ENHANCED ANALYTICAL MODEL FOR PLANNING THE VERIFICATION, VALIDATION & TESTING PROCESS

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Abstract

System VVT (verification, validation, and testing) are three tasks of System Engineering that focus on ensuring that systems are designed and delivered to meet customer and engineering requirements in the best way possible. Most organizations use sub-optimal VVT processes and methods. Moreover, in many projects, the project manager should anticipate unexpected outcomes during the VVT process, for example, Cost to complete, or Time to complete exceed Cost or Time predictions prior to commencement of the VVT process. The literature include very little research for associating VVT methods to VVT activities and does not offer an effective recovery procedure to suit unforeseen events. In this paper, we present enhanced analytical model that not only structures the decision process but also outputs the optimal VVT methods given Cost, Risk and Time constraints to suit unpredictable outcomes during the VVT process. The use of the enhanced model is demonstrated on a sample problem incorporating some unexpected outcomes during the VVT process.

Keywords: Design methods, Systems engineering (SE), verification validation and testing

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1 INTRODUCTION

System Verification, Validation & Testing (VVT) are three tasks in system development for ensuring that systems are designed and delivered to meet their customer, engineering, and other requirements in the best way. While terminology associated with this subject is quite confusing (Barr, 2001; Pressman, 2001; Engel, 2005), the importance of these tasks is not questioned. Specifically, the economic impact of inadequate VVT is quite understood (e.g., Sorqvist, 1998; NIST, 2002) and the usefulness of conducting VVT was demonstrated (Hoppe, Engel and Shachar, 2007).

Wasson (2006) stated two options to engineering and developing systems: Option 1 is to take the hobbyist approach based on the BUILD, TEST, FIX paradigm that applies to "until we get it right" philosophy. Option 2 is to do RIGHT job RIGHT the first time. The second option could be accomplished by instituting the VVT process during the product lifecycle. Some program managers regard applying the VVT process in a project as a pathway leading to success while others view it as an unnecessary hindrance. We definitely agree with Wason's view that although VVT does not necessarily guarantee success, its benefit is a result of the methods and tools used, and the resources allocated to the VVT activity. Basic Verification Methods such as Inspection, Analysis, Demonstration and Test are described in the system engineering handbook (INCOSE, 2007) and resource estimations in order to optimize the VVT strategy were developed by Engel (2005).

In contrast to this extensive and important use of VVT in systems development, most organizations use sub-optimal VVT processes and methods. Even if an optimal and comprehensive VVT was available, it would not be practical due to Cost and Time considerations. Most projects need to implement different methods of VVT to several VVT activities derived from customer or engineering requirements. Therefore, project managers face the dilemma about which methods of VVT, on a cost effective basis, should be implemented.

The literature include few studies for associating VVT methods to VVT activities in order to allocate resources, engineering, and managerial effort in an optimal manner (Berguland, 2006), creating a gap between the importance of VVT and its suboptimal use in practice. Shabi and Reich (2012) presented an analytical model based on the Subjective Objective System (SOS) – a method for generating good quality product concepts (Ziv-Av and Reich, 2005). This model addresses the gap in order to assist the program manager in a structured and flexible decision making process to determine optimal VVT methods (from those appropriate to the particular system and development phase and are available to the organization) while trading off their relative benefit versus Risk to ensure the most cost effective VVT program for an acceptable level of Risk. The choice of methods could be described as maximizing a quality Q as a function of the vector of methods M, such that each verification or validation method m in the vector M could be selected (m=1) or not (m=0), while maintaining the Cost Risk and Time of the plan ($C(M)$,$R(M)$,$T(M)$) under a prescribed limit (c, Cost limit; r, Risk limit; t, Time limit):

$$\begin{aligned} &\max Q(M) \\ &s.t. \\ &\forall m \in M, m = 0,1 \\ &C(M) \le c \\ &R(M) \le r \\ &T(M) \le t \end{aligned} \tag{1}$$

The previous model maximized Quality subject to Cost and Risk constraints (Shabi and Reich, 2012). In this paper, we present enhanced capabilities of the analytical model that not only structures the decision process but also outputs the optimal VVT methods given Cost, Risk and also Time constraints in order to suit unpredicted outcomes during the VVT process, for example, Cost-to-Complete, or Time-to-Complete exceed Cost or Time predictions prior to commencement of the VVT process. Due to the subjective nature of the way that Risk and Quality were treated in the previous model, in this present study, the behaviour of the enhanced analytical model was examined and compared by algorithm executions with two additional models of Risk assessment and a less subjective Quality model.

