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# An evidential reasoning approach for the earned value management

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**Abstract.** Earned Value Management (EVM) is a project management technique used to measure project progress by integrating efficient management of the most important three elements in a project i.e. cost, schedule, and scope. This paper presents an Evidential Reasoning (ER) based model for estimating the Earned Value (EV) of the projects activities with uncertainties in progress data. Since the subjective nature of EV measurement can incorporate errors and uncertainties which cause biased judgments, and as the uncertainty is inherent in real-life activities, the developed ER based model is very useful to evaluate the EV of a project wherein uncertainty arises. A case study is provided to illustrate how the new model will be used and can be implemented in reality.



## 1. Introduction

According to Project Management Institute [1,2], Earned Value Management (EVM) is a management methodology for objectively measuring project performance and progress, and forecasting project outcome. Estimating EV is the basis of EVM and hereby, other cost and time indices in EVM can be calculated. Also, progress of a project could be measured by comparing the planned and actual data of activities to their corresponding EVs. The "Earned Value" of a project at a point in time is the estimated amount of work done up to that point [3]. EVM advantages in projects are widely investigated and studied by many experts and practitioners. Earned Value Method (EVM) is one such multidimensional project control method that integrates cost, schedule, technical performance, and scope [1,2,4-6]. VM can be said to bring cost and schedule variance analyses together to provide managers with a more accurate status of a project. Mirzazadeh and Safari [7] studied project risks assessment by using the mathematical theory of evidence under uncertainty conditions.

Anbari [8] enhanced the effectiveness of EV implementation. Kim et al. [9] studied implementation of the EV in different types of organizations and projects. Cioffi [4] presented a new notation for the EV analysis to make EV mathematics more transparent and flexible. Pajares and López-Paredes [10] proposed two new metrics that combine Earned Value Management (EVM) and Project Risk Management for project controlling and monitoring, Cost Control Index (CCoI), and Schedule Control Index (SCoI). Moslemi et al. [11] incorporated the fuzzy principles into Earned Value (EV) calculations, developing a technique to measure and evaluate the performance and progress of a project and its activities under uncertainty, using linguistic terms for measuring the Schedule and Cost Performance Indices (SPI/CPI), and introducing the problem of calculating the fuzzy ESch. Maravas and Pantouvakis [12] introduced S-surface (as opposed to the traditional S-curve) in a

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cash flow calculation methodology for projects including activities with fuzzy durations and/or costs that can be useful for performing earned value analysis. Bagherpour et al. [13] modeled the uncertainty associated with activity duration in earned value to design a control mechanism, which was applicable through production control. Ponz-Tienda et al. [14] took into consideration not only the duration, but also the cost and production in the formulation of the fuzzy EV. Lipke et al. [15] used mathematics of statistics for analyzing cost and duration of project to improve a solution to the problem of uncertainty and imprecision in predictions. Lipke [16] introduced the Earned Schedule Method (ESM) and calculated two alternative schedule performance measures, referred to as SV(t) and SPI(t). Since then, various authors have validated the new earned schedule method on both fictitious and real life project data. The applicability and reliability of ES has been studied and approved by many experts [17-19]. Other efforts on earned value management in recent years are Hunter et al. [20], Acebes et al. [21], Khamooshi and Golafshani [22], etc.

Measuring EV is not simple and how to determine it is a matter of discussion between EVM practitioners. The subjective nature of EV measurement can incorporate errors and uncertainties which cause biased judgments. The idea to overcome this problem is to use Evidential Reasoning Approach in estimating the EV of each activity as the imprecise and uncertain data of activity performance and progress, which is common to arise. Using ER approach in EVM forms the basis of our novel idea.

The remaining of this paper is organized as follows. Section 2 brings an introduction into the EV measurement methods, their advantages, and applications. Section 3 reviews the Evidential Reasoning approach and explains, briefly, an innovation to ER concept i.e., the IER algorithm. Developing the ER based model for EV estimation and its corresponding indices and estimates is presented in Section 4. A simple example is studied in details in Section 5. Finally, this paper ends with the conclusion.

## 2. Earned value measurement methods

PMI [2] states that the methods for measuring the performed work are selected during project planning prior to commencing the work, and they are the basis for performance measurement during project execution.

According to Project Management Institute Practice Standard for Earned Value Management [2], there are three classes of work, as follows:

- Discrete effort (Fixed Formula, Weighted Milestone, Percent Complete, Physical Measurement);
- Apportioned effort;
- Level of effort.

There is not so much uncertainty in estimating EV by the fixed formula method. Therefore, it is not mentioned in this paper. Incorporating uncertainties in Weighted Milestone EV measurement method results in interval Planned Value which is not in scope of this research and could be studied in future research. Apportioned Effort is a rarely used technique for special related work packages [6]. Because of their small role in the overall calculated EV of project, we ignore uncertainties in this method of EV measurement.

We disregard studying Physical Measurement method to make our research shorter, and as it is stated in conclusion and future research section, it is better to be discussed in future studies.

The EV measurement of LOE activities is not considered to have uncertainties, because these kinds of activities do not directly produce definitive end products that can be delivered or measured objectively; LOE activities will not have a schedule variance, too.

So, this paper studies uncertainty in estimating EV of activities with Percent Complete EV Measurement Method, which is the most used technique in this area.

## 3. Evidential reasoning

In this paper, assessments of beliefs about subsets of adjacent grades (or intervals of grades) will be used in the context of MCDM (Multi Criteria Decision Making). The Evidential Reasoning (ER) approach is the latest development in the MCDM area [23].

The ER approach is developed for handling Multiple Criteria Decision Analysis (MCDA) problems having both quantitative and qualitative information with uncertainties and subjectivity [23-25]. Its algorithm is developed for aggregating multiple attributes based on a belief decision matrix and the evidence combination rule of the Dempster-Shafer (D-S) theory [26].

Since, in addition to singletons set of hypotheses, the D-S theory allows belief degrees to be assigned to any subsets of hypotheses, and also ignorance can be modeled, the D-S theory is regarded to be more flexible than traditional Bayes theory in modeling uncertainties. The D-S combination rule can also provide more rigorous yet useful results. For example, it can generate a lower bound and an upper bound of a belief degree to which a hypothesis is believed to be true. More discussion on the potential and advantages of the D-S theory in decision making under uncertainty can be found in [27].

Extensive research dedicated to the ER approach has been conducted in recent years, and it has been applied with some successes to such topics as face recognition, statistical classification, and target identification. Additional applications center on multi-source information, including medical diagnosis and plan recognition [27]. But it has not been used widespread in topics such as project management, in which many uncertainty and vagueness could arise in the real data of projects; especially, it could be more useful when, based on these kinds of data, a decision should be made by the project management team.

In real situations, however, experts or decision makers may often feel it too restrictive and difficult to give precise (crisp) assessments due to incompleteness or lack of information [28-30]. To deal with these situations, experts are encouraged to give interval-valued assessments which are Interval-valued Belief Structures (IBSs). Correspondingly, the ER approach is extended as the Interval-valued ER (shortly called IER) approach [31]. The IER algorithm provides a general modeling framework and an attribute aggregation process to deal with both local ignorance (where decision makers may not always be confident enough to provide subjective assessments to individual grades only, but at times wish to be able to assess beliefs of subsets of adjacent grades), and global ignorance (situations where decision makers are restricted to provide assessments for individual assessment grades only and any ignorance is assigned to the whole space of grades) in MADA (Multi Attribute Decision Analysis).

## 4. Using evidential reasoning in estimating earned value management indices

The application of the proposed method arises in situations where the activity progress cannot be clearly estimated or the total amount of the work required to perform the activities is unknown or uncertain and it is out of control. It is because of uncertainty in subjective judgments and/or uncertainty due to lack of data or incomplete information. In projects such as research and developments, these uncertainties are so common and determining an absolute value as earned value is not reliable. Our proposed method transforms uncertainties into an Interval Earned Value (IEV).

