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Using the AHP in the Capability Maturity Model Integration for Development

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Summary: *Tens of thousands of companies have been pursuing process improvement based on Capability Maturity Models. Process capability/maturity appraisal based on the models has been used as a basis for many important decisions, including actions to improve internal processes, large-scale acquisitions, and contract monitoring. The 2006 updated version CMMI-DEV (Capability Maturity Model Integration for Development) from CMMI includes a process area, namely Decision Analysis and Resolution (DAR), which emphasizes a formal evaluation of identified alternatives against established criteria. The DAR process area is very similar to the AHP (Analytic Hierarchy Process). This study addresses similarities and differences between the AHP and the DAR process area. Then, this study identifies process areas that the AHP is usefully applied to. Results of this study are capable of providing a substantiated basis for process improvement and appraisal.*

1. Introduction

Tens of thousands of companies have been pursuing process improvement based on Capability Maturity Models since its announcement by the SEI (Software Engineering Institute) in the 1990s. Process capability/maturity appraisals based on the models have been used as a basis for many important decisions, including actions to improve internal processes, large-scale acquisitions, and contract monitoring (Herbsleb et al. 1997).

The 2006 updated version 1.2, CMMI-DEV (Capability Maturity Model Integration for Development), from CMMI v1.1 includes a process area, namely Decision Analysis and Resolution (DAR), which emphasizes a formal evaluation of identified alternatives against established criteria. In detail, the DAR process area (PA) involves establishing guidelines to determine which issues (problems) should be subjected to a formal evaluation and then applying it to issues chosen. The DAR process area has very similar characteristics of the AHP (Analytic Hierarchy Process) (Saaty 1990 and 2001).

The DAR process area belongs to Support Category. Thus if applicable, all of the 22 CMMI-DEV process areas including DAR itself should use a formal evaluation to attain high capability/maturity level. The DAR process area is potentially applicable to a wide range of activities, including planning, budgeting, architecture, design, supplier selection, test planning, logistics, make-or-buy decisions, and others. The purpose of this study is first to address similarities and differences between the AHP and the DAR process area. Then, we identify CMMI-DEV process areas that the AHP is usefully applied to. This study is capable of providing a substantial basis for using the AHP in CMM-DEV.

This paper is organized as follows. The next section introduces CMMI-DEV and the DAR process areas under subject to this study. Section 3 provides CMMI-DEV process areas that the AHP can be applied to. In Section 4, we present discussion and final remarks including further studies. Appendix 1 provides a summarized description of the AHP.

2. CMMI-DEV and DAR Process Area

2.1 CMMI-DEV

The updated version CMMI-DEV (2006) from CMMI (2002) developed by the SEI at Carnegie Mellon University provides a comprehensive integrated solution for development and maintenance activities applied to products and services. The basic premise of CMMI models is that the quality of a system is highly influenced by the quality of the process used to acquire, develop, and maintain it. CMMI-DEV helps organizations set improvement objectives and improve processes based on best practices.

CMMI-DEV includes a total of 22 process areas as shown in Table 1. Process area implies “cluster of related practices in an area that, when implemented collectively, satisfy a set of goals considered important for making improvement in that area” (CMMI-DEV 2006).

Table 1: CMMI-DEV Process Areas

Process Management	Organizational Process Focus (OPF)
	Organizational Process Definition (OPD)
	Organizational Training (OT)
	Organizational Process Performance (OPP)
	Organizational Innovation and Deployment (OID)
Project Management	Project Planning (PP)
	Project Monitoring and Control (PMC)
	Supplier Agreement Management (SAM)
	Integrated Project Management + IPPD (IPM + IPPD)
	Risk Management (RSKM)
	Quantitative Project Management (QPM)
Engineering	Requirements Management (REQM)
	Requirements Development (RD)
	Technical Solution (TS)
	Product Integration (PI)
	Verification (VER)
	Validation (VAL)
Support	Configuration Management (CM)
	Process and Product Quality Assurance (PPQA)
	Measurement and Analysis (MA)
	Decision Analysis and Resolution (DAR)
	Causal Analysis and Resolution (CAR)

There are two ways to arrange the 22 process areas: continuous representation and staged representation. But, we proceed with the continuous representation for the sake of simplicity of explanation. Each process area is depicted by several components as seen in Figure 1. In the figure, each process area begins with a Purpose Statement followed by Introductory Notes for explaining generally process area. A specific goal (SG) applies to a process area and describes some of the unique characteristics that must be present to satisfy the process area. Specific practices (SPs) describe the activities expected to result in achievement of the specific goals of a process area. Typical work products of the specific practices or subpractices are identified.