The remainder of the paper is organized as follows. Section 2 includes an overview of the enhanced model description. Section 3 demonstrates the model by executing the algorithm on a sample problem and incorporating some unforeseen events during the VVT process. Section 4 analyses the results and Section 5 summarizes the study.

2 VVT ENHANCED MODEL

2.1 Different Risk models

Shabi and Reich (2012) presented a simple qualitative model to assess Risk in the VVT process accrued by not implementing one or more of the VVT methods within the given project. Due to the subjective nature of the way Risk was treated in the first study, in this present study, the behaviour of the analytical model was also compared, by performing simulations (algorithm execution), with two additional models of Risk assessment.

Alternate Risk management process I: The Royal Society (1992) defined Risk as: "The probability that a particular adverse event occurs during a stated period of time, or results from a particular challenge". Other authors have further developed this perspective of Risk, such as Mitchell (1995) and Gillet (1996). Mitchell (1995) defined Risk as "…the probability of loss and the significance of that loss to the organization". Uncertainly of Risk occurrence and severity of Risk impact are two basic elements that affect Risk. The Risk model used in this study is based on the assessment of both likelihood or probability and the impact or consequences for a defined set of Risks in a project, by generating a Risk score matrix as implemented in (Table 1). The system engineer or project manager defines and calibrates individually the impact on performance, cost and schedule along with the probability scale for his project.

Table 1. Risk score matrix

Probability					
81-99% - **5**	5	10	15	20	25
61-80% - **4**	4	8	12	16	20
41-60% - **3**	3	6	9	12	15
21-40% - **2**	2	4	6	8	10
01-20% - **1**	1	2	3	4	5
	1	**2**	**3**	**4**	**5**

Impact on cost, schedule and performance

The horizontal axis of this matrix defines the maximum impact on project objectives, i.e., performance, cost and schedule, with a scale factor from 1 (least impact) to 5 (most extreme impact). Some system engineers use the average value of impact on performance, cost and schedule, while others use the maximum score. In this study, we adopt the latter approach in order to address the worst case scenario. In other words if impact on performance is valued 2 and the impact on cost and schedule are 1 and 4, respectively, the horizontal axis in the Risk score matrix receives the value of 4. The vertical axis of the Risk score matrix defines the probability or likelihood of Risk to materialize. If the probability of the Risk to materialize for a particular VVT activity is estimated by the program manager to be in the vicinity of 50%, the vertical axis receives a value of 3 as defined in Table 1 and the Risk value is calculated by multiplying both horizontal and vertical values to obtain a score of 12. This model defines the Risk severity, R, as follows:

Low Risk $1 \leq R \leq 4$
Medium Risk $5 \leq R \leq 12$ [Risk values: 5, 6, 8, 9, 10, and 12]
High Risk $15 \leq R \leq 25$ [Risk values: 15, 16, 20, and 25]

Alternate Risk management process II: Risk as Cost driver: Some project managers claim that simply assessing the Risk in the VVT process is necessary but not sufficient. It is crucial to also translate this

Risk as a Cost factor and allocate an additional Risk budget in order to take necessary action in case the probability of the Risk does materialize for a particular VVT activity. Thus, in the framework of our study, calculating the Risk as a Cost driver model is preferred and hence the majority of runs of the enhanced model make use of this Risk model. In this alternate Risk model, the total Cost for performing VVT activities in a project is calculated as the sum of actual Cost for performing VVT activities + additional Cost of VVT activities due to the Risk factor:

$$cr_j \text{ is the Risk Cost for each VVT activity } j = P_j \cdot I_j \tag{2}$$

Where

P_j is the probability of Risk occurrence of activity j

I_j is the Cost impact due to Risk occurrence = BD_j (%) $\cdot$ $VVTC_j$

BD_j is the budget deviation for activity j due to Risk occurrence

$VVTC_j$= VVT Cost for a particular VVT activity j.

In general, the system engineer or program manager needs to estimate the Risk Cost factor as a function of the probability of Risk occurrence and its impact on budget deviation of the project. Note that in this study we only consider the influence of Risk on the VVT plan and its additional Cost. The system engineer must equally consider its impact on all other activities. The impact on the Cost of the VVP plan is the additional Cost incurred by having to execute part of a VVT activity again, which is also a function of the probability of Risk occurrence. In our runs, the values in Table 2 were used. The Risk as Cost factor is evaluated during the evaluation stage or the Request for Proposal (RFP) stage of the project and would be considered as an additional budget at the disposal of the program manager during the VVT process of the project.

