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Technical Note

Earned Value Management Agent-Based Simulation Model

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Abstract: Agile project management (APM) can be defined as an iterative approach that promotes satisfying customer requirements, adjusts to change, and develops a working product in rapidly changing environments. Managers usually apply agile management as the project management approach in projects requiring extraordinary speed and flexibility in their processes. Earned value management (EVM) is a fundamental part of project management to establish practical measures. Often, managers use a task board to visually represent the work on a project and the path to completion. Still, managing an agile project can be a challenging endeavor. In this paper, we propose an agent-based model describing the management of tasks within a project using earned value assessment and a task board. Our model illustrates how EVM yields an efficient method to measure a project's performance by comparing actual progress against planned activities, thus facilitating the formulation of more accurate predicted estimations. As proof of concept, we leverage our implementation to calculate EVM performance indexes according to a performance measurement baseline (PMB) in a task board fashion.

Keywords: agile development; earned value management; task board; agent-based simulation

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1. Introduction

Agile project management (APM) can be defined as an iterative approach that promotes satisfying customer requirements, adjusts to change, and develops a working product in rapidly changing environments [1]. Applying agile management as the project management approach requires extraordinary speed and flexibility in your processes and the formation of dedicated teams willing to adapt to changes, according to the Project Management Institute (PMI) [2]. Such a management approach is not only suitable for software development [3], but it has also been expanded to other environments, such as manufacturing, education, and health care, among others within the guide's scope [4].

In the manufacturing sector, there is much interest in understanding the determinants of effective agile project management to save time and energy in a context where customer requirements are broader, and new proposals for technological innovation are appearing [5,6]. For example, there is the proposal of a matrix that suggests agile practices based on the objectives and priority principles for complex project teams [5]. In addition, a scheme has been elaborated with the necessary actions to increase the probability of success in each of the phases of agile projects (planning, implementation, and closure) in a cycle of continuous improvement [6].

The earned value management (EVM) [7] is considered a fundamental part of the project management body of knowledge (PMBOK) [2] to establish practical measures. Over the last four decades, project management professionals have used this method to measure performance and assess the status of a project [8]. Still, managing an agile project can be a challenging endeavor. Often, managers use a task board to visually represent the work on a project and the path to completion. The route includes pending, in-progress, and completed tasks performed by teams. For example, the "Kanban" methodology uses a task board to distribute assignments and activities as a fundamental part of a production process [9].

Implementing agile project management can be a complex, time-demanding undertaking, taking into consideration that different mechanisms influence the project's performance. For example, cultural agency theory [10] proposes that operative play rules, individual traits, and cultural matters interact dynamically to produce emergent behaviors in the production system. From this theory, we could see EVM and a task board as the agency's operative system. Such an approach could be a critical step for a comprehensive understanding of the agile process rules and development. This allows a constant evaluation of the intermediate results and allows adjustments if the users and the interested parties want them. This way, the entire project team, including stakeholders, continuously improves the product. This methodology allows for immediate product modifications as previously unknown requirements are discovered [1].

Therefore, we propose an agent-based model describing the management of tasks within a project using a task board. The model's purpose is to illustrate how the participants in a project complete the tasks represented on the board. We consider the EVM approach to asses performance and control the work completion level compared to the set plan. In this study, we first explicitly identify the problem that motivated this work. Second, we describe the proposed model and briefly discuss the model's benefits and limitations. Finally, we provide a set of conclusions and identify needs for future work and developments.

2. Problem Statement

According to the PMI [2], project management is the application of knowledge, skills, tools, and techniques to project activities to achieve the expected results. Generally speaking, traditional project management has been oriented to projects whose phases were programmable, with predictable endings; tasks, times, and deadlines were clearly established and defined with technical prescriptions. That is, the tasks that make them up were explicitly defined during the project planning process [11].

However, changes in technology, business, economics, and stakeholder expectations imply that project management considers a static component (pre-plannable) and a dynamic component (unpredictable and not initially programmable). Considering this dichotomy, organizations require flexibility to adopt different methodologies and techniques in project execution [12].

In addition, project management involves carrying out a set of functions performed by groups that interact reciprocally and configure an organizational system that must be appropriately coordinated. For the PMI, stakeholders are people and organizations that actively participate and whose interests may be affected due to the project execution [2]. According to the methodology of stakeholders, there are four main processes in project management: planning, design, execution and control, and closure. This study focuses on the execution and control phase, where the promoters and executors participate most in developing the activities planned through the task board [13].

