible for Research and Development (R&D) Investments. R&D is characterized by unpredictable outcomes with unknown delivery dates. Regardless of the uncertainty of R&D, decision makers must set R&D goals and then annually allocate the R&D investment budgets towards those goals. In a Federal budget setting, Congress, Constituents, Agencies, and Researchers want to know "how much money" and "why specific R&D" is chosen for investment. The current federal environment, as published by a research opportunity outlined by the Science of Science Policy: A Federal Research Roadmap [http://colab.cim3.net/file/work/Expedition_Workshop/2008_12_17_Science-Of-Science-Policy/OverviewPresentation_Lane.pdf, accessed October 15, 2010], suggests there is future work needed to develop decision science methods and tools for R&D assessment.

This paper presents a decision support system with a software tool as one solution to address R&D Investment assessment and allocation. An Investment Comparison Tool (ICT) ranks the impacts of different R&D Investments relatively to each other. The ICT uses both R&D Investment goals and R&D performance metrics in developing the rank. ICT's algorithms also address one of the most complex challenges of comparing R&D Investments, which is to equally compare different R&D fields. ICT can be utilized both within an agency and cross agencies supporting many usage scenarios ranging from analyzing a single layer of Investments within a small organization to a Set of Investments between multiple agencies.

The intent of this paper is to provide the reader with an understanding of the implementation, the technical foundation, and the usage of ICT. This paper will describe (1) the Investment Comparison System, the ICT, and ICT's algorithms (2) an assessment and evaluation R&D definition framework, (3) a methodology to utilize the ICT and its technical foundation, (4) a brief example demonstrating the methodology, and (5) the applicability of ICT.

2. Investment Comparison System

The Investment Comparison System (ICS), shown in Figure 1, is comprised of databases, a decision support tool (Investment Comparison Tool), a decision making method to generate data, and reporting tools. The Research and Development Investment Database contains data elements that are allocated to different Investments such as resources, dollars, infrastructure, and Investment time periods. These are often portfolio or budget databases. The Research and Development Performance

Metrics Database contains metric data related to different R&D Investments. This could be the number of Patents related to a specific Investment or the number of jobs generated by an Investment. The reporting tools are tools that generate graphic displays and reports to be utilized by the investors to make decisions.

The Group Decision Making (GDM) is a process related to how groups of individuals use their expertise to make judgments regarding different data elements to be used by the ICS. The types and uses of GDMs are discussed later in the Technical Foundation of the ICS Methodology section of the paper.

The Investment Comparison Tool (ICT) performs data analysis with a set of complex algorithms. The ICT algorithms are the Normalization and Standardization Algorithms and the AHP Algorithm. The algorithms are discussed later in the Technical Foundation of the ICS Methodology section of the paper.

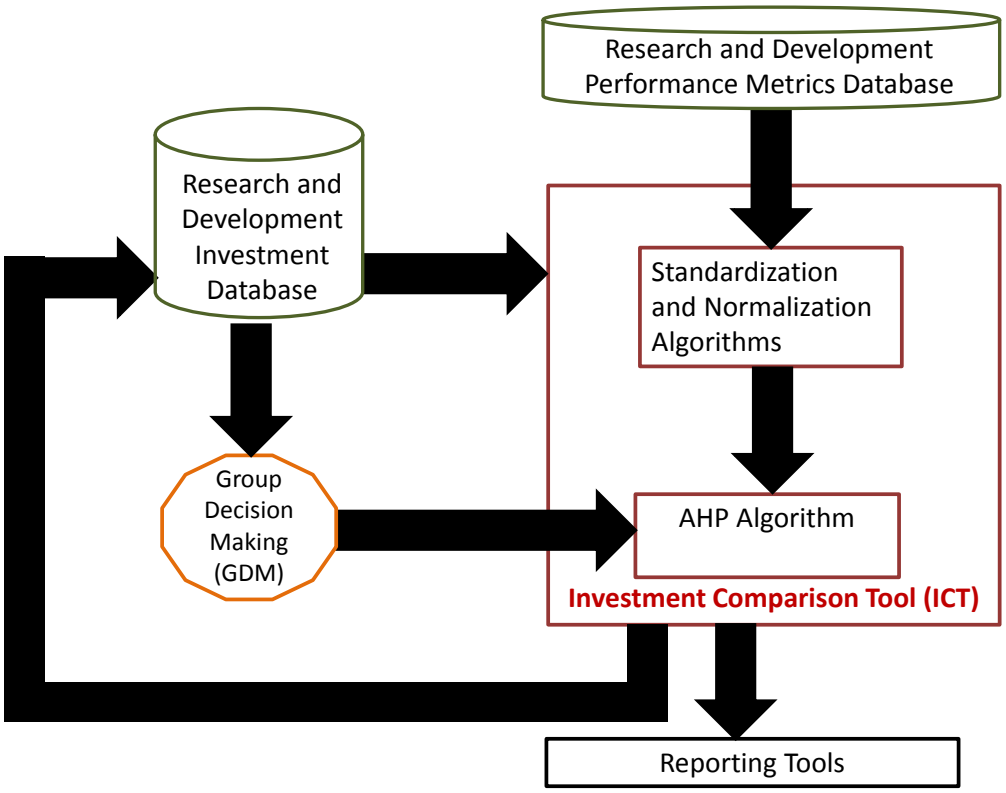

Figure 1. Investment Comparison System Architecture

3. Assessment and Evaluation Framework

The Assessment and Evaluation Framework, shown in Figure 2, will now be introduced to define the ICS data terminology in conjunction with the activities and people that will participate in the usage

of ICS. This Framework is represented by three serial stages of activities grouped into Investments (Stage1), Research (Stage 2), and Assessments (Stage 3). Each stage is comprised of different activities performed by different types of people, the Performers.