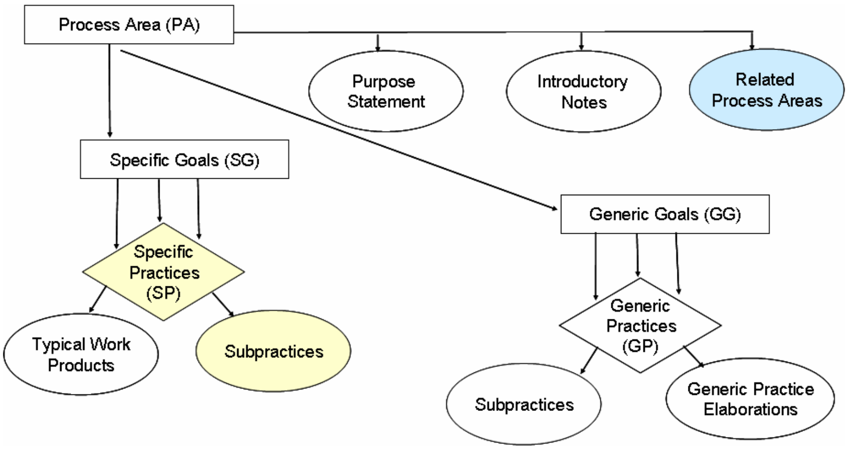

Figure 1: CMMI-DEV Components

Related Process Areas (top-right) lists references to other process areas related and reflects the high-level relationships among the process areas. Some specific practices and subpractices also include References as pointers to additional or more detailed information. The DAR process area is a process area and it is referenced by other processes or their specific practices.

Satisfying all specific goals means the achievement of capability level 1. For the generic practices, there are generic practice elaborations, which convey the application of the generic practice and its subpractices with respect to a particular process area. The achievement of capability levels 2 to 5 is determined by the degree of institutionalization of generic goals. Please refer to CMMI-DEV (2006) for details of ratings 2 to 5. Satisfaction of all specific and generic goals should be shown by work products from the implementation of a set of specific and generic practices.

A basic proposition of process assessment models is that higher process capability or maturity is associated with better project performance and product quality. Frequently cited performance categories are cost, schedule, productivity, quality, customer satisfaction, and return on investment. Information about CMMI benefits is found in the SEI technical report (Gibson et al. 2006).

2.2 Decision Analysis and Resolution

2.2.1 DAR Specific Practices

The purpose of the DAR process area is to analyze possible decisions using a formal evaluation process that evaluates identified alternatives against established criteria. The DAR process area involves establishing guidelines to determine which issues should be subjected to a formal evaluation process and then applying formal evaluation to issues chosen (CMMI-DEV 2006). A formal evaluation process reduces the subjective nature of the decision and has a higher probability of selecting a compromised alternative. As noted, the DAR process area is potentially applicable to a wide range of activities.

A guideline for utilizing DAR processes is necessary when a formal evaluation is required. For example, a formal evaluation may be invoked when medium to high risk issues are considered or when issues affect the ability to achieve project objectives. Both numeric and non-numeric criteria can be used in a formal evaluation process. Numeric criteria use weights to reflect the relative importance of the criteria. Non-numeric criteria use a more subjective ranking scale (e.g., high, medium, or low) (CMMI-DEV 2006).

Like the AHP, the eventual selection of a solution may involve iterative activities of identification and evaluation. Formal evaluation may be also applied to the DAR process area when multiple alternative solutions and evaluation criteria exist.

The DAR process area includes a specific goal (Evaluate Alternatives) and its six specific practices as shown in Figure 2. The six specific practices are summarized as follows:

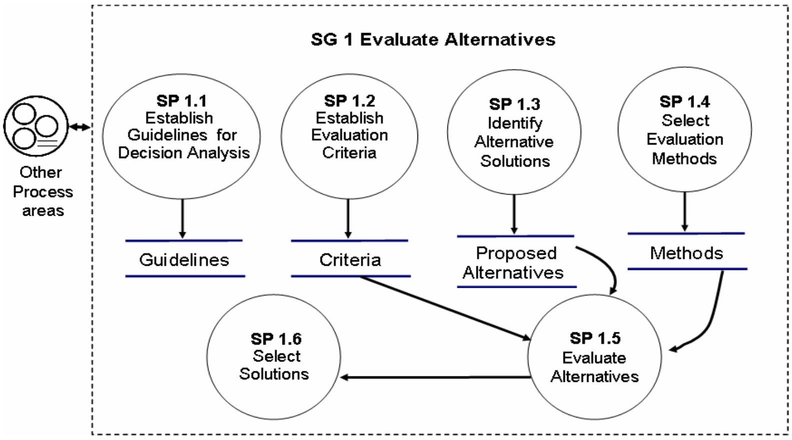

Figure 2: Specific Goal and Its Practices in the DAR Process Area (SEI 2007)

- DAR SP 1.1 Establish Guidelines for Decision Analysis

Since all decisions are not significant, this practice requires development of guidelines for determining when to apply a formal evaluation process. SP 1.1 requires incorporating the use of the guidelines into the defined process where appropriate. CMMI-DEV (2006) provides some of the typical examples as follows:

- On decisions involving the procurement of material when 20 percent of the material parts constitute 80 percent of the total material costs;
- On design-implementation decisions when technical performance failure may cause a catastrophic failure (e.g., safety of flight item);
- On decisions with the potential to significantly reduce design risk, engineering changes, cycle time, response time, and production costs.

- DAR SP 1.2 Establish Evaluation Criteria

This practice requires the evaluation criteria ranked or prioritized for evaluating alternative solutions. Those criteria should be traceable to requirements, scenarios, business case assumptions, business objectives, or other documented sources. Types of criteria considered are technology, limitations, environmental impact, risks, total ownership, and lifecycle costs.

- DAR SP 1.3 Identify Alternative Solutions

This practice requires performing a literature search and brainstorming to identify alternative solutions, and others. The early generation and consideration of multiple alternatives increases likelihood to find an acceptable decision.

- DAR SP 1.4 Select Evaluation Methods

Selection of evaluation methods depends on the purpose for analyzing a decision and on the availability of the information used to support the method. The methods used for evaluating a solution when requirements are weakly defined may be different from ones well defined. This practice provides typical evaluation methods: modeling and simulation, engineering studies, manufacturing studies, cost studies, business opportunity studies, surveys, and extrapolations based on field experience and prototypes, user review and comment, testing, and judgment provided by an expert or group of experts (e.g., AHP or Delphi Method).

- DAR SP 1.5 Evaluate Alternatives

This practice evaluates alternative solutions identified in SP 1.3 using the criteria established in SP 1.1 and method selected in SP 1. 4. Supporting analyses, experimentation, prototyping, piloting, or simulations may be needed to substantiate scoring and conclusions. In cases where the resulting scores differ by relatively small amounts, the best selection among alternatives may not be clear cut. Sensitivity analysis is then required (Triantaphyllou and Sanchez 1997).

- SP 1.6 Select Solutions

This practice is to select solutions from the alternatives based on the evaluation criteria. Risks associated with implementation of the selected solution must be assessed.

2.2.2 Similarities and Differences

As noted in DAT SP 1.4, the AHP is one of the methods to evaluate alternatives. Most of examples in SP 1.4 should follow the DAR SP 1.1 and SP 1.3, and SP 1.6. The criteria for evaluating alternative solution, SP 1.2, may be significantly different across products, depending on product type, operational environment, performance requirements, support requirements, and cost or delivery schedules. As described in previous section, SP 1.4 can also vary in formality, type of criteria, and methods employed. However, several methods can be used to get the best solution together.

SP 1.5 relies on not only evaluation methods chosen in SP 1.4 but also scoring methods such as simple additive weighting (SAW) method, weighted product method, Technique for Order Preference by Similarities and Ideal Solution (TOPIS), Electre, others (Yoon and Hwang 1995). As we noted the examples of the methods in DAR SP 1.4, the AHP may be the most cost effective method.

3. Use of the AHP in Process Areas

This section describes process areas that can utilize the AHP for achieving their purposes and refer to the DAR process area in their Related Process Areas at process area level and References in practice level. This study limits its scope to the AHP application.

3.1 AHP Applications in the Technical Solution (TS) PA

The primary application of a formal evaluation is to technical issues, especially the Technical Solution (TS) process area. The TS process area intensively requires formal evaluations to design, develop, and implement solutions to requirements. TS SG 1 (Select Product Component Solutions) explains that one indicator of a good design process is that the design was chosen after comparing and evaluating it against alternative solutions based on established criteria. Decisions on architecture, custom development versus off the shelf, and product component modularization are typical issues of the design choices.