### *4.1. Estimating earned value*

The complete percent EV measurement method is one of the simplest and mostly used techniques for measuring the EV, in each measurement period. The project management team is responsible for determining earned value and makes an estimate of the percentage of the completed activity. This technique can incorporate errors and uncertainty which cause biased judgments. An idea to overcome this problem is to use belief degrees in estimating the completion percent of each activity, as the imprecise and uncertain data of activity performance and activity progress are common to arise. This forms the basis of our proposed method. Note that our proposed evidential reasoning model consists of two attributes ($A_m$ and $A_n$) as decision makers. The IER aggregation process described below can be done recursively until all $M$ basic attribute assessments are aggregated that means all DMs make their decisions without any limitation.

Project management team should determine these inputs to build the model:

1. The evaluation grades $H_{ii}$ $(i = 1, \cdots, N)$. Bigger $N$ means less uncertainty in EV estimation and vice versa;
2. The utility value is the measure of preference of the decision maker. It is a number within a predefined range assigned by the decision maker to an assessment grade if the attribute is qualitative, or to an attribute value if the attribute is quantitative. Normally, the range can be one of the following: [0,1], [0,10], or [0,100]. The highest number is assigned to the most preferred grade or value while the lowest number is assigned to the least preferred grade or value.

   Utility Values $\{u(H_{ii})$ and $u(H_{jj})$ $(i = 1, \cdots, N, j = i, \cdots, N)\}$ should be determined by project management team to be used in Eqs. (13) and (14);
3. The assessment of an activity progress by project management team as one of our decision makers ($A_m$) is then given by:

$$S(A_m) = \{(H_{ij}, \beta_{ij}, m); i = 1, \cdots, N;$$
$$j = i, \cdots, N; i \leq j\}, \tag{1}$$

   and that of another project management team ($A_n$) is given by:

$$S(A_n) = \{(H_{ij}, \beta_{ij,n}); i = 1, \cdots, N;$$
$$j = i, \cdots, N; i \leq j\}, \tag{2}$$

   where $\beta_{ij,m}, \beta_{ij,n} \geq 0$ is the belief degree associated with the grade interval $H_{ij}$ and, by definition, the total belief degrees should be 1, i.e.:

$$\sum_{i=1}^{N} \sum_{j=i}^{N} \beta_{ij,m} = 1, \tag{3}$$

$$\sum_{i=1}^{N} \sum_{j=i}^{N} \beta_{ij,n} = 1. \tag{4}$$

4. $\omega_m$ and $\omega_n$ are the normalized weights for project management team as our decision makers ($A_m$ and $A_n$), see Eqs. (5)-(8). The weight of each project management team (which are decision makers in

charge of activity EV estimation) as $\omega_i$ can be evaluated based on many factors such as organizational management policy, project management strategy, the opinion of project stakeholders, etc.

$$m_{ij}=\omega_m\beta_{ij,m}\quad (i=1,\cdots,N;j=i,\cdots,N), \tag{5}$$

$$m_H=1-\omega_m\sum_{i=1}^{N}\sum_{j=1}^{N}\beta_{ij,m}=1-\omega_m, \tag{6}$$

$$n_{ij}=\omega_n\beta_{ijn}\quad (i=1,\cdots,N;j=I,\cdots,N), \tag{7}$$

$$n_H=1-\omega_n\sum_{i=1}^{N}\sum_{j=1}^{N}\beta_{ij,n}=1-\omega_n. \tag{8}$$

The combined probability mass for each grade interval $\{H_{ij}\}$ with $i \leq j$, denoted by $C_{ij}$, is presented in Eq. (9):

$$C_{ij}=\frac{1}{1-K}\left(-m_{ij}n_{ij}+\sum_{k=1}^{i}\sum_{l=j}^{N}(m_{kl}n_{ij}+m_{ij}n_{kl}) + \sum_{k=1}^{i-1}\sum_{l=j+1}^{N}(m_{kj}n_{il}+m_{il}n_{kj}) + m_Hn_{ij}+m_{ij}n_H\right), \tag{9}$$

and the probability mass is given by:

$$C_H=\frac{m_Hn_H}{1-K}, \tag{10}$$

where $K$ is the combined probability mass assigned to the empty set $\{\phi\}$:

$$K=\sum_{i=1}^{N}\sum_{j=i}^{N}\sum_{k=1}^{i-1}\sum_{l=k}^{i-1}(m_{kl}n_{ij}+m_{ij}n_{kl}). \tag{11}$$

By applying the above aggregation process, recursively, until all the $M$ basic attribute assessments are aggregated and assuming that the final resultant probability masses are shown as in Eqs. (9)-(11), the overall assessment of an activity progress ($A$) can be expressed as:

$$S(A)=\{(H_{ij},\beta_{ij})(i=1,\cdots,N,j=i,\cdots,N)\},$$

$$\text{with}\quad \beta_{ij}=\frac{C_{ij}}{1-C_H}\ (i=1,\cdots,N,j=I,\cdots,N). \tag{12}$$

And finally, the activity progress is determined by upper and downer limits as follows:

$$u_{\max}(A)=\sum_{i=1}^{N}\sum_{j=i}^{N}\beta_{ij}u(H_{jj}), \tag{13}$$

$$u_{\min}(A)=\sum_{i=1}^{N}\sum_{j=i}^{N}\beta_{ij}u(H_{ii}). \tag{14}$$

For more information about IER algorithm, study Xu et al. [31]. Although implementation of the above algorithm seems to be time consuming, by using Excel software, all the calculations can be quickly done.

To make our model understandable, it is better to have a simple example. Suppose the earned value measurement method for activity B is percent complete. The budget of this activity is $10,000. Two project management team members as our decision makers (DM1 & DM2) want to determine the progress (percent complete) of activity at first measurement point. The evaluation grades are provided in Table 1.

Normalized weight for DM1 ($\omega_1$) is 0.55 and for DM2 ($\omega_2$) is 0.45.

Table 2 shows the assessment of attributes. In this case, DM1 and DM2 estimate the progress of activity B by belief degrees; see Eqs. (1)-(4).

The result of Eqs. (5)-(8) (basic probability masses assigned to the grade interval) is shown in Table 3.

Based on Eqs. (9)-(14), the percent complete is [24% - 29%]. IEV summary of activity B is provided in Table 4.

**Table 1.** Evaluation grades, grades description, and utility values.

| **Evaluation grades ($H_{11},\cdots,H_{1212}$)** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Grades description** | 0% | 1%-10% | 11%-20% | 21%-30% | 31%-40% | 41%-50% | 51%-60% | 61%-70% | 71%-80% | 81%-90% | 91%-99% | 100% |
| **Utility values $u(H_{11}),\cdots,u(H_{1212})$** | 0% | 5% | 15% | 25% | 35% | 45% | 55% | 65% | 75% | 85% | 95% | 100% |

**Table 2.** Belief degrees.

| Belief degrees | | | |
|---|---|---|---|
| $\boldsymbol{S(A_1)}$ | DM1$\{(H_{ij}, \beta_{ij,\text{DM1}}); i = 1, \cdots, 12; j = i, \cdots, 12; i \leq j\}$ | (3-4, 0.8) | (5, 0.2) |
| $\boldsymbol{S(A_2)}$ | DM2$\{(H_{ij}, \beta_{ij,\text{DM2}}); i = 1, \cdots, 12; j = i, \cdots, 12; i \leq j\}$ | (4, 0.6) | (5-6, 0.4) |

**Table 3.** Basic probability masses assigned to the grade interval.

| Basic probability masses | | | |
|---|---|---|---|
| **DM1** | **DM1$_{34}$** | **DM1$_{55}$** | **DM1$_H$** |
| | $0.55 \times 0.8 = 0.44$ | $0.55 \times 0.2 = 0.11$ | 0.45 |
| **DM2** | **DM2$_{44}$** | **DM2$_{56}$** | **DM2$_H$** |
| | $0.45 \times 0.6 = 0.27$ | $0.45 \times 0.4 = 0.18$ | 0.55 |

### *4.2. Estimating the main earned value management indices and estimates*

Now, we can determine the main earned value management indices and estimates by applying IEV in EVM formulae. Because of uncertainties that result in interval earned values, these indices and estimates have to be expressed as interval values, too. Planned Value (PV) is also known as the Budgeted Cost of Work Scheduled (BCWS) and is planned by project management team to be used during the project. Actual Cost (AC) is also known as the Actual Cost of Work Performed (ACWP) and is an indication of the resources that have been used to achieve the actual work performed.