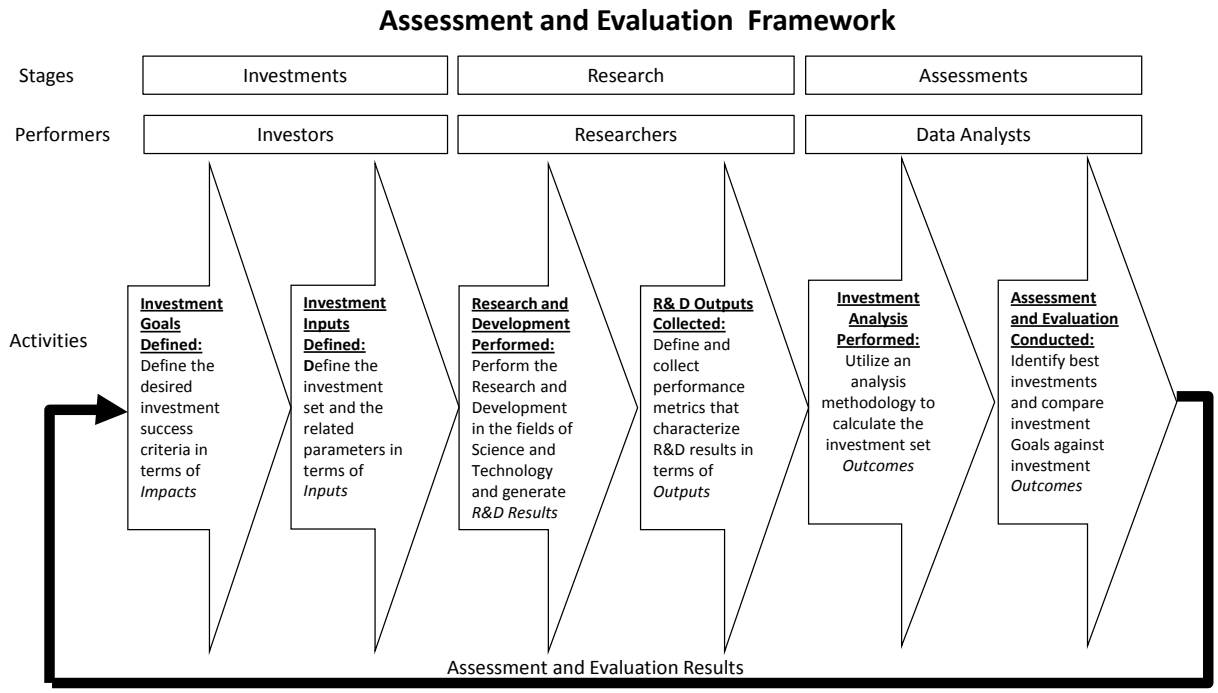

Figure 2. Assessment and Evaluation Framework

3.1. Framework Performers

Each framework stage is performed by different sets of people consisting of the Investors (Stage 1), the Researchers (Stage 2), and the Data Analysts (Stage 3). During each stage of the frameworks' activities, different performers facilitate the stage, but should consult with the other performers to insure the best expertise is leveraged.

Investors are the individuals who are responsible for making R&D Investments. ***Investors* are the overall customers of both the Assessment and Evaluation System and the ICS.** They decide how to invest their resources and also specify the success criteria they desire to accomplish with their Investments. The Investors can make investment decisions in on a variety of ways ranging from personal views to data driven decision making. The methodology in this paper provides a scientific based approach for making these investment decisions. Some examples of Investors are Senior Executive Staff of Federal Agencies who oversee R&D Investments, Division Directors responsible for R&D Budgets, and Corporate Managers of R&D Portfolios.

Researchers are the individuals who are performing the actual R&D. They are experts in their individual fields. They also are knowledgeable about how "research and development" as an entity is exchanged and performance is measured. Different fields of R&D have different performance metrics and values. Some examples of Researchers are Professors in Universities, Scientists in Research Institutes and Corporations, and Technologists in Research Laboratories.

Data Analysts are the individuals who are practitioners of assessment and evaluation. They are the facilitators of the Assessment and Evaluation Framework and the ICS. Data Analysts partner with the Investors to extract what their success criteria are and map it to the assessment and evaluation framework. Data Analysts work with the Researchers to characterize and normalize their performance metrics. Data Analysts calculate and return to the Investors the results of their Investments against their desired success criteria. Some examples of Data Analysts are Assessment and Evaluation Professionals, Operations Researchers, Social Scientists, Economists, Management Scientists, and Industrial Engineers.

3.2. Framework Data Elements

Within the framework, there are three important data elements (*Impacts, Inputs, and Outputs*) that have distinct meanings and importance. Within the construct of the framework, who defines these variables is just as critical as the data itself.

Impacts are "how" the Investors measure success for their Investments. The group of *Impacts* commonly used is (i) economy (growth of the economy), (ii) knowledge (new knowledge obtained), (iii) human capital (growth of people), and (iv) society (quality of life improvement). Investors specify Investment success criteria by assigning a level of relative importance to each *Impact* within the group of *Impacts*.

Inputs define the related parameters of the Investments. *Inputs* include the selected set of R&D Investments, the resources invested, and the Investment time duration. Investors specify the R&D Investment Set and consult with the Analysts on selecting the other parameters. Within the ICS*, Inputs* would be stored in the Research and Development Investment Database as shown in Figure 1.

R&D Results are defined as the actual research that is achieved by doing R&D. *Outputs* are metrics that represent *R&D Results* in the form of R&D Performance Metrics. Within the ICS, *Outputs* would be stored in the Research and Development Performance Metrics Database as shown in Figure 1. An example of *a R&D Result* would be a specific patent that resulted from an innovative research idea. The value of the "Patent" *Output* would be the count of the number of patents.

Outputs are mapped to *Impacts* as a way to quantify *Impacts*. Each *Output* can only be mapped to a single *Impact,* but more than one *Output* can be mapped to an *Impact*. The group of *Outputs* that are linked to an *Impact* is defined as an *Output Cluster.* An *Output Cluster* is the set of metrics that are used to quantify each *Impact*. An example of an *Output Cluster* for the *Impact* economy could be (i) jobs (jobs created), (ii) start-ups (the number of start-ups), and (iii) company revenue. An example of an *Output Cluster* for the *Impact* knowledge could be (i) patents (number of patents obtained) and (ii) citations (number of citations for papers published from the research).

