

The Investment Comparison Tool (ICT): A Method to Assess Research and Development Investments^{1,2}

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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 Investment Assessment Framework, a detailed methodology for comparing investments along 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 applicability of its use. Multiple opportunities to apply ICS methodology exist and are described in the form of use cases.

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1. Introduction

Difficult challenges exist 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” are 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/OverviewPresentationLane.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 different R&D Investments relatively to each other. The ICT uses both R&D Investment goals and R&D performance data 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 uses ranging from analyzing a single layer of Investments within a small organization to a set of Investments between multiple agencies.

A detailed methodology for comparing investments and its technical foundation are presented. The decision making process used in the methodology is the Analytical Hierarchy Process [Forman and Gass 2001, Saaty 1980.] combined with methods for Group Decision Making. The methodology presented focuses on the “*Anticipated Investment Outcomes*” use case. Other use cases for historical Investment analysis and traditional Investment Assessment are discussed.

The intent of this paper is to provide the reader with an understanding of the implementation, technical foundation, and usage of ICT. The paper describes (1) the Investment Comparison System, (2) the ICT and its algorithms, (3) an Investment Assessment Framework, (4) a methodology to utilize the ICT and its technical foundation, (5) a brief example demonstrating the Investment Comparison System methodology, (6) different use cases, and (7) 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), group decision making methods, 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. The data elements are usually contained within portfolio or budget databases. The Research and Development Performance Database contains data related to different R&D Investments. The data 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.

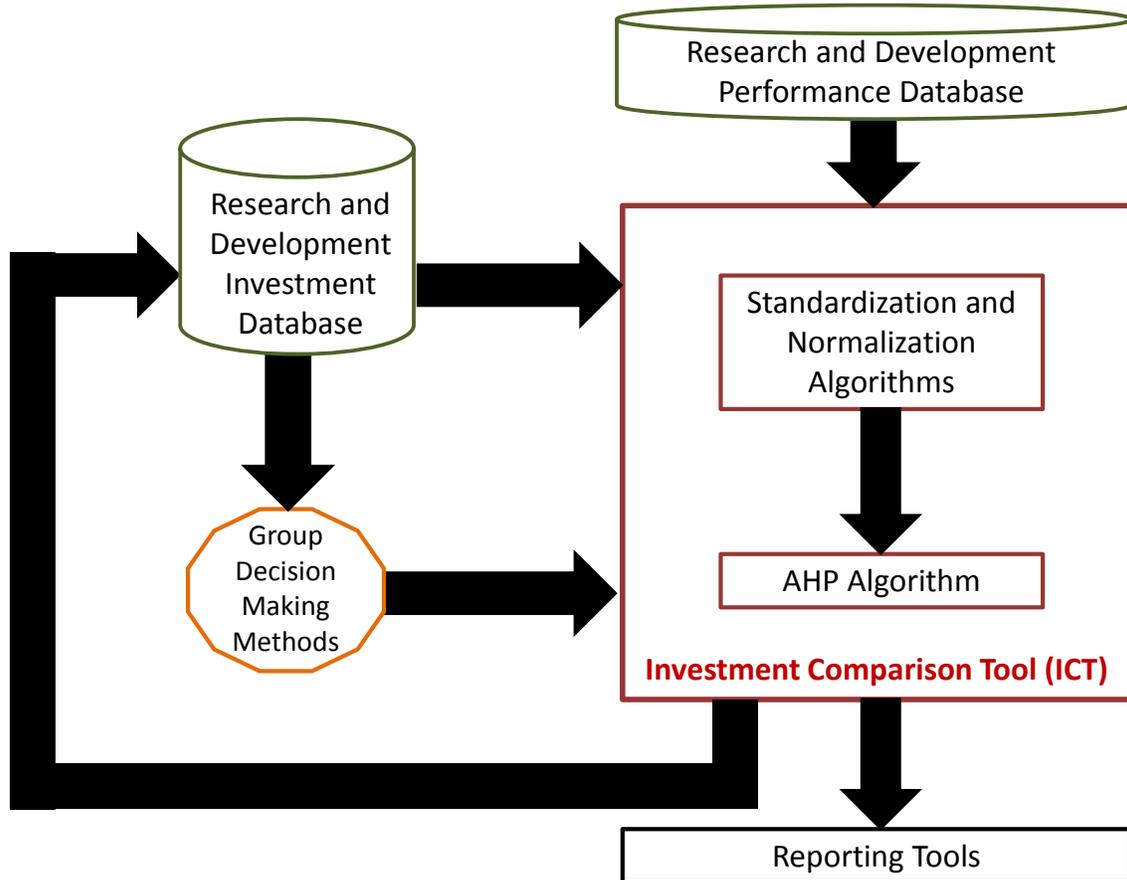


Figure 1. Investment Comparison System Architecture

Group decision making methods contain methods used for Group Decision Making (GDM). Various GDM methods are discussed in the Technical Foundation of the ICS Methodology Section of the

paper. GDM is a process of how a group of individuals use their expertise to make judgments regarding a specific situation or problem; and its use here is regarding different variables and data elements to be used by the ICS.