**Schedule Variance (SV)**

$$\text{SV} = \text{EV} - \text{PV},$$

$$\text{SV} = [\text{EV}_{\min}, \text{EV}_{\max}] - \text{PV} = [\text{SV}_{\min}, \text{SV}_{\max}]. \quad (15)$$

**Schedule Performance Index (SPI)**

$$\text{SPI} = \frac{\text{EV}}{\text{PV}},$$

$$\text{SPI} = \frac{[\text{EV}_{\min}, \text{EV}_{\max}]}{\text{PV}} = [\text{SPI}_{\min}, \text{SPI}_{\max}]. \quad (16)$$

**Cost Variance (CV)**

$$\text{CV} = \text{EV} - \text{AC},$$

$$\text{CV} = [\text{EV}_{\min}, \text{EV}_{\max}] - \text{AC} = [\text{CV}_{\min}, \text{CV}_{\max}]. \quad (17)$$

**Cost Performance Index (CPI)**

$$\text{CPI} = \frac{\text{EV}}{\text{AC}},$$

$$\text{CPI} = \frac{[\text{EV}_{\min}, \text{EV}_{\max}]}{\text{AC}} = [\text{CPI}_{\min}, \text{CPI}_{\max}]. \quad (18)$$

### *4.3. Interpretation of the main earned value management indices*

The (EVM) information obtained during project control serves as early warning control parameters that trigger corrective actions to bring projects back on track in case of problems [32]. The interpretation of SV [$\text{SV}_{\min}$, $\text{SV}_{\max}$], SPI [$\text{SPI}_{\min}$, $\text{SPI}_{\max}$], CV [$\text{CV}_{\min}$, $\text{CV}_{\max}$], CPI [$\text{CPI}_{\min}$, $\text{CPI}_{\max}$] in the proposed model is provided in Table 5. By extending EV indices interpretations in this paper, project management team can make further analysis and incorporate uncertainty in their decisions.

Each project can have its own thresholds and interpretations of EV indices and estimates according to organizational policy, project management strategy, etc., but our model has extended the framework of these interpretations by taking into account lower and upper limits based on the interval earned value.

**Table 4.** IEV summary of activity B.

| | **BAC of activity $B = \$10,000$** | **1st measurement point** | **2nd measurement point** | **3rd measurement point** |
|---|---|---|---|---|
| **Planned value** | Cumulative % complete | 33% | 67% | 100% |
| | Cumulative value | \$3,300 | \$6,700 | \$10,000 |
| **Earned value** | Cumulative % complete | 24% -29% | | |
| | cumulative value | \$2,400-\$2,900 | | |
| **Actual cost** | Periodic value | \$3,500 | | |
| | Cumulative value | \$3,500 | | |

**Table 5.** Interpretation of SV, SPI, CV, and CPI in IEV model.

| Performance measures | | Schedule | | | | |
|---|---|---|---|---|---|---|
| | | $SV_1 > 0$, $SV_2 > 0$ & $SPI_1 > 1$, $SPI_2 > 1$ | $SV_1 < 0$, $SV_2 > 0$ & $SPI_1 < 1$, $SPI_2 > 1$ | $SV_1 \approx 0$, $SV_2 \geq 0$ & $SPI_1 \approx 1$, $SPI_2 \geq 1$ | $SV_1 < 0$, $SV_2 \approx 0$ & $SPI_1 < 1$, $SPI_2 \approx 1$ | $SV_1 < 0$, $SV_2 < 0$ & $SPI_1 < 1$, $SPI_2 < 1$ |
| Cost | $CV_1 > 0$, $CV_2 > 0$ & $CPI_1 > 1$, $CPI_2 > 1$ | Ahead of schedule Under budget | Analysis (1) Under budget | On schedule Under budget | Behind schedule (1) Under budget | Behind schedule Under budget |
| | $CV_1 < 0$, $CV_2 > 0$ & $CPI_1 < 1$, $CPI_2 > 1$ | Ahead of schedule Analysis (2) | Analysis (1) Analysis (2) | On schedule Analysis (2) | Behind schedule (1) Analysis (2) | Behind schedule Analysis (2) |
| | $CV_1 \approx 0$, $CV_2 \geq 0$ & $CPI_1 \approx 1$, $CPI_2 \geq 1$ | Ahead of schedule On budget | Analysis (1) On budget | On schedule On budget | Behind schedule (1) On budget | Behind schedule On budget |
| | $CV_1 < 0$, $CV_2 \approx 0$ & $CPI_1 < 1$, $CPI_2 \approx 1$ | Ahead of schedule Over budget (1) | Analysis (1) Over budget (1) | On schedule Over budget (1) | Behind schedule (1) Over budget (1) | Behind schedule Over budget (1) |
| | $CV_1 < 0$, $CV_2 < 0$ & $CPI_1 < 1$, $CPI_2 < 1$ | Ahead of schedule Over budget | Analysis (1) Over budget | On schedule Over budget | Behind schedule (1) Over budget | Behind schedule Over budget |

**Analysis (1):** If $(SV_{min}+SV_{max})/2 < 0$ or $(SPI_{min}+SPI_{max})/2 < 1$, it should be determined that how much we are behind schedule. In such cases, further analysis, like monitoring project schedule and critical path, is done, and appropriate corrective action should be taken into account. If $(SV_{min} + SV_{max})/2 > 0$ or $(SPI_{min} + SPI_{max})/2 > 1$, further analysis is not needed, unless in some critical conditions. But the project management team should monitor the EVM SV and SPI indices trend more carefully to implement appropriate preventive actions if required.

**Analysis (2):** If $(CV_{min} + CV_{max})/2 < 0$ or $(CPI_{min}+CPI_{max})/2 < 1$, it should be determined that how much we are over budget. In such cases, further analysis like monitoring project budget and activity planned values is done and appropriate corrective action should be taken into account. If $(CV_{min} + CV_{max})/2 > 0$ or $(CPI_{min} + CPI_{max})/2 > 1$, further analysis is not needed, unless in some critical conditions. But the project management team should monitor the EVM CV and CPI indices trend more carefully to implement appropriate preventive actions if required.

**Behind schedule (1):** In such situations, further analysis, like monitoring project schedule and critical path, is done. If required, appropriate corrective action should be taken into account. The project management team should monitor the EVM SV and SPI indices trend more carefully to implement appropriate preventive actions if required.

**Over budget (1):** In such situations, further analysis, like monitoring project schedule and critical path, is done. If required, appropriate corrective action should be taken into account. The project management team should monitor the EVM CV and CPI indices trend more carefully to implement appropriate preventive actions if required.

According to Table 5 and EV indices calculation results of our example, SV=[-\$900, -\$400], SPI=[0.73, 0.88], CV=[-\$1100, -\$600], CPI=[0.69, 0.83], the activity B is behind schedule and under budget.

### *4.4. Estimating other earned value management indices*

There are other important EVM indices which can help the project management team to study current project progress and predict future of the project. By applying IEV, other EVM indices could be calculated as interval values, which means that uncertainty in the progress of project activities is incorporated.