It is critical to understand the differences between *Outputs* and *Impacts*. *Outputs* represent performance metrics that characterize *R&D Results*. *Impacts* numerically characterize the defined success criteria or goals. *Impact*s are calculated using the values of the *Output Clusters*. A clarifying example is that if an Investor is looking to grow the Economy (*Impact*), an *Output Cluster* might be "new jobs" and "patents utilized". "New jobs" and "patents utilized" performance metrics would be included in calculating the desired "Economic Growth" *Impact*. Additional examples of *Inputs, Outputs,* and *Impacts* will be given later in this paper.

Outcomes for each Investment are produced from the Investment Set analysis. *Outcomes* are calculated by utilizing chosen algorithms or methodologies. Within the ICS, this calculation would be done with ICT as shown in Figure 1. Examples of *Outputs* are presented later in the paper as part of the example.

3.3. Framework Stages

Three serial stages of activities are used for the assessment and evaluation framework in this paper. They consist of defining the R&D Investment goals and inputs (Stage1), performing the R&D and collecting R&D performance metrics (Stage 2), and assessing and evaluating the R&D goals (Stage 3).

During the *Investments Stage (Stage 1)*, Investors first set the goals for their Investments and define their desired Investment success criteria in terms of *Impacts*. Next, the Investors define their Investment *Inputs* by choosing the Set of Investments they wish to analyze. Investments are required to be mutually exclusive. Third, the Investors with the help of the Data Analysts define the *Input* parameters related to the Investment Set such as resources allocated and the time horizon for Investments.

During the *Research Stage (Stage 2)*, Researchers (Scientists and Technologists) conduct R&D across various Science and Technology Fields. The efforts of the Researchers' R&D yield results that can be measured in the form of R&D performance metrics. Researchers and Data Analysts work together to

select the best performance metrics that generically characterize their R&D results. The Researchers then determine the performance data for their R&D results for these performance metrics. The R&D performance metrics' data are called *Outputs. Outputs* can occur in the form of both qualitative and quantitative data.

During the Assessments Stage (Stage 3), a Data Analyst conducts an Assessment. First, an Investment analysis is performed that integrates the *Impacts', Inputs'*, and *Outputs'* data. This analysis is conducted by following a methodology and/or utilizing an algorithm to calculate the Investment Set *Outcomes*. Section 5 in this paper contains a methodology that could be followed. Once the *Outcomes* are completed, the Data Analyst generates a report on the *Outcomes of Investments* which contains how the Investments performed with respect to the Investment Goals. This report is shared with the Investors from *Investment Stage (Stage 1)*. The Assessment and Evaluation has now been completed.

4. Technical Foundation of the ICS Methodology

The decision making process used in the Investment Comparison System for assessment and comparison of different R&D Investment is the Analytical Hierarch Process (AHP). AHP was developed by Saaty [1980] and is probably the most used of the Multiple Attribute Decision Making (MADM) processes [ISAHP 2009]. Other MADM processes are discussed in various books, e.g., Steuer 1986, and Yoon, K. P. and C. Hwang 1995. (MADM is one of the areas of Operations Research.) The ICS Methodology uses AHP and other methods such as statistical methods and Group Decision Making methods. AHP allows its inputs for decision making to be both qualitative and quantitative as does the ICS Methodology. The ICS Methodology is general, flexible, and allows the user choices for inputs and decisions. Note in Figure 1 that the Investment Comparison Tool uses the AHP Algorithm along with the Normalization and Standardization Algorithms.

4.1. Analytical Hierarchy Process (AHP)

To solve a decision problem using AHP (and also in using ICS), the problem is first structured as a hierarchy tree and then decomposed into sub-problems that can be analyzed independently. Each level of the hierarchy tree corresponds to some aspect of the problem which in our application corresponds to the Investment goal, impacts, outcomes, and Investments. (Figure 10 in Subsection 6.3 shows these levels in the example's hierarchy tree.) The sub-problems contain portions of the hierarchy tree. Each sub-problem has a set of elements (e.g., outcomes in an output cluster) that must be pair wised compared by decision makers. For each pair wise comparison a value between 1 and 9 is selected to

represent the relative importance of one element over the other element, where a value of 1 means the two elements are of equal importance (i.e., there is no preference) and where a value of 9 means one element has the highest possible importance over the other element. Each sub-problem in AHP is then solved by using an AHP algorithm to derive from the results of the pair wise comparisons a set of relative (ratio) weights for the elements of that sub-problem. After all of the sub-problems are solved, AHP derives relative (ratio) weights for the decision alternatives (the Investments in our application) as its last step. These relative weights can be used to compare and rank the decision alternatives. What is unique about AHP is that a single ratio (mathematical) scale is developed and used for the relative (ratio) weights for all of the elements of the problem (all sub-problems) and for the decision alternatives. This uniqueness allows elements of different kinds to be used and compared in a decision problem. Additional, sensitivity analysis can also be performed to determine the key variables that affect the decision alternatives. (The example later in the paper will illustrate AHP.)

4.2. Group Decision Making (GDM)

Group Decision Making (GDM) is used for making group decisions in different steps of the ICS Methodology. AHP uses GMD as shown in Figure 1, to generate and synthesize Investment data for use by the ICT. To utilize a GDM, decision makers must be carefully selected with the appropriate expertise and endorsement from the representative decision making bodies. Next a GDM method must be selected from the three common GDM methods. If the decision is a numeric value, then one GDM method is to have each member of the group individually specify their choice of the numerical value and to use the geometric mean of all the specified values for the decision [Saaty 1989]. A second GDM method is to us the Group or Panel Consensus Method, where the members of the group meet and interact directly with each other to reach a consensus on the decision [Hillier and Lieberman 2009]. A third GDM method is to use the Delphi Method [Hillier and Lieberman 2009; Saaty 1980; http://en.wikipedia.org/wiki/Delphi_method, accessed October 18, 2010], where the members of the group interact anonymously and iteratively through developed questionnaires. The Delphi Method usually provides the best result but requires more effort and time than the other two methods. The use of the geometric mean requires the least effort but does not provide for interaction among members of the group. (See, e.g., Saaty 1980, Saaty 1989, and Hillier and Lieberman 2009 for discussions on comparisons of these methods.) Note that these are qualitative decisions because they are based on individual judgments.