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.

3. Investment Assessment Framework

The Investment Assessment 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 (Stage 1), Research (Stage 2), and Assessments (Stage 3). Each stage is comprised of different activities performed by different types of people, the Performers.

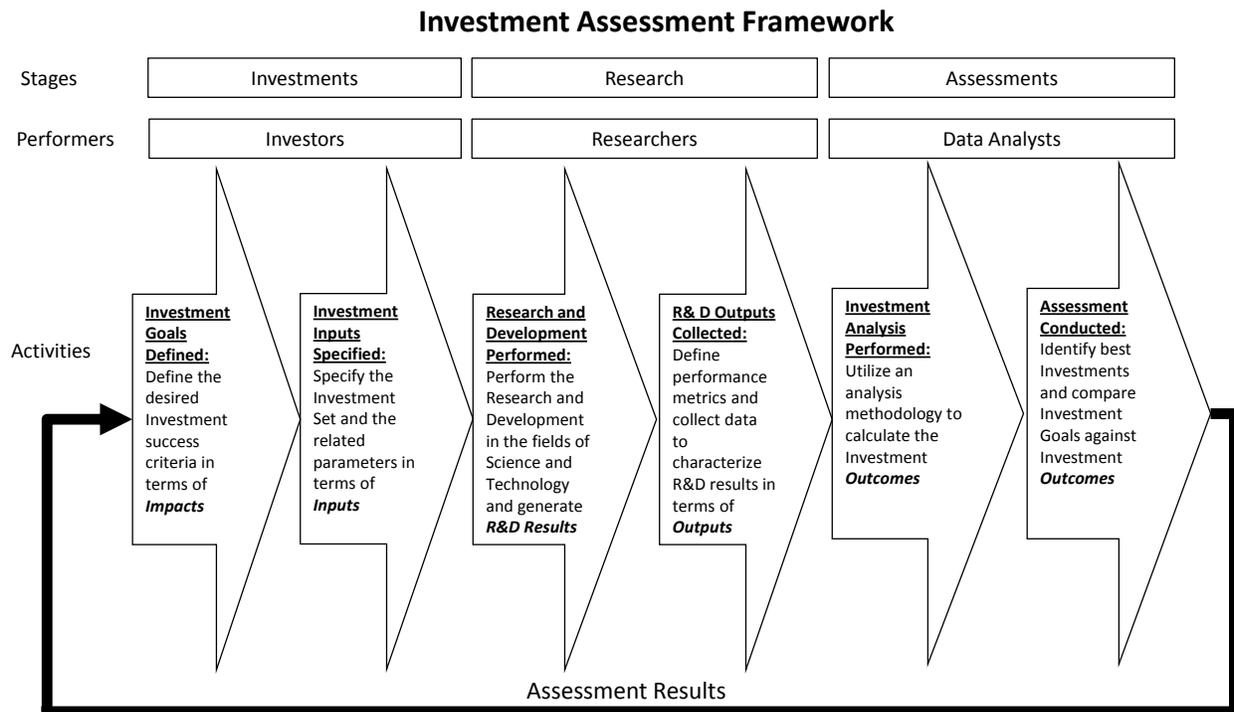


Figure 2. Investment Assessment Framework

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 Investment Assessment Framework 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 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 data 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 Investment Assessment Framework and the ICS. Data Analysts partner with the Investors to extract what their success criteria are and map it to the Investment Assessment Framework. Data Analysts work with the Researchers to characterize and normalize their performance data. 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 Variables

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

Impacts are "how" the Investors measure success for their Investments. The set 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 set of *Impacts* they specify.

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 Investments Set and consult with the Data Analysts on specifying 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 data 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 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 set 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*. Investors should consult with Researchers when developing the *Output Clusters*. An example of an *Output Cluster* for the *Impact* economy could be (i) jobs (the number of 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 (the number of patents obtained) and (ii) citations (the number of citations for papers published from the research).