**Estimate To Complete (ETC)**

$$ETC = \frac{BAC - EV}{CPI},$$

$$ETC = \left[\frac{BAC - EV_{max}}{CPI_{max}}, \frac{BAC - EV_{min}}{CPI_{min}}\right] = [ETC_{min}, ETC_{max}]. \quad (19)$$

**Estimate At Completion (EAC)**

$$EAC = \frac{BAC}{CPI},$$

$$\mathrm{EAC}=\left[\frac{\mathrm{BAC}}{\mathrm{CPI}_{\max}},\frac{\mathrm{BAC}}{\mathrm{CPI}_{\min}}\right]=[\mathrm{EAC}_{\min},\mathrm{EAC}_{\max}]. \tag{20}$$

If we assume that EAC will be influenced by a Performance Factor (PF), which is derived of both cost performance and schedule performance or some other parameters decided by project management team, another equation to calculate the EAC is:

$$\mathrm{EAC_{PF}}=\mathrm{AC}+\frac{\mathrm{BAC}-\mathrm{EV}}{\mathrm{PF}},$$

$$\begin{aligned}\mathrm{PF}=&\alpha[\mathrm{CPI}_{\min},\mathrm{CPI}_{\max}]+\beta[\mathrm{SPI}_{\min},\mathrm{SPI}_{\max}]\\=&[\mathrm{PF}_{\min},\mathrm{PF}_{\max}],\end{aligned} \tag{21}$$

with $\alpha+\beta=1$; or PF = an estimated performance factor by project management team for doing remaining work. Note that if PF is equal to 1, the cost of the remained activities is as planned:

$$\begin{aligned}\mathrm{EAC_{PF}}&=\mathrm{AC}+\left[\frac{\mathrm{BAC}-\mathrm{EV}_{\max}}{\mathrm{PF}_{\max}},\frac{\mathrm{BAC}-\mathrm{EV}_{\min}}{\mathrm{PF}_{\min}}\right]\\&=[\mathrm{EAC}_{\min},\mathrm{EAC}_{\max}].\end{aligned} \tag{22}$$

**Variance At Completion (VAC)**

$$\mathrm{VAC}=\mathrm{BAC}-\mathrm{EAC},$$

$$\begin{aligned}\mathrm{VAC}&=[(\mathrm{BAC}-\mathrm{EAC}_{\max}),(\mathrm{BAC}-\mathrm{EAC}_{\min})]\\&=[\mathrm{VAC}_{\min},\mathrm{VAC}_{\max}].\end{aligned} \tag{23}$$

**To-Complete Performance Index (TCPI)**

$$\mathrm{TCPI(EAC)}=\frac{\mathrm{BAC}-\mathrm{EV}}{\mathrm{EAC}-\mathrm{AC}},$$

$$\begin{aligned}\mathrm{TCPI(EAC)}&=\left[\frac{\mathrm{BAC}-\mathrm{EV}_{\max}}{\mathrm{EAC}_{\max}-\mathrm{AC}},\frac{\mathrm{BAC}-\mathrm{EV}_{\min}}{\mathrm{EAC}_{\min}-\mathrm{AC}}\right]\\&=[\mathrm{TCPI(EAC)}_{\min},\mathrm{TCPI(EAC)}_{\max}],\end{aligned} \tag{24}$$

with $\mathrm{EAC}_{\min}\neq\mathrm{AC}$, $\mathrm{EAC}_{\max}\neq\mathrm{AC}$.

The TCPI for achieving BAC is calculated by:

$$\mathrm{TCPI(BAC)}=\frac{\mathrm{BAC}-\mathrm{EV}}{\mathrm{BAC}-\mathrm{AC}},$$

$$\begin{aligned}\mathrm{TCPI(BAC)}&=\left[\frac{\mathrm{BAC}-\mathrm{EV}_{\max}}{\mathrm{BAC}-\mathrm{AC}},\frac{\mathrm{BAC}-\mathrm{EV}_{\min}}{\mathrm{BAC}-\mathrm{AC}}\right]\\&=[\mathrm{TCPI(BAC)}_{\min},\mathrm{TCPI(BAC)}_{\max}],\end{aligned} \tag{25}$$

with $\mathrm{BAC}\neq\mathrm{AC}$.

### *4.5. Estimating earned schedule indices by using IEV*

The ES concept, as described by Lipke, is as follows. The idea of Earned Schedule is similar to that of Earned Value. However, instead of using cost for measuring schedule performance, we would use time. Earned Schedule is determined by comparing the earned cumulative EV to the performance baseline. The time associated with EV, i.e. Earned Schedule, is found from the PV S-curve. This concept of projecting EV onto PV is not truly new. It is illustrated in many books dealing with EVM. The significance of using the Earned Schedule concept is that the associated schedule indicators behave appropriately throughout the entire period of project performance.

The formulae used for earned schedule are:

$$\mathrm{ES}=C+I,\qquad I=\frac{\mathrm{EV}-\mathrm{PV}_C}{\mathrm{PV}_{C+1}-\mathrm{PV}_C},$$

where $C$ is the number of time increments of the PMB for which EV is greater than or equal to PV; and $I$ is the calculation for the fraction of the subsequent PV increment.

$$\mathrm{ESperiod}_n=\mathrm{ES}_n-\mathrm{ES}_{n-1},$$

where $n$ is the number of time periods from the beginning of the project.

Schedule Variance (time) is obtained by the following equation:

$$\mathrm{SV}_t=\mathrm{ES}-\mathrm{AT}.$$

Schedule Performance Index (time) is obtained by the following equation:

$$\mathrm{SPI}_t=\frac{\mathrm{ES}}{\mathrm{AT}},$$

where AT is the Actual Time.

The ES Planned Duration for Work Remaining (PDWR) is:

$$\mathrm{PDWR}=\mathrm{PD}-\mathrm{ES}_{\mathrm{cum}}.$$

PD is the Planned duration for the project.

To determine the future schedule efficiency required to achieve projected schedule outcomes, the ES "to complete" indices, which are similar to the EVM TCPI for cost, are:

$$\mathrm{TSPI}=\frac{\mathrm{PD}-\mathrm{ES}}{\mathrm{PD}-\mathrm{AT}}.$$

ES provides two formulae for statistically predicting an Independent Estimate At Complete time ($\mathrm{IEAC}_t$):

$$\mathrm{IEAC}_t=\frac{\mathrm{PD}}{\mathrm{SPI}_t},$$

$$\text{IEAC}_t = \text{ES} + \frac{\text{PDWR}}{\text{PF}_t}.$$

$\text{PF}_t$ is a time-based performance factor. So that the Independent Estimate of Completion Date (IECD) would be:

$$\text{IECD} = \text{Project Start Date} + \text{IEAC}_t.$$

In our proposed model, because of the interval value of EV, we should use the following formula:

$$\text{ES}_{\min} = C_{\min} + I_{\min}, \tag{26}$$

$$\text{ES}_{\max} = C_{\max} + I_{\max}, \tag{27}$$

$$I_{\min} = \frac{\text{EV}_{\min} - \text{PV}_C}{\text{PV}_{C+1} - \text{PV}_C}, \tag{28}$$

$$I_{\max} = \frac{\text{EV}_{\max} - \text{PV}_C}{\text{PV}_{C+1} - \text{PV}_C}, \tag{29}$$

$$\text{ESperiod}_{\min}(n) = \min(\text{ES}_{\min}(n) - \text{ES}_{\min}(n-1), \text{ES}_{\max}(n) - \text{ES}_{\max}(n-1)), \tag{30}$$

$$\text{ESperiod}_{\max}(n) = \max(\text{ES}_{\min}(n) - \text{ES}_{\min}(n-1), \text{ES}_{\max}(n) - \text{ES}_{\max}(n-1)), \tag{31}$$

$$\text{SV}(t) = [\text{ES}_{\min}, \text{ES}_{\max}] - AT = [\text{SV}(t)_{\min}, \text{SV}(t)_{\max}], \tag{32}$$

$$\text{SPI}(t) = \frac{[\text{ES}_{\min}, \text{ES}_{\max}]}{\text{AT}} = [\text{SPI}(t)_{\min}, \text{SPI}(t)_{\max}], \tag{33}$$

$$\text{PDWR} = [\text{PD} - \text{ES}_{\max}, \text{PD} - \text{ES}_{\min}] = [\text{PDWR}_{\min}, \text{PDWR}_{\max}], \tag{34}$$

$$\text{IEAC}(t) = \frac{\text{PD}}{[\text{SPI}(t)_{\min}, \text{SPI}(t)_{\max}]} = [\text{IEAC}(t)_{\min}, \text{IEAC}(t)_{\max}], \tag{35}$$

$$\text{IECD} = \text{Project Start Date} + [\text{IEAC}(t)_{\min}, \text{IEAC}(t)_{\max}] = [\text{IECD}_{\min}, \text{IECD}_{\max}]. \tag{36}$$

## 5. Case study

In this section, an example is studied to illustrate the basis of the new evidential reasoning based EV calculations. The project is designing and manufacturing an engineering model of Reaction Wheel, which is a module in ADCS sub-system of a satellite design and manufacturing program called Sat-1.