4.3. Standardization and Normalization

The ICT, which is shown in Figure 1, uses Normalization and Standardization Algorithms in addition to the AHP algorithm. The purpose of the use of the Normalization and Standardization algorithms is to make each Output have a fair comparison among the Investments.

The purpose of the Standardization Algorithms is to standardize the data being used for the Performance Metric of each Output across the different Investments. The Standardization Algorithms calculate the standardizations from data stored in the R&D Performance Metrics Database. Two types of standardization must be made for each *Output*. The first is to standardize within an O*utput* metric; e.g., if the *Output* metric is the number of publications, then the quality of the journals and proceedings containing the publications must be standardized. The other type of standardization is to handle the differences in R&D practices across different professional fields; e.g., the number of publications per year in one professional field often varies considerable from another professional field, and this must be standardized if the *Output* metric is the number of publications. Science for Science Policy Researchers are researching these types of standardizations for different metrics and developing ways to standardize the data. An example is the CWTS crown indicator [http://arxiv.org/abs/1003.5884v1, accessed November 12, 2010]. Standardization Algorithms have to be developed for different types of *Outputs* using the latest research methods for these types of standardization.

The purpose of the Normalization Algorithms is to equate the Investment Data being used from the R&D Investment Database with the Standardized Data developed for each *Output*. Investment data has an Investment time and resource allocation. The Investment time and the resource allocation used for each Investment may be different than what has been developed for the Standardization. These must be equated. The major issue in normalizing this data is whether the results of a performance measure (type of *Output*) is linear as the value of the performance measure is changed; e.g., does an investment time of two years give the same result of some Output Metric as twice the result for one year. If the behavior for an *Output* metric is linear, then the development of a Normalization Algorithm to perform the necessary mathematical calculations should be straight forward. If the behavior is nonlinear, then Standardized data must be developed for the appropriate Investment time or resource amount. A Normalization Algorithm is needed for both the Investment time and resource allocation for each *Output*.

5. Investment Comparison System Methodology

To utilize the Investment Comparison System, the ICS Methodology consisting of the three phases shown in Figure 3 should be followed. Phase 1, the *Definition Phase*, selects the Investments to be compared and defines the Investment goals. Phase 2, the *Data Development Phase*, generates two types of data sets. The first is *Investment Importance Data* that numerically represents the Investors' view of success. The second is *Investment Performance Data* that represents both the standardized and normalized *Outputs* of R&D. Phase Three, the *Assessment and Evaluation Phase*, calculates each Investment's relative ranked value resulting in *Outcomes* that can be both shared with the Investors and contrasted against the Investors' goals.

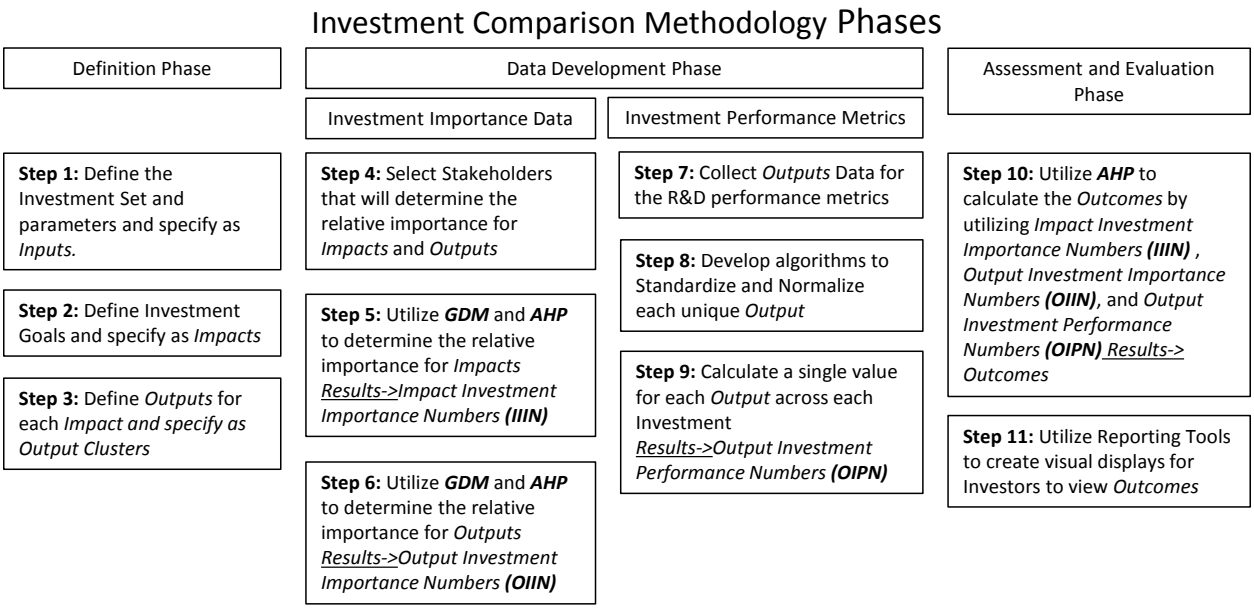

Figure 3. Investment Comparison Methodology Phase

5.1. Phase One: Definition Phase

Phase 1 of the methodology, the Definition Phase, is comprised of three steps with the overall phase objective to define the Set of R&D Investments to be compared, determine the Investment goals, and select the performance metrics used to measure the Investment goals.

In Step 1, R&D Investments are selected for comparison. These chosen Investments define the Investment Set where each individual Investment is required to be mutually exclusive from one another. Two Investment parameters are chosen that characterize each R&D Investment. They are (1) the Investment time period and (2) the resources allocation. (When choosing the R&D Investment time period, it is desirable to select multiple years because R&D Investments take significant time to generate

R&D Results.) The Investment Set and the parameters are defined and stored as *Inputs* in the Research and Development Investment Database (See Figure 4). Data stored within the Research and Development Investment Database is "raw" data and has not been normalized.