It is critical to understand the differences between *Outputs* and *Impacts*. *Outputs* represent performance data that characterize *R&D Results*. *Impacts* numerically characterize the defined success criteria or goals. *Impacts* 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 data would be included in calculating the desired “Economic Growth” *Impact*. Additional examples of *Inputs*, *Outputs*, and *Impacts* will be given later in this paper.

An *Outcome* for each Investment is produced from the Investment Set analysis. *Outcomes* are calculated by utilizing chosen algorithms or methodologies. Within the ICS, these calculations would be performed with ICT that is shown in Figure 1. Examples of *Outcomes* are presented later in the paper as part of the example.

3.3. Framework Stages

Three serial stages of activities are used for the Investment Assessment 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 data (Stage 2), and assessing 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 data. Researchers and Data Analysts work together to select the best performance metrics that generically characterize their R&D results. The Researchers then collect the performance data for their R&D results for these performance metrics. The R&D performance 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 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 [Forman and Gass 2001, ISAHP 2009]. (Other MADM processes are discussed in various books, e.g., Steuer 1986, and Yoon and Hwang 1995. MADM, also referred to as Multiple Criteria Decision

Analysis, 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 wise 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. To utilize 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. There are 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 use 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 Database. Two types of standardization must be made for each *Output*. The first is to standardize within an *Output* 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 data 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 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.

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

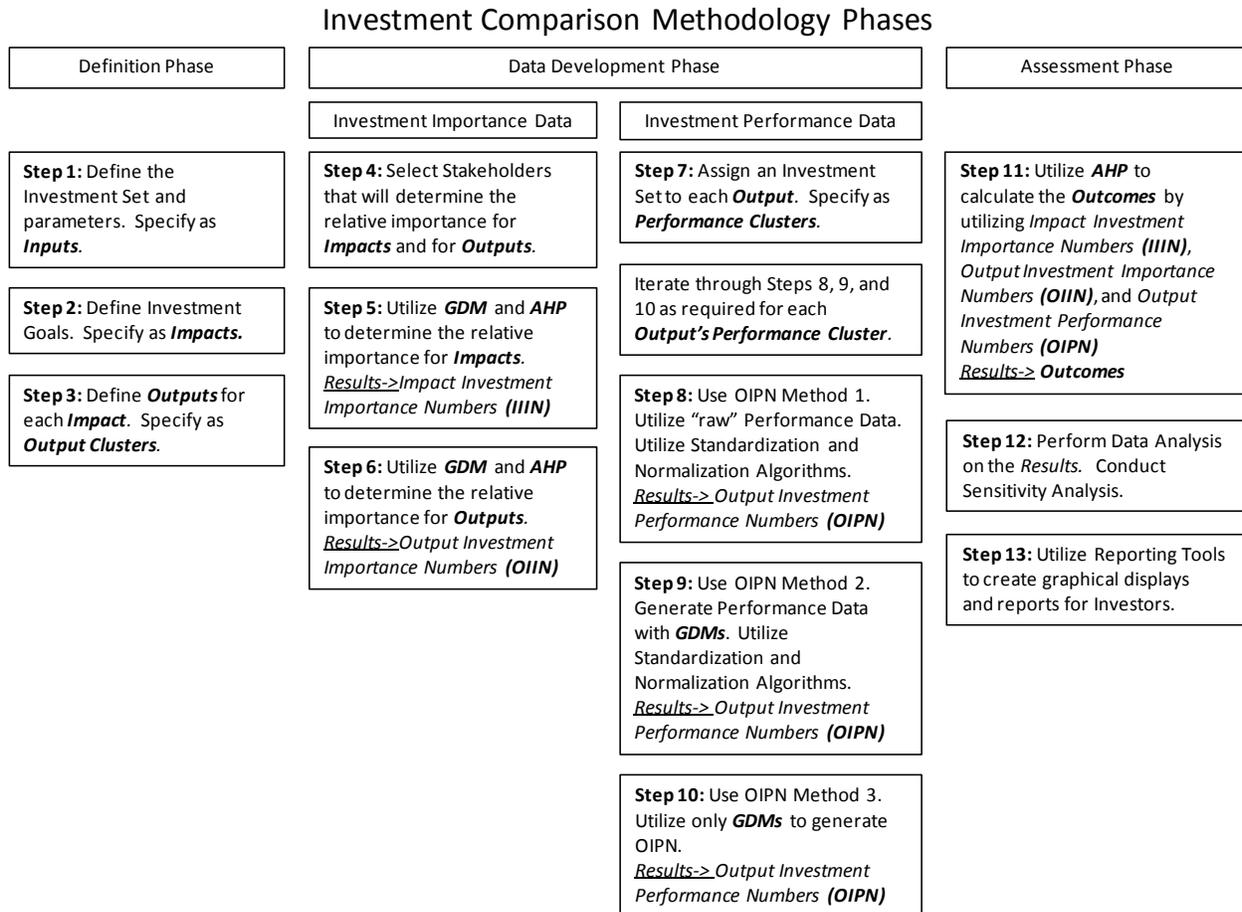


Figure 3. Investment Comparison Methodology Phases

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 are "raw" data and have not been normalized.