Using this conceptual framework, it is possible to evaluate the elements involved in the planning and development of organizational projects with the help of models. Therefore, we propose developing an agent-based model to explore different scenarios that seek to manage the increasing complexity of the systems to be designed and implemented as an alternative solution to specific problems in project management. The EVM technique is used to compute the performance and control the level of work achieved compared to the plan [14], addressing the following questions: How do employee conditions affect the performance of an agile project? Do the number of employees and the number of tasks each simultaneously affect cost performance? Does the likelihood of employees performing their tasks faster or slower cause convenient advances or inconvenient delays affecting cost performance? Under what circumstances do projects become so unpredictable that they could be considered complex?

3. Methodology

Social simulation has been gaining ground in the social sciences as a way of approaching the complexity of social systems. Computational social science has now incorporated data science into its arsenal of techniques but has also included alternative methods, such as agent-based modeling, from the outset. Agent-based modeling (ABM) is a method of computational modeling and simulation to study complex systems' organization and dynamics.

We consider that project management is complex for several reasons: first, because it is a process where humans make decisions (not as rational as one would expect); second, because there are structural constraints that condition their behavior; and finally, because social processes affect the culture of organizations. Consequently, we regard earned value management as a model that reduces the issue's complexity to create the illusion of simplicity due to focusing on optimizing performance and costs.

We based the methodology's sequence on the well-known social simulation approach in which the procedure selected and represented real-life targets in a simplified way through a model executed and outputs data [15]. In this work, we use an agent-based system to approach the EVM agency as an operating system (structure and imperatives for decisions, operative intentions, etc.) and simulate hypothetical scenarios from an exploratory and illustrative point of interest in cultural agency theory [10].

3.1. Modeling and Simulation Method

The following is a brief description of the adopted modeling and simulation easyABMS methodology [16]. In this process, all steps can go back to the previous step, so the analyst and modeler can generate multiple approaches til the objective. We finalize with results analysis, as seen in Figure 1.

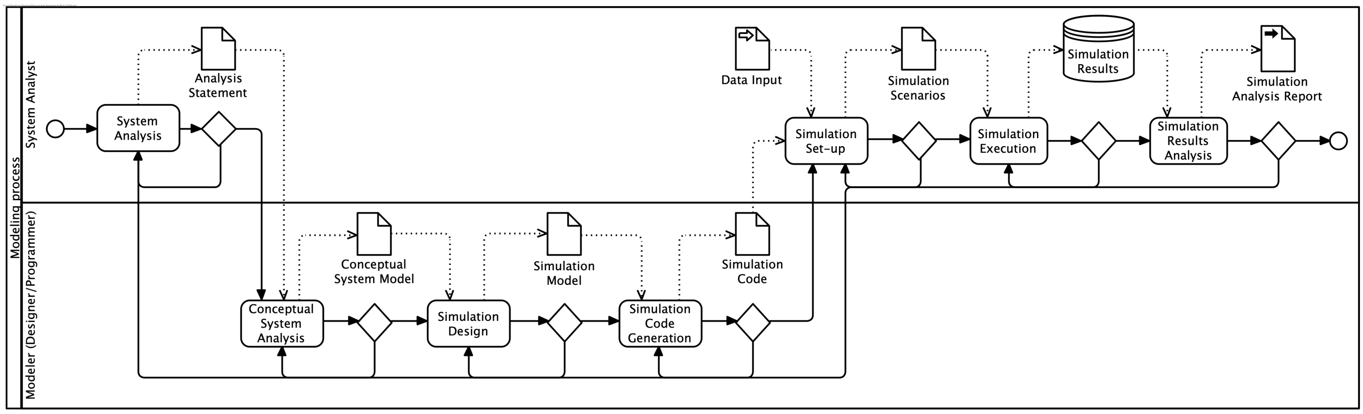


Figure 1. The adopted modeling and simulation process based on easyABMS methodology [16].

- System analysis. In this activity, we establish the aim of the model based on the research questions. The result is an analysis statement. In our case, it is a narrative document based on the ODD protocol that defines the purpose and details of the model we built.