The Earned Value reporting period is every two weeks and this project has 18 planned reporting periods. The current date is on week 22 reporting period. The information about activities is available in Table 6.

As it is clear, our method is useful in EV estimation of activities with Percent Complete EV Estimation Method, RW-1-3, RW-1-4, RW-1-6, RW-2-3, RW-2-4, and RW-2-6. The calculation of Activity RW-1-3 EV is shown in Table 7. In this case, there are two decision makers who are the mechanical manager and project manager, each having their own estimation of EV based on belief degrees. Beside these DMs, for other activities, decision makers are On-Board Computer Manager (OBC Man), Structure Manager (STR Man), and Electrical Manager (ELC Man). Other IEV calculations for activities are presented in Appendix A.

The result of EV calculation for RW Project is shown in Tables 8 and 9. Because of uncertainty in EV estimation for just 6 activities among RW project activities, the uncertainty of overall project EV indices and estimates is low. The wider an interval is, the greater the uncertainty associated with that measurement will be. It is clear that because of real data outbreak, the closer the project to its end, the lower uncertainties in the overall EV indices and estimates. Since the RW project management team has considered uncertainties in EV estimation, they are more confident about the EVM results.

The Earned Schedule calculation results are provided in Table 10. In period 11 (Week 22), the planned value is 1054 and The IEV calculation in ES Concept is depicted in Figure 1. Because of IEV, our

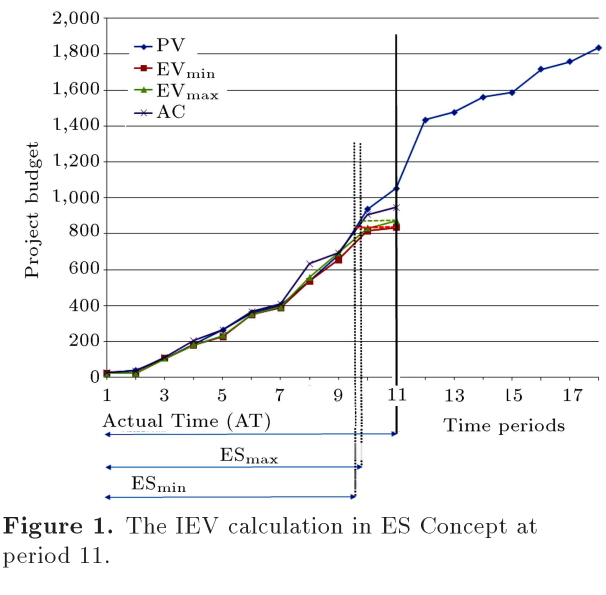


**Figure 1.** The IEV calculation in ES Concept at period 11.

**Table 6.** Reaction wheel project activities description.

| Activity code | Sat-1 project activities | Earned value estimation method | Description of earned value estimation method | Responsible | BAC (100 $) |
|---|---|---|---|---|---|
| **RW** | **Reaction wheel** | | | | 1836 |
| **RW-1** | **Mechanical segment** | | | Mechanism department | 846 |
| RW-1-1 | Completion of detail design | Weighted milestone | M1 till W2 (wheel design)<br>M2 till W4 (ball bearing design)<br>M3 till W8 (motor design)<br>M4 till W10 (case and brackets design) | Mechanism dep | 120 |
| RW-1-2 | Documentation of detail design | Apportioned effort | Apportioned effort 0.05 of (RW-1-1 activity) | Documentation dep | 6 |
| RW-1-3 | Simulation and analysis of functional specification | Percent complete | At each reporting period (W8, W10, W12) | Mechanism dep | 50 |
| RW-1-4 | Modelling and analysis | Percent complete | At each reporting period (W10, W12, W14) | Mechanism dep | 70 |
| RW-1-5 | Establishing the manufacturing drawings | Fixed formula | 0/100 fixed formula (0% for W14 and 100% for W16) | Structure dep | 40 |
| RW-1-6 | Manufacturing the engineering parts | Percent complete | At each reporting period (W16, W18, W20, W22, W24) | Structure dep | 450 |
| RW-1-7 | Quality control of manufactured parts | Apportioned effort | Apportioned effort 0.1 of (RW-1-6 activity) | Quality control dep | 45 |
| RW-1-8 | Assembly and integration | Fixed formula | 20/80 fixed formula (20% for W24 and 80% for W26) | Structure dep | 25 |
| RW-1-9 | Mechanical segment functional tests | Fixed formula | 0/100 fixed formula (0% for W26 and 100% for W28) | Mechanism dep | 40 |
| **RW-2** | **Electrical segment** | | | **On-board control dep** | **715** |
| RW-2-1 | Completion of detail design | Weighted milestone | M1 till W6 (driver design)<br>M2 till W12 (controller design) | On-board control dep | 100 |
| RW-2-2 | Documentation of detail design | Apportioned effort | Apportioned effort 0.07 of (RW-2-1 activity) | Documentation dep | 7 |
| RW-2-3 | Simulation and analysis of functional specification | Percent complete | At each reporting period (W10, W12, W14, W16) | On-board control dep | 40 |
| RW-2-4 | Analysis and programming | Percent complete | At each reporting period (W14, W16, W18) | On-board control dep | 60 |

**Table 6.** Reaction wheel project activities description (continued).

| Activity code | Sat-1 project activities | Earned value estimation method | Description of earned value estimation method | Responsible | BAC (100 $) |
|---|---|---|---|---|---|
| RW-2-5 | Establishing the printed circuit board drawing | Fixed formula | 0/100 fixed formula (100% for W18) | On-board control dep | 15 |
| RW-2-6 | Manufacturing the printed circuit board | Percent complete | At each reporting period (W18, W20) | Electrical manufacturing dep | 70 |
| RW-2-7 | Procurement of electrical parts | Weighted milestone | M1 till W20 (sending purchase order) M2 till W24 (parts delivery) | Procurement dep | 35 |
| RW-2-8 | Assembly of electronic board | Fixed formula | 20/80 fixed formula (20% for W24 and 80% for W26) | Electrical manufacturing dep | 25 |
| RW-2-9 | Quality control of electronic board | Apportioned effort | Apportioned effort 0.12 of (RW-2-8 activity) | Quality control dep | 3.0 |
| RW-2-10 | Electronic segment functional tests | Fixed formula | 0/100 fixed formula (0% for W26 and 100% for W28) | Quality control dep | 45 |
| **RW-3** | **Assembly and integration** | | | Mechanism dep | 275 |
| RW-3-1 | RW integration (electronic segment and mechanical segment) | Fixed formula | 20/100 fixed formula (20% for W28 and 80% for W30) | Mechanism dep | 25 |
| RW-3-2 | RW integration tests | Fixed formula | 0/100 fixed formula (0% for W30 and 100% for W32) | Quality control dep | 100 |
| RW-3-3 | RW environmental tests | Weighted milestone | M1 till W32 (thermal cycle) M2 till W34 (thermal vacuum) M3 till W36 (vibration test) | Quality control dep | 150 |

model has introduced Interval Earned Schedule (IES) incorporating uncertainties into crisp estimated earned schedule value.

## 6. Conclusion

Measuring the Earned Value (EV) is one of the most important parts of earned value management technique implementation. The simplest and mostly used method in EV measurement is Percent Complete. Because of subjective judgment of this method in estimation of completed work, this paper incorporated evidential reasoning approach to model EV measurement uncertainties in real project data. This paper explained how the IEV (Interval Earned Value) and other EVM indices and estimates can be developed by using ER approach.