In Step 2, the Investors determine how to measure their Investment goals by specifying a Set of *Impacts*. *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 set of *Outputs* mapped to each *Impact* forms that *Impact's Output Cluster*. Investors should consult with the Researchers during Step 3 when developing the *Output Clusters*.

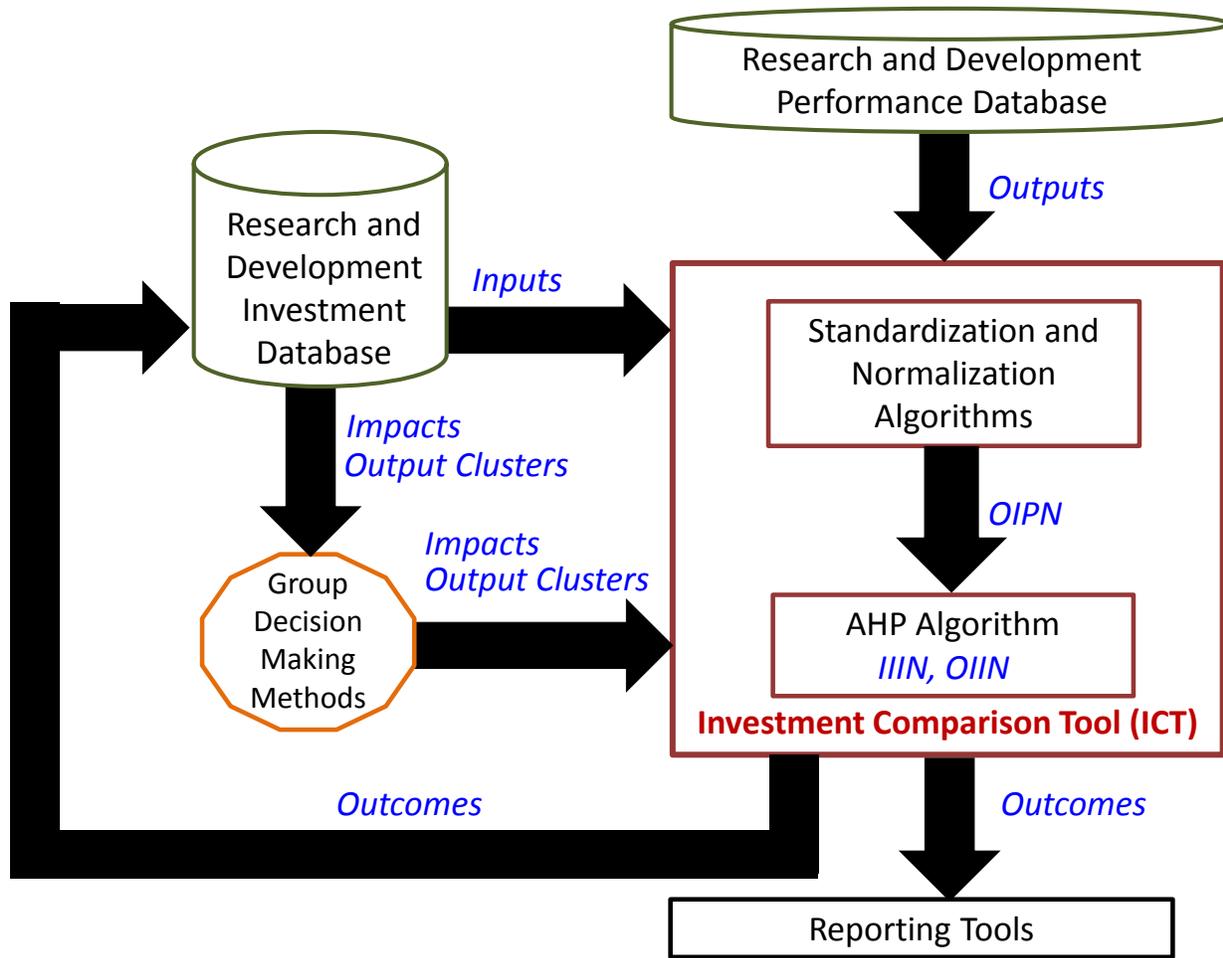


Figure 4. Investment Comparison System Data Architecture

5.2. Phase Two: Data Development Phase

In the Data Development Phase, there are two data sets that need to be developed. The first is *Investment Importance Data* and the second is *Investment Performance Data*. *Investment Importance Data* are based on preferences and goals of the Investors. *Investment Performance Data* are 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 the individuals 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 *Impact 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 *Output Investment Importance Numbers (OIIN)*.