- Conceptual modeling of the system. In this activity, we analyze the problem domain's language to make a first approximation. The result is a conceptual system model. We use the Unified Modeling Language (UML) to represent the abstractions produced in the analysis of the problem language.
- Simulation design. In this activity, we design the simulation. The result is a simulation model based on a specific framework or tool. We use the Netlogo tool as the technological basis for the design.
- Simulation Code Generation. In this activity, we write a computer executable code that implements the designed model in the selected tool. The result is a simulation code. The generated code is written in Logo for Netlogo and implements the simulator design.
- Simulation Setup. In this activity, we configure the experiment in the simulator. Using input data, we specify simulation scenarios. We used Netlogo's BehaviorSpace tool to experiment with a dataset based on a typical software project management template with 61 core tasks and a max of seven employees. This experimentation consisted of 2100 runs resulting from the combination of input variables and their possible valid values.
- Simulation execution. In this activity, we ran the experiment within the pre-set parameters. We obtained simulation results. The data obtained are the product of each "tick" (the discrete-time in Netlogo) and the states of all the input variables, agents, and earned value management metrics produced in each of the 2100 runs. The resulting data give us system state information in the entire parameter space.
- Simulation Results Analysis. In this activity, we analyze the results to contribute to the clarification of the proposed research questions. We use the resulting data to generate a simulation analysis report. We performed the following: (a) a t-Student test to compare dissimilarities in the results of simple scenario simulations between our prototype and tools suggested by PMI to analyze the EVM in hypothetical projects; (b) a sensitivity assessment to support the interpretation; (c) an explanation of simulation model outcomes and an active nonlinear test to examine the necessary considerations in the simulation structure and thereby begin to approach complexity.

3.2. Model Description

To formalize the proposed model, we followed the "S1: ODD Guidance and Checklists," proposed in [17], which provides guidance and checklists for writing "Overview, Design Concepts, Details" protocol (ODD) descriptions of agent-based or other simulation models. It is based on the ODD version published in earlier versions [18,19].

3.3. Model Validation

To validate the proposed model, firstly, we compared the results of simple scenario simulations between our prototype and tools suggested by PMI to analyze the EVM in hypothetical projects. For example, The Earned Value Management Calculator [20] or EVM Worksheet Package [21] could help compare results. Further, we applied a sensitivity assessment to support the interpretation and explanation of simulation model outcomes. Finally, we executed nonlinear active tests (ANTs) [22] to examine the necessary considerations in the simulation structure and thereby begin to approach complexity.

4. Results

Earned value management is founded on a set of metrics focused on evaluating the progress of a project from a cost and schedule standpoint. Figure A2 in the Appendix A.3.3 shows graphically how a project can be evaluated in execution time and how these metrics characterize its development. The cost performance index (CPI) and schedule performance index (SPI) metrics measure project performance. For example, the cost performance index (CPI) depends on comparing whether the actual cost (AC) corresponds to the estimated cost (EC). The earned value (EV) metric measures whether the project has economic gains or losses. The model shows the behavior of these metrics during an artificial execution of a project (either using data obtained from a data file or artificially generated). We describe full EVM metrics in Table A4 in Appendix A.3.3.

The concept of EVM is introduced in the model, which is simulated through a spatial model of agents developed in the Netlogo programming environment [23]. A complete, detailed model description, following the ODD [17–19], is provided in Appendix A.

4.1. Netlogo Prototype

As a result of the agent-oriented analysis and design process, we produced an agent-oriented model in NetLogo based on our core code [24]. Figure 2 shows an EVM model NetLogo prototype screenshot. The NetLogo prototype used in this paper is available in [25] and can be downloaded directly from the repository online.