Table 2. Values used for Matlab runs

Risk Factor	P	BD (%)
Very Low	0.10	0
Low	0.40	10 %
Medium	0.70	40 %
High	0.90	60 %

2.2 Handling unexpected Cost-to-Complete and Time-to-Complete related issues

The previous model maximized Quality subject to Cost and Risk constraints only. Since for most projects, time constraints are of significant importance, in this study Time constraints were also incorporated. For example, with the assumption of total availability of all required resources required to perform VVT activities, the total duration to perform these activities would be obtained and tradeoffs be performed to confer with Time constraints. Furthermore, since in real life situations, total availability of VVT method resources, exactly when required, is seldom possible, sequencing techniques and Time or Cost-to-Complete related issues need to be addressed. Figure 1 is an algorithm to address unforeseen outcomes during the VVT process with respect to the Cost constraint.

The analytical model could initially assist the program manager in the Request for proposal (RFP) process by outputting the budget (C_{opt}) required to Maximum Quality (Q_{max}) in the VVT process. The algorithm also addresses the events when the customer may not approve the optimal Quality VVT budget or demands a certain budget cut after project budget approval. The algorithm handles even a situation where after spending some project budget, the project manager realizes that Cost-to-Complete the VVT process exceeds the residue Cost. In these scenarios, an alternate VVT plan should be generated by the analytical model by constraining the Cost to a lower budget, i.e., Cost-to-Go or Cost-to-Complete of VVT activities not yet performed or partially performed, should be less or equal to new budget minus budget already spent.

$\max Q(M)$ (formulation of $Q(M)$ is given in (Shabi and Reich, 2012)) (3)

s.t.

$\forall m \in M, m = 0,1$ (some m would be 0 because they were already executed or not selected)

$C(M) \leq c_{togo} = c_{approved} - c_{spent} - c_{risk}$

c_{togo} is the Cost needed to complete the VVT process

$c_{approved}$ is the Cost approved initially

c_{spent} is the Cost already spent in the VVT process

$c_{risk} = \sum_j cr_j$, cr_j as defined in equation (2)