Future research can focus on studying estimation of other EV measurement methods, such as physical measurement and weighted milestone in evidential reasoning space. On the other hand, evidential reasoning can also be applicable in estimating other EVM parameters like Planned Value (PV) and Planned Duration (PD) estimation.

**Table 7.** Calculation of activity RW-1-3 earned value.

| **RW-1-3:** | **Simulation and analysis of functional specification** | | | **Budget At completion (100 $): 50** | | | | | **Percent complete** | | **Earned value** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight | W8 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{44}$ | $DM1_{55}$ | Min | Max | Min | Max |
| 0.6 | MC Man | DM1 | 4 | 0.6 | 5 | 0.4 | 0.36 | 0.24 | 0.26 | 0.28 | 13.00 | 14.00 |
| | | | | | | | $DM2_{34}$ | $DM1_{55}$ | | | | |
| 0.4 | PRJ Man | DM2 | 3-4 | 0.75 | 5 | 0.25 | 0.3 | 0.1 | | | | |
| Weight | W10 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{89}$ | $DM1_{1010}$ | | | | |
| 0.6 | MC Man | DM1 | 8-9 | 0.5 | 10 | 0.5 | 0.3 | 0.3 | 0.71 | 0.75 | 35.50 | 37.50 |
| | | | | | | | $DM2_{78}$ | $DM1_{99}$ | | | | |
| 0.4 | PRJ Man | DM2 | 7-8 | 0.6 | 9 | 0.4 | 0.24 | 0.16 | | | | |
| Weight | W12 | M3 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1010}$ | $DM1_{1111}$ | | | | |
| 0.6 | MC Man | DM1 | 10 | 0.7 | 11 | 0.3 | 0.42 | 0.18 | 0.87 | 0.89 | 43.50 | 44.50 |
| | | | | | | | $DM2_{1011}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 10-11 | 1 | | | 0.4 | | | | | |
| Weight | W14 | M4 | $H_{ij}$ | $\beta_{ij}$ | | | $DM1_{1212}$ | | | | | |
| 0.6 | MC Man | DM1 | 12 | 1 | | | 0.6 | | 1.00 | 1.00 | 50.00 | 50.00 |
| | | | | | | | $DM2_{1212}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 12 | 1 | | | 0.4 | | | | | |

**Table 8.** Results of RW project earned value calculation (main EVM indices).

| **Weeks** | **BAC** | **AC** | **EV** | | **SV** | | **SPI** | | **CV** | | **CPI** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\mathbf{EV_{min}}$ | $\mathbf{EV_{max}}$ | $\mathbf{SV_{min}}$ | $\mathbf{SV_{max}}$ | $\mathbf{SPI_{min}}$ | $\mathbf{SPI_{max}}$ | $\mathbf{CV_{min}}$ | $\mathbf{CV_{max}}$ | $\mathbf{CPI_{min}}$ | $\mathbf{CPI_{max}}$ |
| W2 | 1836 | 28 | 24 | 24 | 0.00 | 0.00 | 1.00 | 1.00 | -3.95 | -3.95 | 0.86 | 0.86 |
| W4 | 1836 | 37 | 24 | 24 | -15.75 | -15.75 | 0.61 | 0.61 | -12.35 | -12.35 | 0.66 | 0.66 |
| W6 | 1836 | 113 | 105 | 105 | 0.00 | 0.00 | 1.00 | 1.00 | -7.83 | -7.83 | 0.93 | 0.93 |
| W8 | 1836 | 206 | 180 | 181 | -5.50 | -4.50 | 0.97 | 0.98 | -26.03 | -25.03 | 0.87 | 0.88 |
| W10 | 1836 | 266 | 226 | 234 | -38.55 | -30.75 | 0.85 | 0.88 | -39.68 | -31.88 | 0.85 | 0.88 |
| W12 | 1836 | 368 | 349 | 353 | -11.40 | -7.70 | 0.97 | 0.98 | -19.55 | -15.85 | 0.95 | 0.96 |
| W14 | 1836 | 408 | 387 | 391 | -16.20 | -11.80 | 0.96 | 0.97 | -21.55 | -17.15 | 0.95 | 0.96 |
| W16 | 1836 | 635 | 537 | 558 | 1.05 | 21.30 | 1.00 | 1.04 | -97.40 | -77.15 | 0.85 | 0.88 |
| W18 | 1836 | 692 | 655 | 693 | -26.70 | 12.15 | 0.96 | 1.02 | -37.20 | 1.65 | 0.95 | 1.00 |
| W20 | 1836 | 906 | 815 | 830 | -119.73 | -104.88 | 0.87 | 0.89 | -90.50 | -75.65 | 0.90 | 0.92 |
| W22 | 1836 | 946 | 835 | 870 | -218.28 | -183.63 | 0.79 | 0.83 | -110.40 | -75.75 | 0.88 | 0.92 |
| W24 | 1836 | 1126 | 960 | 995 | -473.75 | -439.10 | 0.67 | 0.69 | -166.60 | -131.95 | 0.85 | 0.88 |
| W26 | 1836 | 1195 | 1059 | 1069 | -417.15 | -407.25 | 0.72 | 0.72 | -135.80 | -125.90 | 0.89 | 0.89 |
| W28 | 1836 | 1556 | 1434 | 1434 | -127.40 | -127.40 | 0.92 | 0.92 | -122.05 | -122.05 | 0.92 | 0.92 |
| W30 | 1836 | 1608 | 1476 | 1476 | -110.00 | -110.00 | 0.93 | 0.93 | -132.35 | -132.35 | 0.92 | 0.92 |
| W32 | 1836 | 1693 | 1526 | 1526 | -190.00 | -190.00 | 0.89 | 0.89 | -167.25 | -167.25 | 0.90 | 0.90 |
| W34 | 1836 | 1736 | 1546 | 1546 | -213.00 | -213.00 | 0.88 | 0.88 | -190.15 | -190.15 | 0.89 | 0.89 |
| W36 | 1836 | 1902 | 1686 | 1686 | -150.00 | -150.00 | 0.92 | 0.92 | -216.05 | -216.05 | 0.89 | 0.89 |
| W38 | 1836 | 1958 | 1716 | 1716 | -174.67 | -174.67 | 0.91 | 0.91 | -242.25 | -242.25 | 0.88 | 0.88 |
| W40 | 1836 | 1998 | 1759 | 1759 | -186.33 | -186.33 | 0.90 | 0.90 | -238.95 | -238.95 | 0.88 | 0.88 |
| W42 | 1836 | 2067 | 1836 | 1836 | -164.00 | -164.00 | 0.92 | 0.92 | -231.35 | -231.35 | 0.89 | 0.89 |