In detail, TS SP 1.1 (Develop Alternative Solutions and Selection Criteria) identifies and analyzes alternative solutions across the life of the product. These solutions are based on proposed product architectures that address critical product qualities. These alternative solutions can also include the use of commercial off-the-shelf (COTS) solutions in the product architecture. Alternative solutions frequently encompass alternative requirement allocations to different product components. TS SP 1.1

suggests typical criteria for selection: costs (e.g., time, people, and money), benefits (e.g., performance, capability, and effectiveness), and risks (e.g., technical, cost, and schedule). Integrated Process and Product Development (IPPD) Addition describes the involvement of relevant stakeholders in the activity of selecting alternative solutions and issues to be subject to decision analyses. The AHP is a useful tool to select the best solution among alternatives by using an analysis of benefits, costs, and risks (Saaty 2001).

TS SP 1.2 (Select Product Component Solutions) selects the best set of alternative solutions that satisfy the established selection criteria. This practice requires establishing and maintaining the documentation of the solutions, evaluations, and rationale. Note that in CMMI, "establishing and maintaining" explicitly implies documentation and usage throughout the organization. The DAR process area can be directly applied to this practice. Jung and Choi (1999) used the AHP based on the access frequencies of the modules to select COTS product among alternatives.

TS SP 2.1 (Design the Product or Product Component) requires establishing and maintaining design evaluation criteria. This practice also provides examples of criteria: modular, clear, simple, maintainable, verifiable, portable, reliable, accurate, secure, scalable, and usable. The AHP can be utilized to find the best design by using the above criteria.

TS SP 2.3 (Design Interfaces Using Criteria) specifies the use of criteria in the evaluation of the interface design alternatives. The criteria of interfaces frequently reflect critical parameters that must be defined, or at least investigated, to ascertain their applicability. The AHP can be a useful method to compare interface design alternatives.

TS SP 2.4 (Perform Make, Buy, or Reuse Analyses) requires using formal decision making to evaluate whether the product components should be developed, purchased, or reused based on established criteria. It is frequently referred to as a "make-or-buy analysis" in CMMI-DEV.

3.2 AHP Applications in the Project Planning (PP) PA

Non-technical issues can also be evaluated by using the AHP. While many issues in project planning may be solved by using the AHP, multiple methods can be applied to some issues.

The DAR process area can be applied in Project Planning (PP) that is to "establish and maintain plans that define project activities." Specific issues requiring a formal evaluation are identified during project planning. The PP process area provides typical issues such as selection among architectural or design alternatives, use of reusable or commercial off-the-shelf (COTS) components, supplier selection, engineering support environments or associated tools, test environments, delivery alternatives, and others. The AHP can be applied to perform the PP process area as follows:

PP SG 1 (Establish Estimates) is to establish and maintain estimates of project planning parameters. These parameters include all information needed by the project to perform the necessary planning, organizing, staffing, directing, coordinating, reporting, and budgeting. PP SG1 requires that estimates of planning parameters should have a sound basis to instill confidence. Any plans based on these estimates are capable of supporting project objectives.

In PP SP 1.2 (Establish Estimates of Work Product and Task Attributes), the AHP can be applied for making decisions on architectural features, such as distributed or client/server, state-of-the-art, or established technologies to be applied.

In PP SP 1.4 (Determine Estimates of Effort and Cost), the AHP can be used to estimate project effort and cost for the work products based on estimation rationale. Effort and schedule are estimated by using regression models based on project size measured by lines of code or function points. A well known model for these estimates is COCOMO (COnstructive COst Model) and its variants (Boehm and Papaccio 1988). Statistical methods including regression models need historical data not only to build the model, but also to test its accuracy, i.e., training and testing.

However, there may be occasions that the historical data is not enough or available to apply statistical models, such as where efforts are unprecedented or where the type of task does not fit available models. Sheppered and Cartwright (2001) employed an AHP approach to estimate the level of effort for future projects. Their analysis considers the following criteria: the number of programs, functionality, level of difficulty, skill of the staff, number of groups, similarity to previous work, any problems expected, and personal pressure. Results from their AHP usage were able to generate more accurate results than the ordinary least squares analysis with full data set. Miranda (2001) also utilized an AHP for estimating software size, when the knowledge available to project team members is mostly qualitative. He concludes that the AHP is promising.