$C(M) = \sum_l c_{jl} \cdot x_{jl}$

c_{jl} is the Cost it takes to complete VVT method l for VVT activity j, j=1,N

N is the number of VVT activities

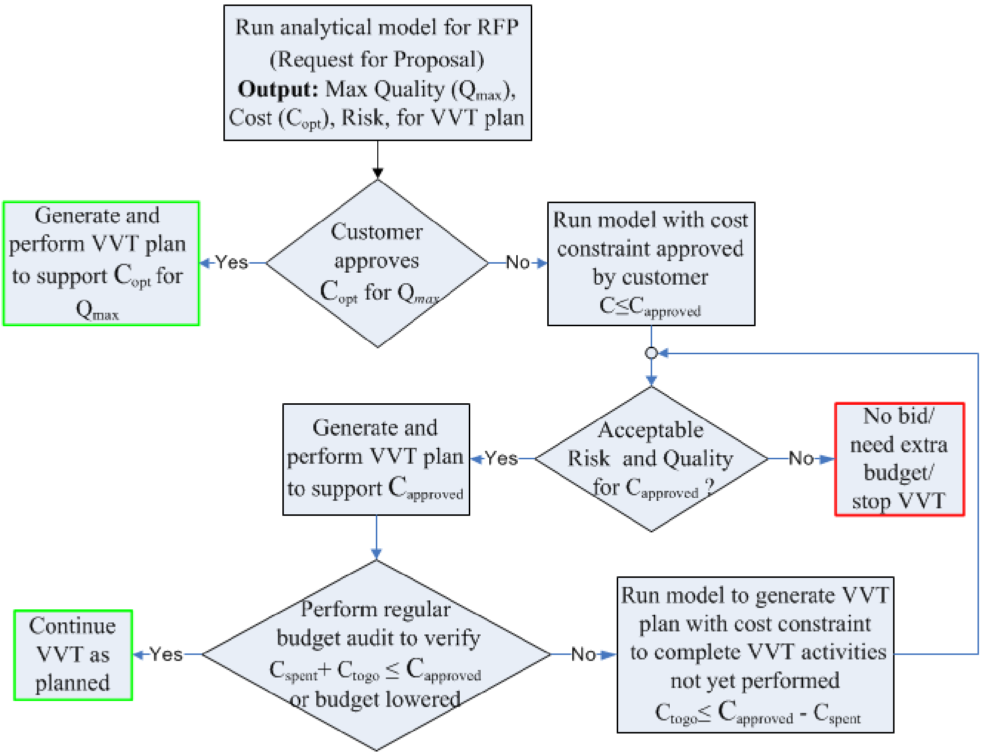

Figure 1. Algorithm for handling changes in Cost-to-Complete or Cost prediction

Many projects include a severe schedule deadline due to Time-to-Market or other issues. Hence the VVT plan duration should be constantly monitored by the program manager. The enhanced analytical model could be initially executed to output the VVT plan duration for maximum Quality. If the VVT duration plan exceeds deadline schedule it might be necessary to apply sequencing techniques or try reducing Time duration by adding work hours (working overtime additional work power, etc.).

Dealing with Time depends on the situation.

In the worst case, VVT resources required to perform the methods are not available when necessary and there are sequential requirements imposed by the program manager on the methods for implementing particular VVT activities. We do not assume any constraint between different VVT activities. In other words, any VVT activity could start by choice of the program manager but once the VVT activity is selected, verification methods for that VVT activity need to be performed by a defined sequence, for example analysis before testing. In this case, the program manager needs to also consider the time needed to wait due to sequential requirement to perform each VVT activity in addition to the time consumed or time needed to wait (delta Time) due to unavailability of resources. Hence the total Time for completing all VVT activities would be the maximum duration necessary to complete the longest VVT activity or the longest verification method (in case where the Time to perform verification methods is large and greater than the delta Times due to unavailability of resources and sequential requirements). Altogether, the model would be:

$$\max Q(M) \tag{4}$$

s.t.

$\forall m \in M, m = 0,1$ (some m would be 0 because they were already executed or not selected)

$C(M) \leq c_{togo} = c_{approved} - c_{spent} - c_{risk}$

c_{togo} , $c_{approved}$, c_{spent} as defined in equation (3)

$T(M) \leq t_{togo} = t_{approved} - t_{elasped}$

t_{togo} is the Time needed to complete the VVT process

$t_{approved}$ is the Timeframe approved initially

$t_{elapsed}$ is the Time already elapsed in the VVT process

and,

T_j is Time for verifying VVT activity j, j=1,N by all VVT methods

$T_j = \sum_l t_{jl} \cdot x_{jl}$ + $delta\ t_l$ + $delta\ t_{jlm}$ + $delta\ t_{j,j-1}$, j=1,N , $l = s,a,t,d$, $m = s,a,t,d$

T_l is Time for verifying all N VVT activities by Verification by method l, $l = s,a,t,d$

$delta\ t_l$ is Time/duration for unavailability of resources required to perform Verification by method l, $l = s,a,t,d$

$delta\ t_{jlm}$ delta Time required after completing Verification by l and starting Verification by m for activity j, j=1,N

$delta\ t_{j,j-1}$ delta Time required before starting methods of Verification for activity j

t_{jl} is the Time it takes to complete VVT method l for VVT activity j, j=1,N

N is the number of VVT activities

x_{jl}, $j=1,N$ verification method s selected for VVT activity j (x=1) or not selected (x=0)

3 SAMPLE PROBLEM AND RESULTS

3.1 Sample problem

In this paragraph, we first provide a brief reminder of a simplified sample problem used in the model, Shabi and Reich (2012), and later demonstrate the enhanced model capability in the same sample problem. In order to certify a new payload on an aircraft, the engineer needs to address and generate appropriate system requirements. These requirements are multidisciplinary and need extreme expertise in order to avoid safety hazards. A system requirements checklist may include, System missions, Target and Threats, Deployability, Electromagnetic Radiation, etc. The simplified sample problem will include the following customer requirements, VVT activities, and VVT methods derived from the customer requirements:

Customer Requirements: We assume a total of 3 customer requirements in this sample problem.

$R_i=i$; i=1,2,3

i=1; Safety

i=2; System Mission

i=3; Environmental Conditions

VVT Activities: We assume a total of 7 VVT activities derived in order to satisfy all customer requirements:

For customer requirement i=1; Safety, the following 2 VVT activities are generated:

j=1 - Fault Tree Analysis (FTA)

j=2 - Safety of Flight (SOF) clearance.