5.2.2 Phase Two: Investment Performance Data

The purpose of Phase Two, Investment Performance Data, is to calculate an *Output Investment Performance Number (OIPN)* for each Investment within each *Output*. There are three OIPN Methods, OIPN Method 1, OIPN Method 2, and OIPN Method 3, for calculating an *OIPN* that are described in Steps 8, 9, and 10, respectively. These methods differ depending on the availability of R&D Investment Performance Data and Standardization and Normalization Algorithms. OIPN Method 1 is the preferred method, followed by OIPN Method 2, and lastly OIPN Method 3. *OIPN* is the value of an *Output* of an Investment.

In Step 7, a *Performance Cluster* is constructed for each *Output* by first assigning repeatedly the Investment Set to each *Output* and then mapping each Investment in each Investment Set to its assigned *Output*. The *OIPN* of each Investment in a *Performance Cluster* must be calculated using the

same OPIN Method. Proceed by following the instructions at Step 8 for each *Performance Cluster*. After all of the *Performance Clusters* have been process, proceed to Step 11.

In Step 8 (OIPN Method 1), determine for the selected *Performance Cluster* if performance data exists in the R&D Performance Database for each of its Investments. If this data exist, proceed with Step 8, otherwise proceed to Step 9. The performance data stored in the R&D Performance Database are “raw” data, which have not been standardized or normalized.

Standardization and Normalization Algorithms must be developed or existing ones obtained for each Investment in the selected *Performance Cluster* to convert the “raw” performance data from the R&D Performance Database into standardized and normalized data. If the needed Algorithms cannot be developed or obtained, proceed to Step 10. As discussed in Section 4, the Technical Foundation of the ICS Methodology, the development of these algorithms can vary from being straight forward to very complex. For each Investment in the selected *Performance Cluster*, process its “raw” performance data first through its Standardization Algorithm and then its Normalization Algorithm to obtain its *OIPN*.

In Step 9 (OIPN Method 2), the “raw” performance data for each Investment in the selected *Performance Cluster* are obtained by GDM because this data does not exist in the R&D Performance Database. Prior to obtaining data by GDM, Standardization and Normalization Algorithms should be developed or existing ones obtained for each Investment in the selected *Performance Cluster* as described in Step 8. If the needed Algorithms cannot be developed or obtained, proceed to Step 10.

If the needed algorithms can be developed or obtained then the “raw” performance data for each Investment in the selected *Performance Cluster* is obtained by GDM using the Decision Makers selected in Step 4 to determine the relative importance of *Outputs*. The *OIPN* for each Investment in the selected *Performance Cluster* is calculated using the “raw” performance data and algorithms for that Investment.

In Step 10 (OIPN Method 3), the *OIPN* for each Investment in the selected *Performance Cluster* is obtained solely by GDM. The Decision Makers, selected in Step 4 to determine the relative importance of *Outputs*, determine the *OINP* of each Investment by using some GDM method. Extreme care must be used by these Decision Makers in determining this set of *OIPNs* to ensure that fair comparisons are being made among the Investments in the *Performance Cluster* as these *OIPNs* must take into account Standardization and Normalization.

A GDM method not discussed in Section 4 that might want to be used in steps 9 and 10 is Decision Conferencing [<http://www.inescc.pt/~ewgmcdca/ForPhillips.html>, accessed November 28, 2010]. This method can give better results than the Delphi Method but requires considerable more

effort than the Delphi Method. A series of decision conferences (working meetings) run by one or more facilitators lead the decision makers to reach a decision. This decision is obtained with the help of a model developed by the decision makers to evaluate different alternatives. AHP would be the model used in Decision Conferencing to determine the needed data values in Steps 9 and 10.

5.3. Phase Three: Assessment Phase

In Step 11, 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. ICT's *Outcomes* are utilized to provide guidance to the Investors regarding Investments.

In Step 12, perform data analysis on the results of the various steps and conduct sensitivity analysis. First perform data analysis. This might include data analysis of (1) the *Impact Investment Importance Numbers (IIIN)* to determine the values of the relative weights of the different *Impacts*, (2) the *Output Investment Importance Numbers (OIIN)* to determine the values of the relative weights of the different *Outputs* of each *Impact*, and (3) the *Output Investment Performance Numbers (OIPN)* to determine the values of the *Outputs* of each Investment.