In IPM (Integrated Project Management)+IPPD, SP 1.3 (Establish the Project's Work Environment) provides examples of equipment and tools for the project, where decision support software including the AHP can be listed. Ahmad and Laplante (2006) used an AHP approach to select an appropriate software project management tool among alternatives.

3.3 AHP Applications in Other Process Areas

In the Organizational Process Definition (OPD)+IPPD process area, SP 2.1 (Establish Empowerment Mechanisms) refers to the DAR process area. Once an integrated team project structure is established and training is provided in IPPD, decision making and issue resolution also need to be provided.

In the Organizational Training (OT) process area to develop the skills and knowledge of people, OT SP 1.4 (Establish Training Capability) refers to the DAR process area as a Related Process Area for how to apply decision-making criteria when determining training approaches and developing training materials. The AHP can be usefully applied in this practice.

In the Suppler Agreement Management (SAM) process area, SP 1.2 (Select Suppliers) requires the selection of suppliers based on a formal evaluation of their ability to meet the specified requirements and established criteria. Sarfaraz and Balu (2006) address the multi-objective criteria pertaining to supplier selection process by a combination of Quality Function Deployment (QFD), AHP, and Preemptive Goal Programming (PGP) techniques, where the AHP helps in systematically prioritizing the relative importance of the requirements enumerated as part of the QFD.

In the Risk Management (RSKM) process area, SP 2.2 (Evaluate, Categorize, and Prioritize Risks) evaluates and categorizes each identified risk using the defined risk categories and parameters, and determines its relative priority. Formal evaluation process using the AHP is often used to address issues with identified medium or high risks. The AHP may be used to assign relative importance to each identified risk. Work product from this practice is a list of risks with a priority assigned.

The Quantitative Project Management (QPM) process area is to quantitatively manage the project’s defined process to achieve the project’s established quality and process-performance objectives. QPM SP 1.3 (Select the Subprocesses that Will Be Statistically Managed) selects appropriate subprocesses from the defined process to manage quantitatively. The AHP can be applied to select subprocesses for statistical management. The selected subprocesses are controlled by statistical method.

The Requirement Development (RD) process area is to produce and analyze customer, product, and product component requirements. RD SG 1 (Develop Customer Requirements) states that stakeholder needs, expectations, constraints, and interfaces are collected and translated into customer requirements. Software system developers are often faced with many requirements and not enough time or money to implement them all. They must therefore find a way to prioritize the requirements to select those that will add the most to a system implementation and eliminate those not worth the cost (Jung 1998). For solving those issues, Karlsson and Ryan (1997) used the AHP process to prioritize each requirement’s value and cost in relation to other requirements. Then they selected the implemented requirements based on the intuitive inspection of the relative cost-value ratio. Jung (1998) extended their model to select requirements to be implemented by using an optimization model called knapsack.

The Process Integration (PI) process area is to assemble the product from the product components, and deliver the product. The DAR process area may be used to develop an integration strategy. PI SP 1.1 (Determine Integration Sequence) specifies the selection of the appropriate integration sequence and procedures. For this purpose, an optimizing model including scheduling can be utilized rather than the AHP for find an optimal sequence.

The Verification (VER) process area is to ensure that selected work products meet their specified requirements. On the other hand, the Validation (VAL) process area is to demonstrate that a product or product component fulfills its intended use when placed in its intended environment. All of SP 1.2 in the PI, VER, and VAL process areas specify the establishment of product integration, validation, verification environment, respectively. The type of required environment will depend on the work products or product. However, the AHP can be usefully utilized for make-or-buy analysis.

4. Discussions and Final Remarks

Since process capability/maturity appraisals based on CMMI-DEV are used as a basis for many important decisions, exact interpretation and implementation of its goals and practices are very important to organizations improving their processes. However, the AHP is not familiar topic to many process-people. Despite formal evaluation as necessary in all process models, CMMI-DEV only includes the DAR process among over 10 process models including ISO/IEC 15504:2003 (Process Assessment).

This study investigates CMMI-DEV process areas that may utilize the AHP and reviews previous studies on how the AHP has been applied. This study is mostly based on Related Process Areas and References stated in process areas. We find that the AHP can be applied to thirteen process areas. The PP and TS processes can be intensively utilized by the AHP. Further study may find practices that are not described in CMMI-DEV Related Process Areas or Reference but process areas that are important enough to improve processes. The application of the AHP in capability levels 2 to 5 is also an important research area.