For customer requirement i=2; System Mission, the following 3 VVT activities are generated:

j=3 - Payload Release Envelope

j=4 - Emergency Release Envelope

j=5 - Flight Release Envelope

For customer requirement i=3; Environmental Conditions, the following 2 VVT activities are generated:

j=6 – Random Vibrations Certification

j=7 – Temperature Conditions Certification

3.2 Optimization solution

There are 167 possible combinations of methods that could be used for the required activities. Table 3 displays the first 5 Pareto optimal results, when considering Quality, Risk, and Cost as 3 objectives. It may be seen that the maximum Quality (97) is obtained at a Cost of 81 units and with a specified Risk factor 51 as described in case 1 in Table 3. The verification methods associated for obtaining maximum Quality with the relevant Cost and Risk are derived by the algorithm, as seen in columns 5 through 11 in Table 3. An optimization solution using Integer programming (Table 3, case 6) shows identical results to the Pareto solution (Table 3, case 1).

Table 3. Maximum Quality and corresponding Cost and Risk for all VVT activities with different models, where S= Verification by Similarity; A= Verification by Analysis; T= Verification by Testing; D= Verification by Demonstration

Model		**Case**	**Quality**	**Cost**	**Risk**	***j*=1**	***j*=2**	***j*=3**	***j*=4**	***j*=5**	***j*=6**	***j*=7**
Pareto		1	97	81	51	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	A,T
		2	93	79	46	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	T
		3	90	71	50	A	S,A,T	T	S,A,T,D	S,A,T,D	A,T	A,T
		4	89	67	59	A	S,A,T	S	S,A,T,D	S,A,T,D	A,T	A,T
		5	85	65	54	A	S,A,T	S	S,A,T,D	S,A,T,D	A,T	T
Integer Programming		6	97	81	51	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	A,T
Alternate Risk Model (I)		7	97	81	242	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	A,T
Risk as Cost driver (II):	Optimal Budget 81	8	97	81	30	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	A,T
	Budget cut to 71	9	85	71	30		S,A,T	T,D	S,A,T,D	S,A,T,D	A	A,T
	Budget cut to 65	10	81	65	30	A	S,A,T	T	S,A,T,D	S,A,T,D		A,T
	Total budget 71, activities (j=2 & j=4) completed at Cost 40 instead of 21	11	38	31	21.4	A	done before	-	done before	S,A,T,D	-	-

3.3 Different Risk model and results

In order to examine the behaviour of the analytical model, the algorithm was executed using two additional models of Risk assessment. Table 3, case 6 shows optimal results using the initial qualitative Risk model. Table 3, case 7 shows optimal results using the alternate Risk management process I and Table 3, case 8 displays the optimal results by the alternate Risk management process II.

3.4 Enhanced model capabilities and results

In this paragraph, the enhanced model capabilities are demonstrated by the sample problem. We chose two typical examples of project based problems that could be imposed on the project manager during the VVT process. The first set of problems could occur due to a VVT budget cut imposed during any timeframe of the VVT process, or during regular budget audits as required to be performed by the program manager and realizing that budget already spent plus budget needed to complete VVT process is more than the approved budget. In order to simulate this first set of problems, the model algorithm was executed to obtain maximum Quality by changing Cost constraint (Cost-to-Complete) from initial budget of 81 units to budget cut representing 71 and 65 units. Table 3, case 8 shows optimal results for initial budget and Table 3, cases 9 and 10 display optimal results due to the budget cuts respectively. The other set of typical problems that are likely to occur during the VVT process are Time-to-Complete or project deadline related problems. Table 4, displays optimal results including Time constraints in addition to Risk and Cost constraints, and assuming non- availability of all required resources and sequential requirements for performing VVT activities.

Table 4. Maximum Quality and corresponding Cost, Risk and Time for all VVT activities for model with Risk as Cost driver, non- availability of resources and sequential requirement,, where S= Verification by Similarity; A= Verification by Analysis; T= Verificatio

Model	**Case**	**Quality**	**Cost**	**Risk as Cost**	**Time**	**j=1**	**j=2**	**j=3**	**j=4**	**j=5**	**j=6**	**j=7**
No Cost or Time constraint	12	97	81	30	460	A	S,A,T	T,D	S,A,T,D	S,A,T,D	A,T	A,T
No Time constraint, Cost constraint=55	13	75.2	55	30	460		S,A,T		S,A,T,D	S,A,T,D		A
No Cost constraint, Time constraint=360	14	59.9	55	30	360	A	S,A,T	T,D	S,A,T	S,A,T	A,T	A,T

4 DISCUSSION OF RESULTS

4.1 Different Risk models

The selected VVT methods obtained by the two Risk models described above (Table 3, cases 8 and 9) were identical to the results obtained by the original Risk model (Table 3, case 6). The simulations included sensitivity analysis to the Risk values generated from these alternate Risk models, without any change in results.