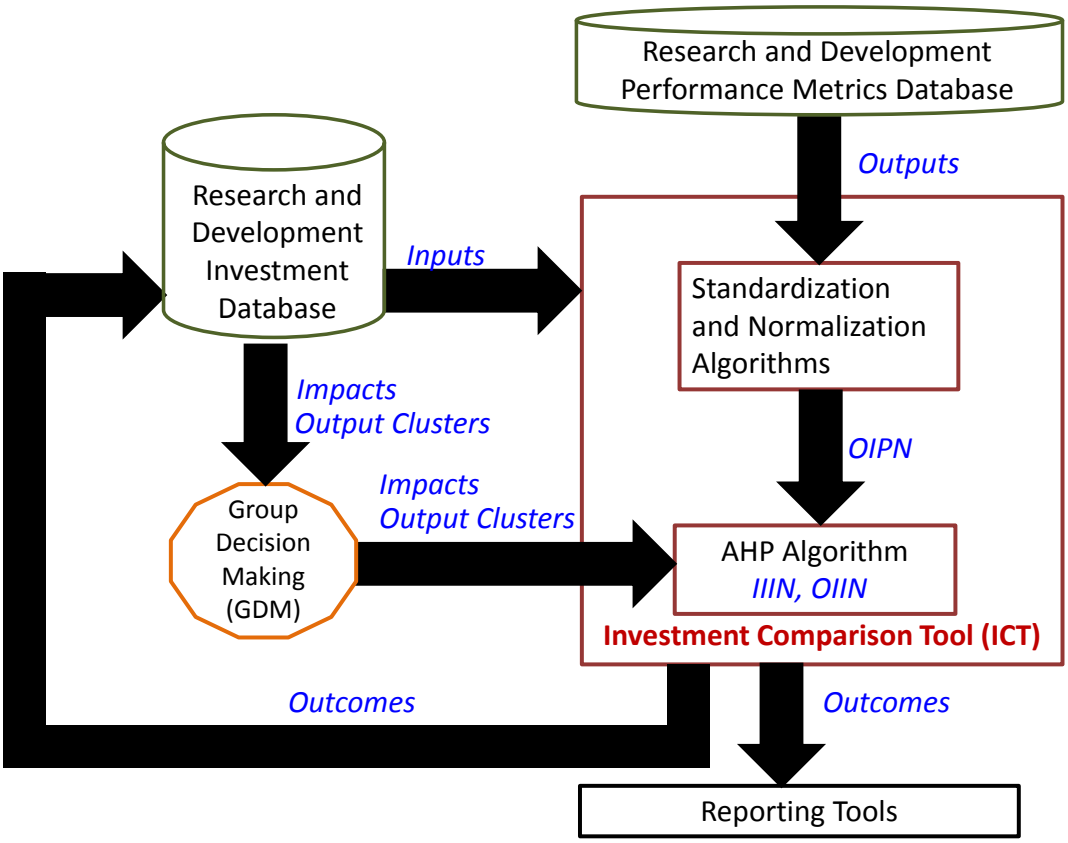

Figure 4. Investment Comparison System Data Architecture

In Step 2, the Investors determine how to measure their Investment goals by specifying an *Impact* List. *Impacts* are chosen as "what" the Investors judge as success for their Investments. Examples of *Impacts* are (i) economy (growth of the economy), (ii) knowledge (new knowledge obtained), (iii) human capital (growth of people), and (iv) society (quality of life improvement).

In Step 3, *Outputs* are defined, selected, and linked to *Impacts*. *Outputs* are the chosen R&D performance metrics that measure the *R&D Results.* Each *Output* is mapped to a single *Impact* and the group of *Outputs* mapped to each *Impact* forms the *Output Cluster*. Investors should consult with the Researchers during Step 3 when developing the *Output Clusters*.

5.2. Phase Two: Data Development Phase

In the Data Development Phase, there are two distinct types of data sets that need to be transformed from independent data sets into synthesized data sets. The first is *Investment Importance Data* and the second is *Investment Performance Metrics*. *Investment Importance Data* is based on preferences and goals of the Investors. *Investment Performance Data* is based on *R&D Outputs.*

5.2.1 Phase Two: Investment Importance Data

In Step 4, Decision Makers are carefully selected to determine *Impacts'* and *Outputs'* relative importance. The Investors are the Decision Makers who determine the relative importance of *Impacts*. Investors and R&D Researchers representing the Investment fields of study are the Decision Makers who determine the relative importance of *Outputs*. It is critical that this step is managed with the upmost thoughtfulness because the resulting values for the *Impacts'* and *Outputs'* relative importance determined by the Decision Makers can have a significant effort on the relative rankings of the Investment *outcomes*. Furthermore, the acceptance of the outcomes of this methodology will be based on who are chosen as the Decision Makers.

In Step 5, the chosen Decision Makers (selected in Step 4) will decide as a group the relative importance of the *Impacts* based on the Investment Goals. Since an Investor group will be used to specify the relative importance, a GDM method for the Investor group to make decisions should be selected for use. The Investor group makes pair wise comparisons between the *Impacts* and decides on a value for each comparison between 1 and 9 per the discussion on AHP in the Technical Foundation section. The AHP Algorithm in the ICT (Figure 4) then uses these pair wise values to calculate a set of relative weights for the *Impacts*. Each *Impact* now has a single numerical value for its relative weight. The numerical values for all of the *Impacts are* the *Investment Importance Numbers (IIIN).* The sum of all the *Impact* relative weights equals one.

In Step 6, the chosen Investors and R&D Researchers (selected in Step 4) will decide as a group the relative importance of the *Outputs* within each *Output Cluster* (determined in Step 3). Since this group will be utilized to develop the relative importance for the *Outputs*, a GDM method should be selected. Identical to the Step 5, the chosen Investors and R&D Researchers will make pair wise comparisons between the *Outputs* in each *Output Cluster*. Then the AHP algorithm in the ICT is used to calculate a set of relative weights for each *Output* in each *Output Cluster* using the set of values from the pair wise comparisons of that *Output Cluster.* Each output now has a single numerical value for its

relative weight. The relative weights for the outputs in each *Output Cluster* sum to one. The numerical values for all of the *Outputs* are the Investment Importance Numbers (OIIN).