Next, conduct sensitivity analysis on Investments. Sensitivity analysis might include determining the sensitivity of *Outcomes* to *Inputs* (values of Investment time periods and resource allocations), *Impacts* (values of *Impact Investment Importance Numbers (IIIN)*), and *Outputs* (values of both *Output Investment Importance Numbers (OIIN)* and *Output Investment Performance Numbers (OIPN)*).

ICS can also be used to run scenario planning for Investments at the individual Investment level and for aggregated Investments. Opportunities exist for optimizing Investments.

In Step 13, Reporting Tools are used to create both graphical displays and reports for Investors to view the results of the Steps 11 and 12. A useful Reporting Tool should address one of the biggest challenges for Investors which is how to easily interpret the results of analyses and then incorporate these results into their decision making processes. ICT could also serve as a tool for discussions with Researchers regarding performance data (*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.

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 each Investment in the Investment Set will have a time duration of 3 years and an Investment amount of \$100M yearly. For this example, all Investment parameters are identical.

In Step 2, the Investment Goal was determined from the guidance in the Office of Science and Technology Policy (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 Impacts

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

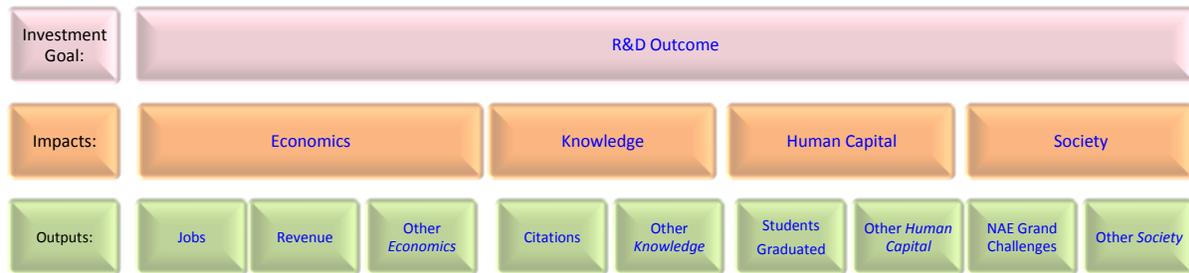


Figure 7. Investment Goal, Impacts, and Outputs

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.		

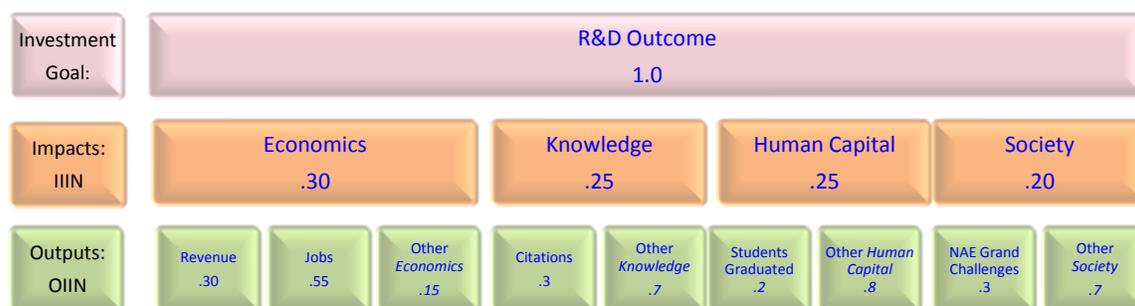


Figure 8. Investment Performance Data

6.2.2 Phase Two: Investment Performance Data

In Step 7, a *Performance Cluster* is constructed for each *Output*. For this example, the *Performance Cluster* for each *Output* is the Investment Set of Chemistry, Biology, and Energy. (Figure 9.)