**Table 9.** Results of RW project earned value calculation (other EVM indices).

| Weeks | EAC (BAC/CPI) | | TCPI (EAC) | | TCPI (BAC) | | ETC | | PF (0.6 CPI+ 0.4 SPI) | | EAC AC+(BAC-EV)/PF | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $EAC_{min}$ | $EAC_{max}$ | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max |
| W2 | 2136.30 | 2136.30 | 0.86 | 0.86 | 1.00 | 1.00 | 2108.20 | 2108.20 | 0.916 | 0.916 | 2,006.17 | 2,006.17 |
| W4 | 2774.91 | 2774.91 | 0.66 | 0.66 | 1.01 | 1.01 | 2738.41 | 2738.41 | 0.64 | 0.64 | 2,868.25 | 2,868.25 |
| W6 | 1972.69 | 1972.69 | 0.93 | 0.93 | 1.00 | 1.00 | 1859.69 | 1859.69 | 0.958 | 0.958 | 1,919.89 | 1,919.89 |
| W8 | 2089.73 | 2101.33 | 0.87 | 0.88 | 1.02 | 1.02 | 1883.58 | 1895.18 | 0.91 | 0.92 | 2,004.91 | 2,025.78 |
| W10 | 2086.22 | 2158.19 | 0.85 | 0.88 | 1.02 | 1.03 | 1820.42 | 1892.39 | 0.85 | 0.88 | 2,086.45 | 2,160.12 |
| W12 | 1918.55 | 1938.91 | 0.94 | 0.96 | 1.01 | 1.01 | 1550.20 | 1570.56 | 0.958 | 0.968 | 1,900.02 | 1,920.19 |
| W14 | 1916.53 | 1938.34 | 0.94 | 0.96 | 1.01 | 1.02 | 1508.38 | 1530.19 | 0.954 | 0.964 | 1,906.96 | 1,926.87 |
| W16 | 2090.08 | 2168.86 | 0.83 | 0.89 | 1.06 | 1.08 | 1455.43 | 1534.21 | 0.91 | 0.944 | 1,988.81 | 2,062.47 |
| W18 | 1831.63 | 1940.35 | 0.92 | 1.04 | 1.00 | 1.03 | 1139.88 | 1248.60 | 0.954 | 1.008 | 1,825.93 | 1,929.95 |
| W20 | 2003.34 | 2039.84 | 0.89 | 0.93 | 1.08 | 1.10 | 1097.69 | 1134.19 | 0.888 | 0.908 | 2,013.93 | 2,055.77 |
| W22 | 1995.85 | 2078.63 | 0.85 | 0.95 | 1.09 | 1.12 | 1050.05 | 1132.83 | 0.844 | 0.884 | 2,038.76 | 2,132.02 |
| W24 | 2079.60 | 2154.67 | 0.82 | 0.92 | 1.19 | 1.23 | 953.15 | 1028.22 | 0.778 | 0.804 | 2,172.02 | 2,251.96 |
| W26 | 2052.28 | 2071.47 | 0.88 | 0.91 | 1.20 | 1.21 | 857.63 | 876.82 | 0.822 | 0.822 | 2,128.09 | 2,140.26 |
| W28 | 1992.31 | 1992.31 | 0.92 | 0.92 | 1.44 | 1.44 | 436.66 | 436.66 | 0.92 | 0.92 | 1,992.96 | 1,992.96 |
| W30 | 2000.63 | 2000.63 | 0.92 | 0.92 | 1.58 | 1.58 | 392.28 | 392.28 | 0.924 | 0.924 | 1,997.61 | 1,997.61 |
| W32 | 2037.23 | 2037.23 | 0.90 | 0.90 | 2.17 | 2.17 | 343.98 | 343.98 | 0.896 | 0.896 | 2,038.98 | 2,038.98 |
| W34 | 2061.82 | 2061.82 | 0.89 | 0.89 | 2.90 | 2.90 | 325.67 | 325.67 | 0.886 | 0.886 | 2,063.31 | 2,063.31 |
| W36 | 2071.27 | 2071.27 | 0.89 | 0.89 | -2.27 | -2.27 | 169.22 | 169.22 | 0.902 | 0.902 | 2,068.30 | 2,068.30 |
| W38 | 2095.19 | 2095.19 | 0.88 | 0.88 | -0.98 | -0.98 | 136.94 | 136.94 | 0.892 | 0.892 | 2,092.53 | 2,092.53 |
| W40 | 2085.41 | 2085.41 | 0.88 | 0.88 | -0.48 | -0.48 | 87.46 | 87.46 | 0.888 | 0.888 | 2,084.71 | 2,084.71 |
| W42 | 2067.35 | 2067.35 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.902 | 0.902 | 2,067.00 | 2,067.00 |

**Table 10.** Earned schedule calculation results until period 11.

| ID | Weeks | PV | BAC | AC | EV | | PD | ES | | SV(t) | | SPI(t) | | PDWR | | TSPI | | IEAC(t) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $EV_{min}$ | $EV_{max}$ | | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max | Min | Max |
| 1 | W2 | 24 | 1836.00 | 28 | 24 | 24 | 18 | 1 | 1 | 0 | 0 | 1 | 1 | 17 | 17 | 1 | 1 | 18 | 18 |
| 2 | W4 | 40 | 1836.00 | 37 | 24 | 24 | 18 | 1 | 1 | -1 | -1 | 0.5 | 0.5 | 17 | 17 | 1.06 | 1.06 | 36 | 36 |
| 3 | W6 | 105 | 1836.00 | 113 | 105 | 105 | 18 | 3 | 3 | 0 | 0 | 1 | 1 | 15 | 15 | 1 | 1 | 18 | 18 |
| 4 | W8 | 186 | 1836.00 | 206 | 180 | 181 | 18 | 3.93 | 3.94 | -0.07 | -0.06 | 0.98 | 0.99 | 14.06 | 14.07 | 1 | 1 | 18.26 | 18.31 |
| 5 | W10 | 265 | 1836.00 | 266 | 226 | 234 | 18 | 4.51 | 4.61 | -0.49 | -0.39 | 0.9 | 0.92 | 13.39 | 13.49 | 1.03 | 1.04 | 19.52 | 19.95 |
| 6 | W12 | 360 | 1836.00 | 368 | 349 | 353 | 18 | 5.88 | 5.92 | -0.12 | -0.08 | 0.98 | 0.99 | 12.08 | 12.12 | 1.01 | 1.01 | 18.25 | 18.37 |
| 7 | W14 | 403 | 1836.00 | 408 | 387 | 391 | 18 | 6.62 | 6.72 | -0.38 | -0.28 | 0.95 | 0.96 | 11.28 | 11.38 | 1.03 | 1.03 | 18.74 | 19.03 |
| 8 | W16 | 536 | 1836.00 | 635 | 537 | 558 | 18 | 8.01 | 8.15 | 0.01 | 0.15 | 1 | 1.02 | 9.85 | 9.99 | 0.99 | 1 | 17.68 | 17.98 |
| 9 | W18 | 681 | 1836.00 | 692 | 655 | 693 | 18 | 8.82 | 9.05 | -0.18 | 0.05 | 0.98 | 1.01 | 8.95 | 9.18 | 0.99 | 1.02 | 17.9 | 18.38 |
| 10 | W20 | 935 | 1836.00 | 906 | 815 | 830 | 18 | 9.53 | 9.59 | -0.47 | -0.41 | 0.95 | 0.96 | 8.41 | 8.47 | 1.05 | 1.06 | 18.78 | 18.89 |
| 11 | W22 | 1054 | 1836.00 | 946 | 835 | 870 | 18 | 9.61 | 9.74 | -1.39 | -1.26 | 0.87 | 0.89 | 8.26 | 8.39 | 1.18 | 1.2 | 20.32 | 20.61 |

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## Appendix A

### *Activity IEV calculations*

Table A.1 presents the results of EV and percent complete of IEV calculations.