For practitioners, practices related to the AHP should be transformed to process descriptions including the AHP for everyday process users. If the AHP is understood well in organizations, the AHP application to the thirteen process areas does not result in problems in process establishment and improvement.

CMMI-DEV arranges process areas in a category of continuous representation by the order of implementation. The first group of process areas (called basic process areas) should be implemented before the second group called advanced process areas. In support category, basic process areas include Process and Product Quality Assurance (PPQA), Configuration Management (CM), and Measurement and Analysis (MA) process areas. Advanced support processes cover Causal Analysis and Resolution (CAR) and DAR process areas. The advanced Support process areas provide the projects and organization with an improved support capability. Each of these process areas in support category relies on specific inputs or practices from other process areas.

Appendix 1: The AHP approach

This appendix provides information for understanding the AHP approach. A rigorous approach with advanced mathematics can be found in Saaty (1990). The AHP starts by breaking down the decision issue or problem into a hierarchy of interrelated decision elements (criteria, attributes, or factors). Each criterion should have a different weight (priority) depending on its effect on its goal.

Let w_1, w_2, … w_n be their corresponding weights. Then, a relative importance matrix between criteria, called the comparison matrix, $A_{ij} = (w_i / w_j) = (a_{ij})$, is created by performing pairwise comparisons of criteria and judging their relative importance with a scale of numbers shown in Table 2. Thus, every element (i, j) of the lower sub-matrix A satisfies the reciprocal property, i.e.

$a_{ji} = 1/a_{ij}$. Diagonal elements of self-comparison have a value of 1. For instance of a_{12}, criterion 1 has an importance of a_{12} times more compared to criterion 2. For n criteria, $n(n-1)/2$ comparisons are required to generate matrix A . Note that we are going to find the weights w_j s.

Table 2: Measurement Scale of the Comparison Matrix (Saaty 1990)

Intensity of importance (a_{ij})	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or Strong importance
7	Very Strongly importance
9	Extreme importance
2, 4, 6, 8	Intermediate values
Reciprocal	$a_{ji} = 1/a_{ij}$.

If a comparison matrix is perfect (consistent), i.e., $a_{ij} \times a_{jk} = a_{ik}$ for all i , j , and k , then the following holds $AW = nW$, where n is the number of criteria and W is the vector of (relative) weights. The term 'relative' means that the sum of weights becomes 1. However, perfect comparison is not usually common. Specifically, matrix A has inconsistencies such that weight vector W is estimated by $A\ W = \lambda_{\max}\ W$, where $\lambda_{\max}$ is the largest eigenvalue of matrix A and is considered the estimation of n . Saaty (1990) has shown that $(\lambda_{\max} - n)\ \geq 0$ holds. The closer the $\lambda_{\max}$ is to n , the more consistent matrix A . This concept has brought the consistency index (CI), as $(\lambda_{\max} - n)/(n-1)$, which measures the deviation from a consistent comparison. Furthermore, the extent of the consistency of matrix A is measured as a consistency ratio (CI), CR=CI/RI, where RI is the average index of randomly generated weights from the scale (Saaty and Kearns 1985). The RI for different order random matrices is shown in Saaty and Kearns (1985).

If matrix A has a perfect consistency, then CI and CR become zero since $(\lambda_{\max} - n) = 0$. If CR is less than or equal to 0.1, Saaty (1990) recommends that the estimate of the weights be accepted. In addition, he proposed that if CR $\geq$ 0.1, the iterative computation be utilized to estimate the weights in order to meet the CR requirement.

AHP allows cardinal, ordinal, or a mixture of ordinal and cardinal scales to measure criteria. If the measured value has an ordinal scale such as A (excellent), B (above average), C (average), D (below average), or E (poor), then the ordinal value is transformed to a numerical value utilizing the weight assignment scheme in the AHP (Saaty 1990).

The final step of the AHP method aggregates the weights and the measured values of criteria. There are several aggregation methods such as a simple additive weighting (SAW) and weighted product methods (Yoon and Hwang 1995). The best-known method is the SAW method because of its simplicity and ease of understanding. For a mathematical expression of the method, let n be the number of criteria. Let w_j and a_j be the weight and measured value of criterion j , respectively. With these notations, the SAW method computes the aggregated value of a process attribute to be $V = \sum_{j=1}^{n} w_j a_j$, where $\sum_{j=1}^{n} w_j = 1$ and the aggregated value V has a value between 0 and 1.

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