5.2.2 Phase Two: Investment Performance Data

In Step 7, the *Output* data (R&D performance metrics) are collected at the end of the Investment time period and periodically such as yearly, and stored in the R&D Performance Metrics Database for each *Investment* (Figure 4). Data that are stored in the R&D Performance Metrics Database are "raw" data by Investment and have not been normalized or standardized. It is important to note that metrics can be both qualitative and quantitative.

An example of an R&D performance metric is "Jobs". This is as an *Output* for the *Impact* "Economy". The data collected and stored would be the number of jobs created, e.g., yearly for each of the chosen R&D Investments. If we chose "Citations" as an *Output* for the *Impact* "Knowledge", the data collected would be number of citations occurring, e.g., yearly for each of the chosen R&D Investments. Because citations lag past the Investment time period significantly, the collection of citations data would need to include a lag time.

In Step 8, the Standardization and Normalization Algorithms (Figure 4) within ICT must be developed for each unique *Output* across each *R&D field.* As discussed in Section 4, the Technical Foundation of the ICS Methodology, some of these algorithms are very straight forward while others are very complex and are subjects of immense interest and research. The algorithms become increasingly complex when normalizations, standardizations, and comparisons are performed across different R&D fields.

In Step 9, using the Standardization and Normalization Algorithms for each unique *Output*, a single numerical value is calculated for each Investment's *Output*. To use the algorithms, data are extracted from both the R&D Investment Database and the R&D Performance Metrics Database (Step 7). The numerical values calculated for all of the Investments are the *Output Investment Performance Numbers* (OIPN).

5.3. Phase Three: Assessment and Evaluation Phase

In Step 10, the *Impact Investment Importance Numbers* (IIIN), *Output Investment Importance Numbers* (OIIN), and *Output Investment Performance Numbers* (OIPN) are processed through the AHP Algorithm within ICT. The AHP algorithm calculates a single numerical value for each Investment representing its relative rank, its *Outcome*. The total relative rankings representing the *Outcomes* for the Set of Investments will sum to one. Through a relative simple data mining process, ICT also provides the

relative ranking for each Investment's *Outputs* and *Impacts*. ICT's *Outcomes* are utilized to provide guidance of Investments.

In Step 11, Reporting Tools are used to create visual displays for Investors to view *Outcomes.* A useful Reporting Tool will address one of the biggest challenges for Investors which is how to easily interpret and then incorporate data into their decision making processes. ICT could also serve as a tool for discussions with Researchers regarding performance metrics (*Outputs*) against goals (*Impacts*).

ICT data should be archived and stored in the Research and Development Investment Database to create a data repository to aid in better understanding of R&D Investment and Research trends. The data can be aggregated to enhance the predictability of R&D projections for certain Investment types and or certain research groups. ICT can also be used to run scenario planning and sensitivity analysis for Investments at the individual Investment level and for aggregated Investments.

6. Methodology Example

6.1. Phase One: Definition Phase

In Step 1, the Investments within the R&D Investment Set chosen are Chemistry, Biology, and Energy. The parameters for the Investment Set will have time durations of 5 years and an Investment amount of $100M yearly. For the example, all Investments are the same.

In Step 2, the Investment Goal was determined from the guidance in the OSTP July 21, 2010 memorandum (M10-30) on the Science and Technology Priorities for the FY2010 Budget. This memorandum stated that Investments should reflect high risk R&D that is characterized by high return R&D. The Investment goal is to determine the highest returns for R&D Investments (Figure 5).

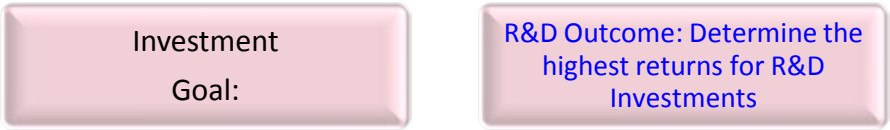

Figure 5. Investment Goal

This Investment goal is defined to maximize the *Impacts* for growth of the economy, knowledge, human capital, and society (Figure 6).

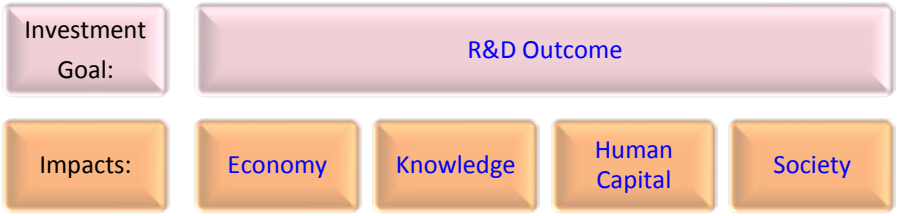

Figure 6. Investment Goal and Impact

In Step 3, the *Outputs* are defined, selected, and mapped to the *Impacts* forming *Output Clusters*. (Figure 7.)

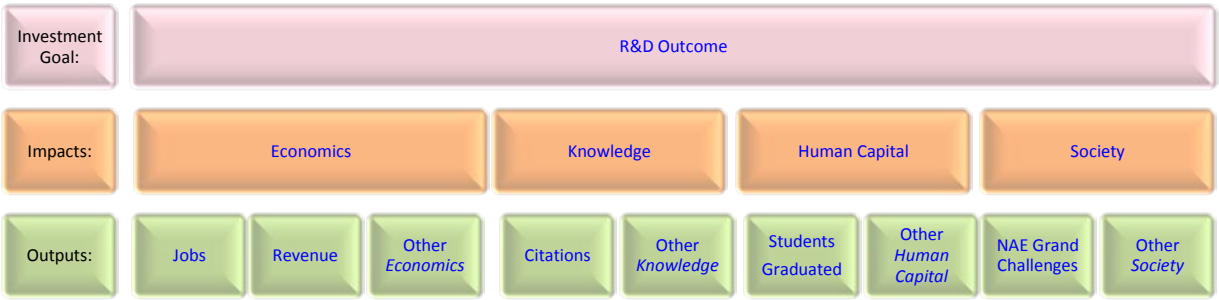

Figure 7. Investment Goal, Impacts, and Outputs

6.2. Phase Two: Data Development Phase

6.2.1 Phase Two: Investment Importance Data

In Step 4, Decision Makers are carefully selected to determine the relative importance for both the *Impacts* and *Outputs*. For this example, Investors determine the relative importance of the *Impacts*. Investors, Researchers and R&D Program Directors determine the relative importance of *Outputs*.