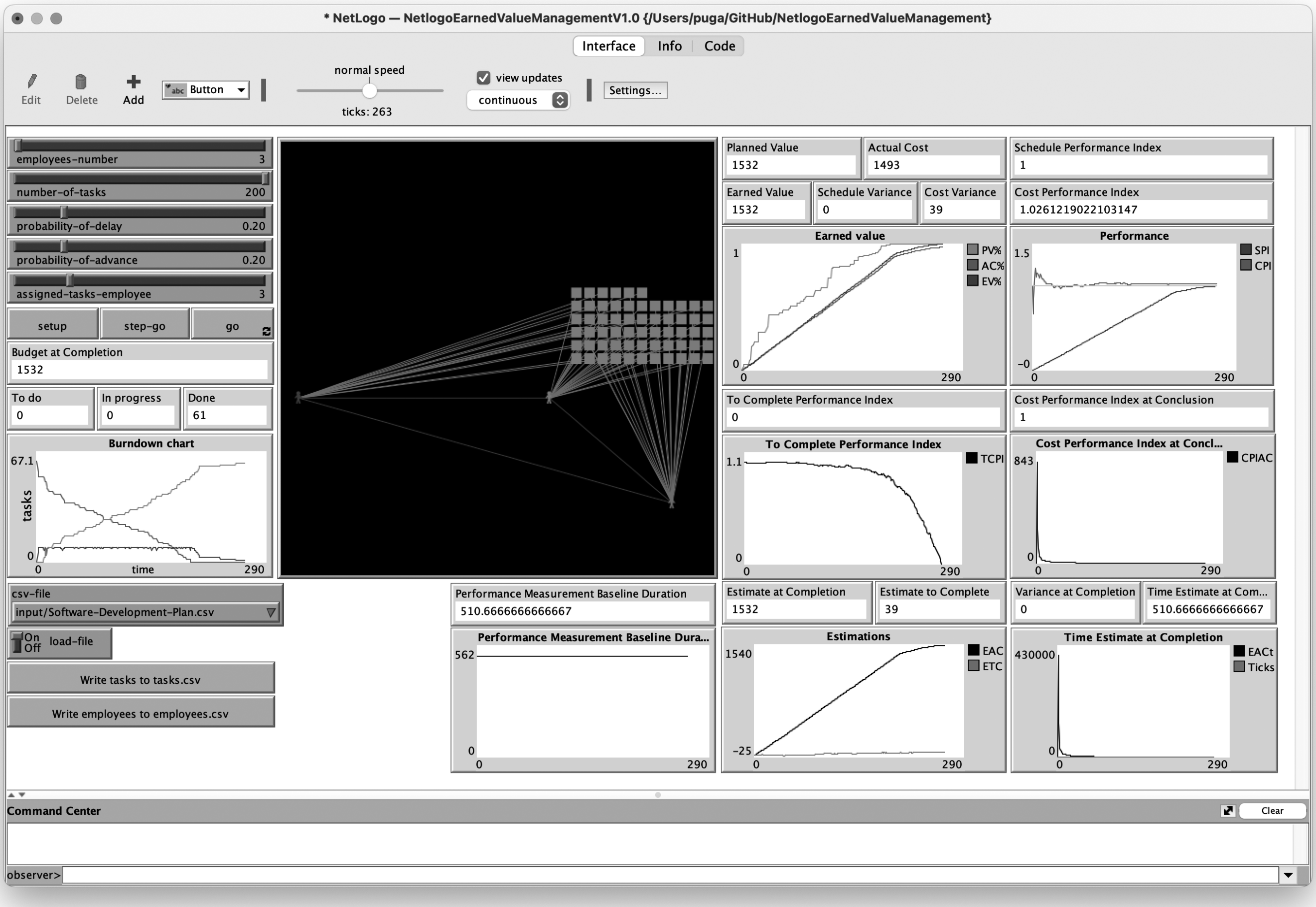
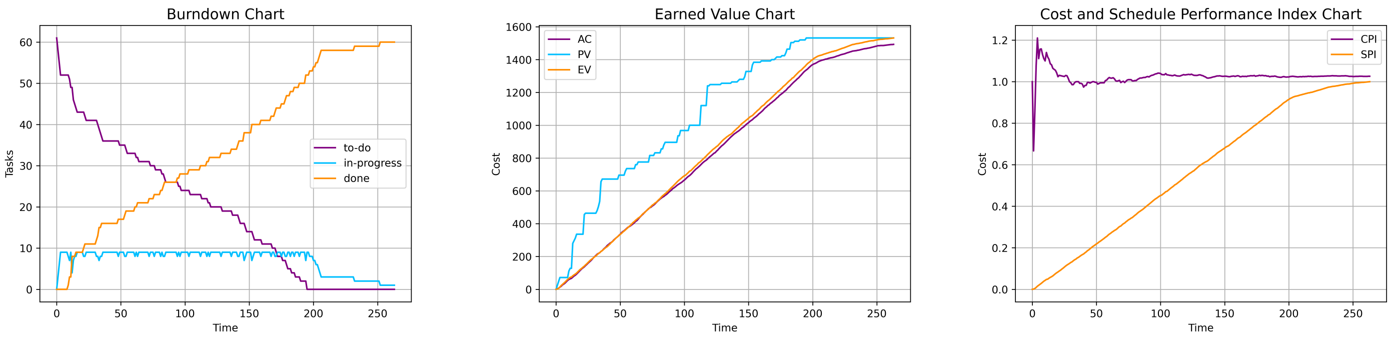


Figure 2. Earned value management (EVM) model in NetLogo.