**Table A.1.** Results of EV and percent complete of IEV calculations.

| **RW-1-4:** | **Modeling and analysis** | | | | | | **Budget at completion (100 \$): 70** | | **Percent complete** | | **Earned value** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight | W10 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{45}$ | DM1$_{66}$ | Min | Max | Min | Max |
| 0.6 | MC Man | DM1 | 4-5 | 0.75 | 6 | 0.25 | 0.45 | 0.15 | 0.25 | 0.31 | 17.50 | 21.70 |
| | | | | | | | DM2$_{34}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 3-4 | 1 | | | 0.4 | | | | | |
| Weight | W12 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{99}$ | DM1$_{1010}$ | | | | |
| 0.6 | MC Man | DM1 | 9 | 0.6 | 10 | 0.4 | 0.36 | 0.24 | 0.77 | 0.78 | 53.90 | 54.60 |
| | | | | | | | DM2$_{89}$ | DM1$_{1010}$ | | | | |
| 0.4 | PRJ Man | DM2 | 8-9 | 0.7 | 10 | 0.3 | 0.28 | 0.12 | | | | |
| Weight | W14 | M3 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{1010}$ | DM1$_{1111}$ | | | | |
| 0.6 | MC Man | DM1 | 10 | 0.4 | 11 | 0.6 | 0.24 | 0.36 | 0.88 | 0.90 | 61.60 | 63.00 |
| | | | | | | | DM2$_{910}$ | DM1$_{1111}$ | | | | |
| 0.4 | PRJ Man | DM2 | 9-10 | 0.7 | 11 | 0.3 | 0.28 | 0.12 | | | | |
| Weight | W16 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{1212}$ | | | | | |
| 0.6 | MC Man | DM1 | 12 | 1 | | | 0.6 | | 1.00 | 1.00 | 70.00 | 70.00 |
| | | | | | | | DM2$_{1212}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 12 | 1 | | | 0.4 | | | | | |
| **RW-2-3:** | **Simulation and analysis of functional specification** | | | | | | **Budget at completion (100 \$): 40** | | **Percent complete** | | **Earned value** | |
| Weight | W10 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{34}$ | | Min | Max | Min | Max |
| 0.55 | OBC Man | DM1 | 3-4 | 1 | | | 0.55 | | 0.15 | 0.19 | 6.00 | 7.60 |
| | | | | | | | DM2$_{33}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 3 | 1 | | | 0.45 | | | | | |
| Weight | W12 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{67}$ | | | | | |
| 0.55 | OBC Man | DM1 | 6-7 | 1 | | | 0.55 | | 0.46 | 0.51 | 18.40 | 20.40 |
| | | | | | | | DM2$_{56}$ | DM1$_{77}$ | | | | |
| 0.45 | PRJ Man | DM2 | 5-6 | 0.6 | 7 | 0.4 | 0.27 | 0.18 | | | | |
| Weight | W14 | M3 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{99}$ | | | | | |
| 0.55 | OBC Man | DM1 | 9 | 1 | | | 0.55 | | 0.72 | 0.75 | 28.80 | 30.00 |
| | | | | | | | DM2$_{89}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 8-9 | 1 | | | 0.45 | | | | | |
| Weight | W16 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{1212}$ | | | | | |
| 0.55 | OBC Man | DM1 | 12 | 1 | | | 0.55 | | 1.00 | 1.00 | 40.00 | 40.00 |
| | | | | | | | DM2$_{1212}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 12 | 1 | | | 0.45 | | | | | |
| **RW-2-4:** | **Analysis and programming** | | | | | | **Budget at completion (100 \$): 60** | | **Percent complete** | | **Earned value** | |
| Weight | W14 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | DM1$_{44}$ | | Min | Max | Min | Max |
| 0.55 | OBC Man | DM1 | 4 | 1 | | | 0.55 | | 0.22 | 0.25 | 13.20 | 15.00 |
| | | | | | | | DM2$_{34}$ | | | | | |

**Table A.1.** Results of EV and percent complete of IEV calculations (continued).

| **RW-2-4:** | **Analysis and programming** | | | | | | **Budget at completion (100 $): 60** | | **Percent complete** | | **Earned value** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.45 | PRJ Man | DM2 | 3-4 | 1 | | | 0.45 | | | | | |
| Weight | W16 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{78}$ | | | | | |
| 0.55 | OBC Man | DM1 | 7-8 | 1 | | | 0.55 | | 0.50 | 0.59 | 30.00 | 35.40 |
| | | | | | | | $DM2_{57}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 5-7 | 1 | | | 0.45 | | | | | |
| Weight | W18 | M3 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{910}$ | | | | | |
| 0.55 | OBC Man | DM1 | 9-10 | 1 | | | 0.55 | | 0.72 | 0.79 | 43.20 | 47.40 |
| | | | | | | | $DM2_{89}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 8-9 | 1 | | | 0.45 | | | | | |
| Weight | W20 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1111}$ | | | | | |
| 0.55 | OBC Man | DM1 | 11 | 1 | | | 0.55 | | 0.91 | 0.91 | 54.60 | 54.60 |
| | | | | | | | $DM2_{1010}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 10 | 1 | | | 0.45 | | | | | |
| Weight | W22 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1212}$ | | | | | |
| 0.55 | OBC Man | DM1 | 12 | 1 | | | 0.55 | | 1.00 | 1.00 | 60.00 | 60.00 |
| | | | | | | | $DM2_{1212}$ | | | | | |
| 0.45 | PRJ Man | DM2 | 12 | 1 | | | 0.45 | | | | | |
| **RW-1-6:** | **Manufacturing the engineering parts** | | | | | | **Budget at completion (100 $): 450** | | **Percent complete** | | **Earned value** | |
| Weight | W16 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{33}$ | $DM1_{44}$ | Min | Max | Min | Max |
| 0.6 | STR Man | DM1 | 3 | 0.5 | 4 | 0.5 | 0.3 | 0.3 | 0.15 | 0.18 | 67.50 | 81.00 |
| | | | | | | | $DM2_{23}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 2-3 | 1 | | | 0.4 | | | | | |
| Weight | W18 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{56}$ | | | | | |
| 0.6 | STR Man | DM1 | 5-6 | 1 | | | 0.6 | | 0.33 | 0.40 | 148.50 | 180.00 |
| | | | | | | | $DM2_{45}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 4-5 | 1 | | | 0.4 | | | | | |
| Weight | W20 | M3 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{77}$ | | | | | |
| 0.6 | STR Man | DM1 | 7 | 1 | | | 0.6 | | 0.49 | 0.52 | 220.50 | 234.00 |
| | | | | | | | $DM2_{56}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 5-6 | 1 | | | 0.4 | | | | | |
| Weight | W22 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{78}$ | | | | | |
| 0.6 | STR Man | DM1 | 7-8 | 1 | | | 0.6 | | 0.52 | 0.59 | 234.00 | 265.50 |
| | | | | | | | $DM2_{66}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 6 | 1 | | | 0.4 | | | | | |
| Weight | W24 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{89}$ | | | | | |
| 0.6 | STR Man | DM1 | 8-9 | 1 | | | 0.6 | | 0.63 | 0.70 | 283.50 | 315.00 |
| | | | | | | | $DM2_{78}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 7-8 | 1 | | | 0.4 | | | | | |
| Weight | W26 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1010}$ | | | | | |
| 0.6 | STR Man | DM1 | 10 | 1 | | | 0.6 | | 0.83 | 0.85 | 373.50 | 382.50 |
| | | | | | | | $DM2_{910}$ | | | | | |
| 0.4 | PRJ Man | DM2 | 9-10 | 1 | | | 0.4 | | | | | |
| Weight | W28 | M4 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1212}$ | | | | | |
| 0.6 | STR Man | DM1 | 12 | 1 | | | 0.6 | | 1.00 | 1.00 | 450.00 | 450.00 |

**Table A.1.** Results of EV and percent complete of IEV calculations (continued).

| **RW-1-6:** | **Manufacturing the engineering parts** | | | **Budget at completion (100 $): 450** | | | | **Percent complete** | | **Earned value** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $DM2_{1212}$ | | | | |
| 0.4 | PRJ Man | DM2 | 12 | 1 | | | 0.4 | | | | |
| **RW-2-6:** | **Manufacturing the printed circuit board** | | | **Budget at completion (100 $): 70** | | | | **Percent complete** | | **Earned value** | |
| Weight | W18 | M1 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1010}$ | Min | Max | Min | Max |
| 0.55 | ELM Man | DM1 | 10 | 1 | | | 0.55 | 0.82 | 0.85 | 57.40 | 59.50 |
| | | | | | | | $DM2_{910}$ | | | | |
| 0.45 | PRJ Man | DM2 | 9-10 | 1 | | | 0.45 | | | | |
| Weight | W20 | M2 | $H_{ij}$ | $\beta_{ij}$ | $H_{ij}$ | $\beta_{ij}$ | $DM1_{1212}$ | | | | |
| 0.55 | ELM Man | DM1 | 12 | 1 | | | 0.55 | 1.00 | 1.00 | 70.00 | 70.00 |
| | | | | | | | $DM2_{1212}$ | | | | |
| 0.45 | PRJ Man | DM2 | 12 | 1 | | | 0.45 | | | | |

## Biographies

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