The Delphi method was the GDM method chosen for use in Steps 5 and 6. For Step 5, Investors will make pair wise comparisons between the *Impacts* by deciding on a value for each comparison between 1 and 9 from Table 1 [Saaty 1980] and entering that value into the ICT. Then the AHP Algorithm is used to calculate the IIIN. For Step 6, Investors, Researchers and R&D Program Directors make pair wise comparisons *between the Outputs* within each Output Cluster by selecting values from Table 1. These values are entered into the ICT and then the AHP Algorithm is used to calculate the OIIN. The numerical values for IIIN and OIIN are shown in Figure 8.

Table 1. The Fundamental Scale for Pairwise Comparisons

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

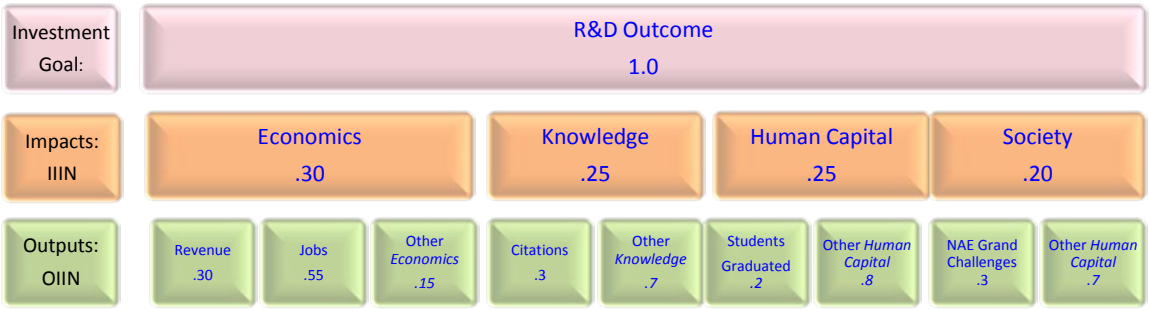

Figure 8. Investment Performance Data

6.2.2 Phase Two: Investment Performance Data

In Step 7, *Outputs* that represent each Investment type (Chemistry, Biology, and Energy) are retrieved from the R&D Performance Metrics Database. (See Table 2).

Table 2. Data for Revenue Output from the Research and Development Performance Metrics Database

Investments	Year 1 Revenue in $M	Year 2 Revenue in $M	Year 3 Revenue in $M
Chemistry	$10M	$30M	$50M
Biology	$30M	$40M	$40M
Energy	$100M	$50M	$100M

In Step 8, "Revenue" algorithms must be developed to support normalization and standardization for the Investments. It is determined that only a normalization algorithm is needed. (No standardization algorithm is needed.) The chosen Revenue Normalization Algorithm will be mathematically expressed as the sum of the *Output* Revenues per Investment adjusted by the resources allocated per Investment. It should be noted that for this specific Revenue Normalization Algorithm example, we have chosen not to incorporate the time value of money for simplicity purposes.

In Step 9, the Standardization and Normalization Algorithms are used to calculate a single numerical value for each *Output* for every Investment. In this example, the Revenue Normalization Algorithm from Step 8 is utilized to calculate the normalized "Revenue", the *OIPN,* for each Investment (Table 3). This algorithm uses the *Output* revenues per Investment from the Research and Development Performance Metrics Database (Table 2) and the resource allocation per Investment from the Research and Development Investment Database (Table 3). In this example, the resource allocation data shows Chemistry receiving 50% of the resources per year that Biology and Energy were allocated. Assuming that the Revenues are linear outputs of Investments, Chemistry resources would be adjusted by a factor of 2X to become normalized with the Biology and Energy resource allocation (Table 3).

Table 3. Output Investment Performance Numbers

Investments	**Revenue (Table 3)** *R&D Performance Metrics Database*	**Resource Allocation** *R&D Investment Database*	**Normalization Revenue Calculation**	**Output Investment Performance Numbers (OIPN)**
Chemistry	$90M	$25M	$90M x 2 =	$180M
Biology	$110M	$50M	$110M =	$110M
Energy	$250M	$50M	$250M =	$250M

6.3. Phase Three: Assessment and Evaluation Phase

In Step 10, the AHP algorithm utilizes the IIIN, OIIN, and OIPN data for the ICT Outcomes calculation. Figure 9 displays the complete hierarchical dataset used by the AHP algorithm.

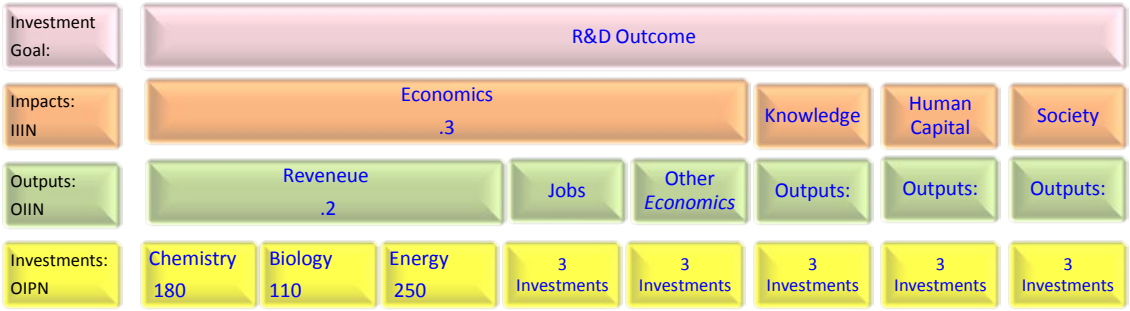

Figure 9. AHP Hierarchy Tree and Data

The ICT Outcomes generated by the AHP Algorithm are a set of numerical relative rankings. The Outcomes for each R&D Investment are listed Table 4.