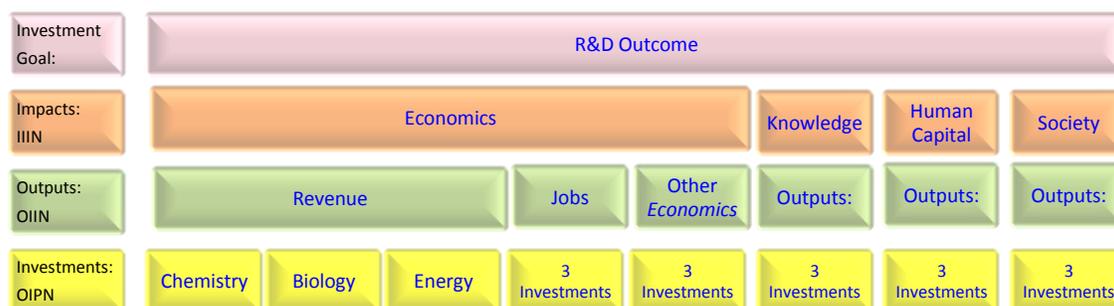


Figure 9. Output Performance Clusters

In Step 8, a determination is made that OIPN Method 1, the preferred OIPN Method, can be used to calculate the “Revenue” Performance Cluster’s *OIPNs*. Performance Data for Revenue *Output* exists in the R&D Performance Database for Chemistry, Biology, and Energy, and are shown in Table 2. Performance Data needs to be standardized and normalized through the use of Standardization and Normalization Algorithms. For this example, it is determined that only a normalization algorithm is needed and can be developed. No standardization algorithm is needed.

Table 2. Revenue Output from the Research and Development Performance 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

The normalization algorithm is now developed. First collect the sum of the revenue outputs over the three years for each of the Investments, which is the sum of each of the rows of Table 2, and then list them in column two of Table 3. From the R&D Investment Database the Resource Allocations for these revenues can be obtained and are given in column three of Table 3. 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 need to be adjusted by a factor of 2X to become normalized with the Biology and Energy resource allocation as shown in column four of Table 3. In Step one it was determined that each Investment in the Investment Set will have an Investment amount of \$100M yearly, thus no normalizations adjustments need to be made regarding the investment amount made in each of the Investments. The OIPNs are given in column six of Table 3. (Note: the time value of money was not considered for simplicity purposes.) Also note that the Investments are made for three years, the time period of the Revenue *Output* from the R&D Performance Database.

In this example we show only the use of OIPN Method 1. Thus Steps 9 and 10 will not be used as they use OIPN Methods 2 and 3.

6.3. Phase Three: Assessment Phase

In Step 11, the AHP algorithm utilizes the IIIN, OIIN, and OIPN data for the ICT Outcomes calculation. Figure 10 displays the complete hierarchical dataset used by the AHP algorithm.

Table 3. Output Investment Performance Numbers

Investments	Revenue (Table 2) <i>R&D Performance Database</i>	Resource Allocation <i>R&D Investment Database</i>	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



Figure 10. 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 12, a determination is made for this example that only data analysis, and no sensitivity analysis, is to be performed. Data analysis could examine (1) the values of the relative weights of the different *Impacts* and (2) the values of the relative weights of the different *Outputs* of each *Impact*. These values are shown in Figure 8 as the *Impact Investment Importance Numbers (IIN)* and the *Output Investment Importance Numbers (OIIN)*. The *IIN* and *OIIN* are contained in the report for the Investors as part of Step 13. The report could highlight that Jobs have an *OIIN* value of 0.55 compared to 0.30 for Revenue and 0.15 for Other Economics as the relative weights for *Outputs* for the *Impact Economics*. When developing the data analysis section of the report, it is important that Investors understand the influence of the Investment Importance Data and how the values factors into the Investment *Outcomes*.

In Step 13, the data calculated by ICT and the AHP algorithm are available for graphical displays and report generation. It is recommended to utilize Reporting Tools to display data generated by the ICT. Investors may be interested in understanding multiple levels of calculated data and their data attributes (Figure 10). Investors should be especially interested in a graphical display (Figure 11) showing Investments verses *Outcomes* to aid in their decision making.