First, the EVM model illustrates a set of tasks (backlog) in a task board (a Kanban task board style) at the top of the visual area of the simulator. The board has three columns, where each column denotes the status of the task: "To-do," "In progress," and "Done" tags. Then, we represent employees in the workspace at the bottom of the visual simulation area. A graphic link connects employees with assigned tasks. They take assignments from the "To-do" column to process the jobs ("In progress" cue) and transfer the finished task mark to the "Done" column. Finally, on the left are input controls to initialize different simulation scenarios, and on the right are additional output controls. The outputs show the results of the EVM in a dynamic way that reacts to the simulation process in real-time.

We designed the interface so the user can see how the variables behave in the form of a dashboard while the model simulates the initially configured scenario. Although the interface can display these inputs and outputs, the Netlogo tool can export a log file for better results processing. For example, Figure 3 plots the most significant inputs and outputs for EVM. These are the reproduction of the "Burndown," "Earned Value," and "Performance" charts shown in Figure 2 from a log file.



(**a**) The burndown chart. (**b**) The earned value chart. (**c**) The performance chart

Figure 3. The plots are the most significant inputs and outputs for EVM. (**a**) The burndown chart, where tasks go through the to-do, in-progress, and done states during project execution. (**b**) The earned value chart compares the planned and actual costs. (**c**) The CPI and SPI chart depicts performance.

In Figure 3a, we show the burndown chart where tasks go through the to-do, in-progress, and done states during project execution. The prototype interface provides this standard visualization of task execution. In Figure 3b, we show the earned value chart that we used to compare the planned and actual costs. The prototype interface also offers this standard visualization of EVM. In Figure 3c, we show The CPI and SPI chart to depict performance. The interface shows the visualization of these metrics too. In this case, we are interested in showing the behavior of the CPI for the scope of this paper.

4.2. Model Validation

To validate the model, we tested with 2100 simulations. We established a fixed set of input tasks based on a typical planning template for a software development project. The template supplied 61 tasks with estimated costs and team members. Based on the information from this simple case study, we adjusted the values of the input variables in suitable ranges to calculate a proper sample of tests. This configuration helped us to observe the behavior of the cost performance index (CPI) and the project's final cost under different conditions. Table 1 shows the input variables of the experiment and their value ranges.

Table 1. Validation settings. (See the Table A3 in the Appendix A to set up the variables description.)

Variable/Metric	Type	Values Range
number-of-tasks	input	61
employees-number	input	1–7
probability-of-delay	input	0.0–0.9
probability-of-advance	input	0.0–0.9
assigned-tasks-employee	input	1–3
step	output	1–n
CPI	output	0–n

The experiment produced much information, but the most relevant is the final state of the variables at the end of each simulation. We obtained a total of 2100 final results. Table 2 shows the statistical description of the data obtained during this process.

Firstly, we used the EVM Calculator ("EVM Calculator V2" MS Excel file), downloadable from the PMI website, to calculate the performance indexes and other EVM metrics using the same simulated data scenarios [6]. Appendix A.3.3 of Appendix A describes the EVM main variables and performance and estimations formulas. We planned an exploratory experiment focused on planned value, actual cost, and earned value, and the scheduled performance index (SPI) and cost performance index (CPI) EVM metrics to compare similarities. Table 2 shows a t-Student test result. Practically, the results are very identical.

Table 2. CPI t-Test: Two-Sample Assuming Unequal Variances.

	CPI-Netlogo Sample	CPI-EVM Calculator Tool Sample
Mean	2.75497723	2.754977232
Variance	14.5634324	14.56343242
Observations	2100	2100
Hypothesized mean difference	0	
df	160	
t stat	0	
P(T <= t) one-tail	0.5	
t critical one-tail	1.6544329	
P(T <= t) two-tail	1	
t critical two-tail	1.97490156	

Subsequently, we performed a sensitivity analysis to understand how the outputs change over the full range of possible inputs. We show the basic statistic dataset description in Table A5 in Appendix B, and we define the requirements verification in Table A6. In Table A7, we observe that 85% of "CPI" cases are within the range of 0.0961164439425309 to 3.5 (about 1880 of the 2100 tests).