4.2 Enhanced model capabilities

Unexpected outcomes due to a VVT budget cut imposed during any timeframe of the VVT process, or during regular budget audits as required to be performed by the program manager: Initially, algorithm runs were performed simulating budget cut from 81 units to 71 units before commencing any VVT activity (Table 3, case 9). The results show an increase of the relative Risk Costs, i.e., actual Cost divided by Risk Cost from 37% (Table 3, case 8, column 4 divided by column 3) to around 42% (Table 3, case 9, column 4 divided by column 3), as expected. The budget cut also eliminates verification methods for activity j=1 and one of the two verification methods for j=6 which could explain the decrease in Quality and an increase in the relative Risk Cost. Additional runs simulated a further budget cut to 65 units (Table 3, case 10) show further decrease in quality and additional increase in the relative Risk Cost to 46%. We also see some changes in verification in order to satisfy the Cost constraint. For this scenario, verification method by Demonstration was eliminated and only verification by Testing was suggested for VVT activity j=3. Furthermore no verification methods for activity j=6 and verification by Analysis was reintroduced. These changes should be analyzed by the program manager and for this sample problem are considered to be acceptable. Thus, for this specific project, a small budget cut would cause little acceptable change in the selected methods and vice versa. Algorithm runs were also made to simulate budget cuts after completing some VVT activities with Cost spent more than anticipated (Table 3, case 11). The results show a big decrease in quality (from 97 units to 38 units) and a significant increase of the relative Risk Costs to the magnitude of 69%. In this case, the model diverts remaining budget to perform activities dealing with certifying the

flight envelope (*j*=5) (an activity of significant importance) and thus eliminating verification methods for activities *j*=3,6,7. The program manager should try to obtain additional budget from customer or reflect the high Risk involved in this situation.
In Table 4, runs were performed with Time or Cost constraints (cases 13 and 14) and compared to the case with no constraints (case 12). In these cases too, we see applying Cost or Time constraints result in deleting of some VVT methods, in order to satisfy these constraints, and hence result in lesser Quality due to the fact that some activities remain untested and have a potential of bugs being detected at a later stage or during acceptance tests performed by customer. In the sample program, deleting verification methods for j=3 (Table 4, case 13) propose significant Risk and would be unacceptable. Sensitivity runs performed show that small budget cuts or Time constraints would cause a small change in Quality and vice versa. As stated above, the program manager needs to evaluate results outputted and determine if the suboptimal VVT methods could be considered acceptable and also consider different options in a similar manner as performed by results of Table 3.

4.3 Practical implications

Initially, this model could assist the program manager in making tradeoffs and in producing a structured estimation of budget, project duration, risk and resources required for performing VVT methods to a given project, as required in the Request for Proposal (RFP) process. Performing an accurate estimation of project resources (testing sites, labor, etc.) would be important for a company managing several projects for different customers. However, the model could also alleviate this necessity. To illustrate, if the same VVT plan is obtained with one set of estimations and with another that varies only in one parameter, we can say that the plan is not sensitive to that change. In contrast, if a small change in parameter changes the plan significantly, then we have detected a sensitive estimation that needs to be done more accurately. Additionally, this analytical model could also output the optimal VVT methods given Cost, Risk and Time constraints to suit unpredicted outcomes during the VVT process of a given project.

5 CONCLUSIONS

We presented an enhanced analytical model to assist the program manager structure the VVT decision making process. The model includes a recovery procedure to suit unforeseen events such as budget cuts, change or additional customer or engineering requirements, for finding the optimal VVT methods in the VVT process. Time constraint and project deadline related issues taking into consideration non availability of required resources to perform VVT activities and also sequential requirement for performing different VVT activities were also incorporated into the analytical model.
The results of this study conclude that the behavior or output of the analytical model is insensitive to the Risk or Quality assessment model used and the program manager could incorporate any other Risk or Quality model as well.
The enhanced model capabilities demonstrated by a sample program show promising results. The major difference in a real case would be a larger number of VVT activities. In our previous study we demonstrated such scaling to 40 VVT activities. We anticipate no major complexity in dealing with a real life problem. In order to provide initial support to this claim, we executed the approach on a real life problem with 38 activities and obtained equally good results. It is intended in future studies to validate this model further in a real test-case and compare the 'optimal' outcome with the normal outcome obtained by the program manager.

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