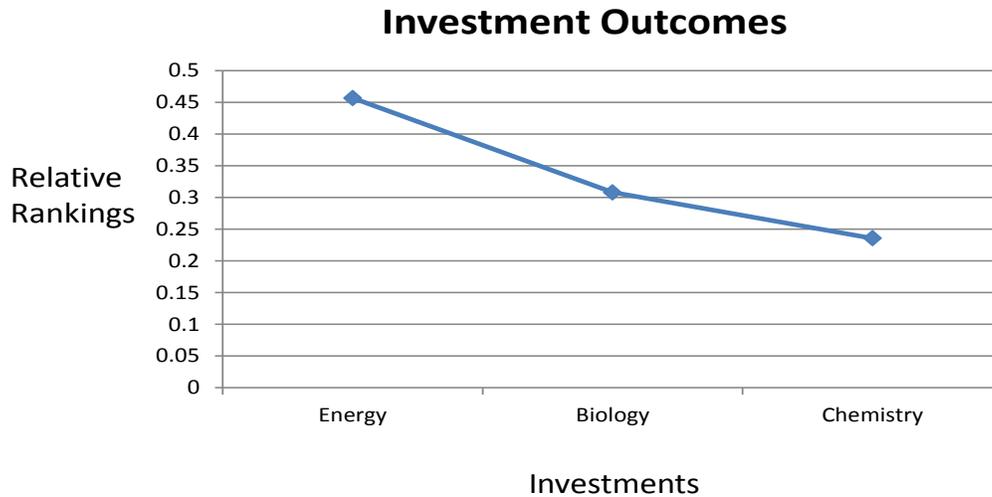


Figure 11. Investment Outcomes

7. Additional ICS Use Cases

The ICS can be utilized to calculate multiple types of Investment *Outcomes*. The paper thus far has focused on the “*Anticipated Investment Outcomes*” use case. Three additional use cases will now be discussed that describe generating the *Outcomes* using different “Investment Performance Data” (Methodology Section 5.2.2) than previously discussed. The first additional use case focuses on measuring *Actual Performance Outcomes*, the second additional use case is a *Performance Comparison* between *Anticipated Investment Outcomes* and *Actual Performance Outcomes*, and the third additional use case is a *Monitoring Function* that trends *Actual Performance Outcomes* against *Anticipated Investment Outcomes*.

The first additional use case measures *Actual Performance Outcomes*. This use case compares past or current Investments using actual data as the “Investment Performance Data” to determine a ranked order of the performance of these Investments. Thus, the methodology given in Section 5.2.2 would replace “raw” data with actual data of the Investments to develop the sets of *Outcomes*.

The second additional use case is a *Performance Comparison* between *Anticipated Investment Outcomes* and *Actual Performance Outcomes*. This use case is straight forward where the *Anticipated Performance Outcomes* are calculated as described in the methodology and the *Actual Performance Outcomes* are calculated as described in the first additional use case. It is critical to note that to insure consistency for the *Performance Comparison*, all data generated in Steps 1-7 of the ICS Methodology must be the same for both the *Anticipated Investment Outcomes* and *Actual Performance Outcomes*

calculations. Upon completion of Step 11, both the *Anticipated Investment Outcomes* and *Actual Performance Outcomes* for an Investment can be directly compared and analyzed.

The third additional use case is a *Monitoring Function* that tracks *Actual Performance Outcomes* against *Anticipated Investment Outcomes*. Similar to use case two, *Actual Performance Outcomes* can be calculated on a set of Investments periodically such as yearly and compared to see how they are performing compared to *Anticipated Investment Outcomes*. It is important to note that monitoring progress of *Actual Investment Outcomes* towards *Anticipated Investment Outcomes* may not track linearly.

8. 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.

8.1 Usability

The ICS can be implemented into any R&D setting such as the Federal Government, Industry, or Research Laboratories. The ICT can be used to leverage existing databases (Research and Development Investment Database and the Research and Development Performance 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.

8.2 Transparency

A significant strength of the ICS is the transparency of how Investment rankings are determined. Transparency was designed into ICS to provide visibility to both the decision making process and the calculated data values for the Stakeholders (Investors, Researchers, and Analysts). For example, as part of the Definition Phase of the ICS Methodology (Figure 3), Investors are required to clearly specify their decision making “success criteria” to define their Investment Goals. This includes specifying the overall

Investment Goal, *Impacts*, and *Outputs* as demonstrated through the Methodology Example (Figure 7). Furthermore, the relative weights for the *Impacts* and the *Outputs*, calculated during the Data Development Phase of the ICS Methodology, are provided and shown in the Methodology Example (Figure 8). Visibility into the ICS decision making criteria and all calculated values provide the Stakeholders opportunities for a closer examination and analysis of what drives the Investment rankings. For example, during the ICS Methodology Assessment Phase, it is transparent to all the Stakeholders that the most valued Investment R&D Results' *Outputs* carry the highest *Outcome* numeric values. To leverage ICS's transparency to achieve the highest Investment rankings, Researchers could identify the Investors' highest value *Outputs* and focus their research to achieve the R&D Results that would translate into the greatest *Outcomes*.

8.3 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 may become challenging.

9. 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 R&D Groups. 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 and Investment data. To support the usage of the ICS, an Investment Assessment 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. Throughout this paper, the ICS methodology primary focus has been on “Anticipated” Investment decision making. Because ICS also has a broader use, additional use cases for decision making were also described to include actual Investment Assessment. Additionally, both data analysis and sensitivity analysis can be performed.

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 <http://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) [http://nrc59.nas.edu/star_info2.cfm, accessed Nov 29,2010].

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