Table 4. ICT Outcomes

Investments	Relative Rank	Rank Order
Energy	0.4566	1
Biology	0.3079	2
Chemistry	0.2355	3

In Step 11, the data calculated by ICT and the AHP algorithm are available for report generation. It is recommended to utilize Reporting Tools to display data generated by the ICT. Data Analysts may be interested in understanding multiple levels of calculated data and their data attributes (Figure 9). Investors would be interested in an ICT graph (Figure 10) representing Investment verses *Outcomes* to be utilized by for decision making.

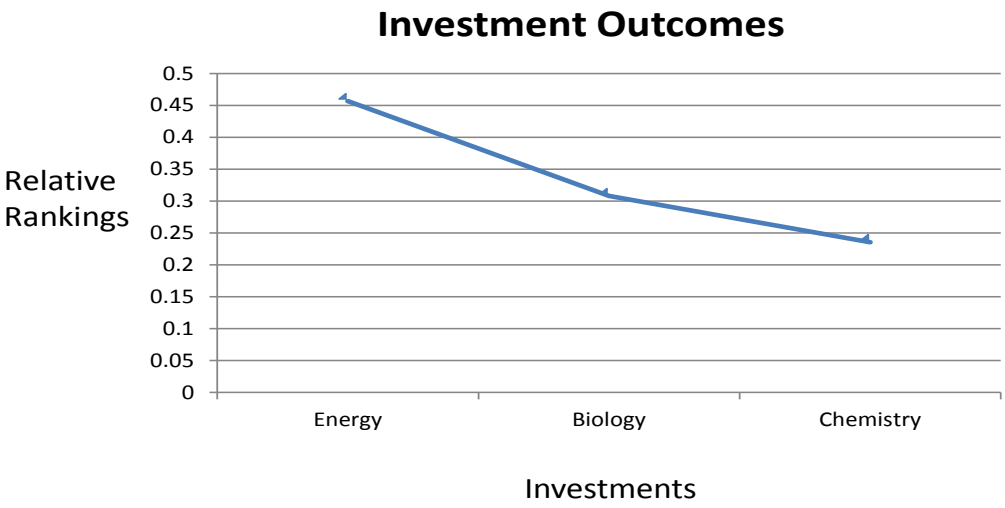

Figure 10. Investment Outcomes

7. Applicability

One of the opportunities for ICS is institutionalization within the Federal Government. ICS is a system that can aid in the challenges that the Federal Agencies have for R&D Investment decision making. The results from ICT are valuable because Investors, Decision Makers, and Leaders can utilize them to support their decision making. ICS has the important properties of a decision support system which are usability, transparency, and scalability.

7.1 Usability

The ICS can be implemented into any R&D setting such as the Federal Government, Industry, or Research Labs. The ICT can be constructed to leverage existing databases (Research and Development Investment Database and the Research and Development Performance Metrics Database) that contain the qualitative and quantitative data needed to support the required calculations. Tools to support GDM, Reporting, and AHP are commercially availability and are relatively inexpensive. The algorithms to support Standardization and Normalization can be leveraged through Science for Science Policy Research. The supplied methodology as part of this paper provides an analyst with step by step instructions as how to utilize the ICS.

7.2 Transparency

One of the strengths of this ICS methodology is both the decision making and data transparency. The ICS methodology requires Investors to visibly outline their Investment goals (decision making views). Because the ICS methodology utilizes GDM, where the Researchers and Investors agree on the selection of *Outputs* and mapping of them to *Impacts*, the Investors' goals outline how the Researchers will be performance measured. As part of ICT's function, data that are collected or calculated by the algorithms are available for reporting, scenario planning, and analysis to Investors, Researchers, and Analysts. One of the additional opportunities for ICS usage, not covered in this paper, is the capability for Analysts to utilize the ICS data to perform sensitivity analysis. This could be especially useful during discussions held by both the Investors and the Researchers.

7.3 Scalability

The use of the Investment Comparison Methodology can be scaled and implemented in multiple types of working environments. Some examples of different environments that can be supported are (1) a single level of Investments at the lowest level of an organization, (2) a Set of Investments between two or more single levels of an organization, (3) a multiple Set of Investments at the middle to top levels

of an organization or Federal Agency, and (4) a Set of Investments between two or more multi-level organizations or Federal Agencies. To apply the ICS across complex environments, the technical implementation does not change. What does change is that with a broader set of diverse Investments and goals, more individuals are involved to represent a broader set of interests. This means that Investment goals would need to be aligned for more Investors involved. For example, if one wanted to compare R&D Investment Outcomes between agencies, multiple leaderships with different goals would need to come to a consensus to allow comparison. The use of the methodology is scalable from a mathematics perspective, but the people aspect of GDM becomes challenging.

8. Conclusions

This paper presented the Investment Comparison System whose purpose is to relatively rank different R&D Investments based upon goals and performance measures specified by the Investors. The intended usage of the ICS is to aid in R&D Investment allocation within and across Government Agencies; however, ICS can also be used by other organizations such as Industry. The ICS consists of an Investment Comparison Tool (comprised of algorithms), databases, Group Decision Making methods, and Reporting Tools that can assesses R&D Investments. The databases contain both qualitative and quantitative historical R&D metric and Investment data. To support the usage of the ICS, an Assessment and Evaluation Framework, a methodology, and an example were also presented. The ICS is based on a scientific foundation and is an applicable decision support system based on its usability, transparency, and scalability. An additional usage of ICS is to perform sensitivity analysis to obtain further insight into R&D Investments and the R&D environment.

ICS can both contribute to and leverage the current research activities of Science of Science Policy and other Federal Investment and Assessment Initiatives. To fully utilize ICS, continued research support is needed to develop additional knowledge for the standardization and normalization algorithms that are used for calculations within the ICT. Because ICS is compatible with the Federal Government Data System, ICS could utilize existing federal databases and future data enclaves being developed by the government agencies. ICS fits nicely within the context of the current data collection and analysis tool activities, such as www.data.gov focused on data transparency and STAR METRICS (Science and Technology in America's Reinvestment – Measuring the EffecT of Research on Innovation, Competitiveness and Science).

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