In Figure 4, we depict the result of a detailed sensitivity analysis. We display a range of possible output values associated with each set of inputs. In our case, we analyze the possible combinations between the number of employees, the number of tasks each worker could perform simultaneously, the possibility of advancing the work, and the possibility of being delayed.

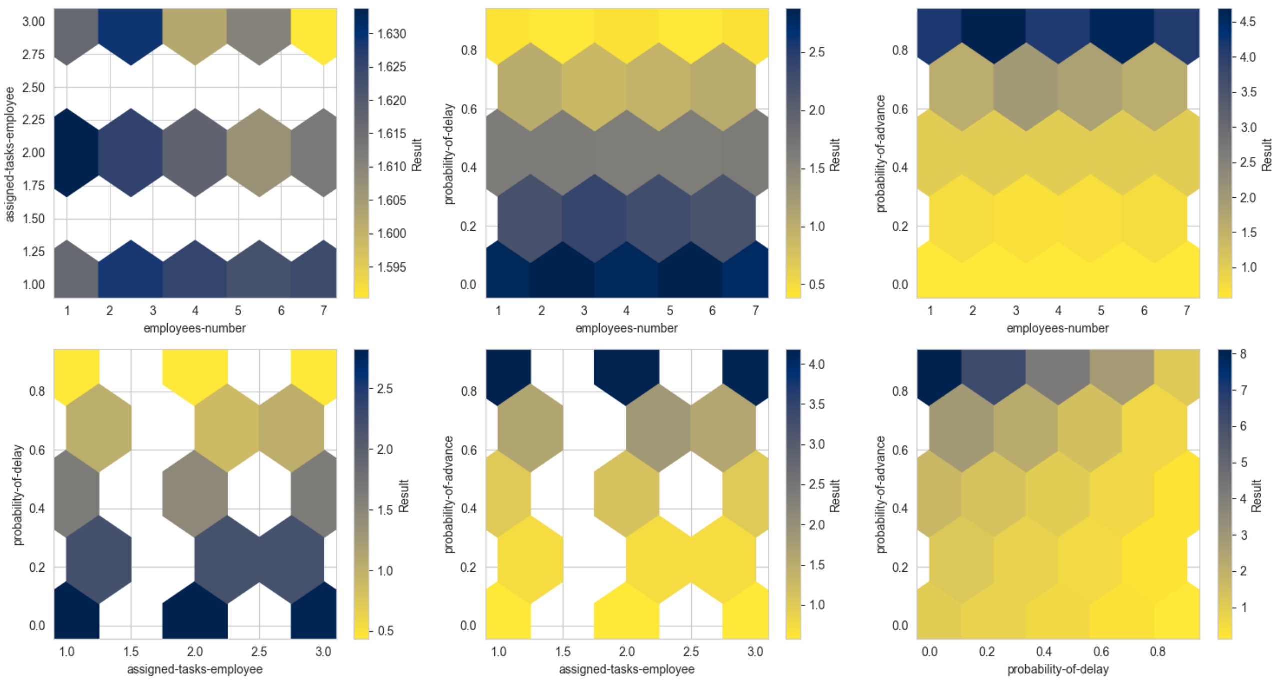


Figure 4. CPI sensitivity analysis results. The output plots.

Table 3 shows the results of the sensitivity analysis of the CPI concerning the number of employees and the tasks assigned to the employee. It shows that the number of employees and the number of tasks do not impact the cost performance index (CPI). The table shows high values in all cases without much variation.

Table 3. CPI sensitivity analysis results. The employees' number versus the assigned tasks to an employee. The darker color in the table means a higher CPI value.

Assigned-Tasks-Employee Employees-Number	1	2	3
1	1.616634	1.633812	1.616834
2	1.633606	1.614470	1.628857
3	1.623663	1.637134	1.629288
4	1.625330	1.617751	1.602271
5	1.628319	1.573290	1.607234
6	1.616457	1.640380	1.613923
7	1.624135	1.612656	1.590358

Table 4 shows the results of the sensitivity analysis of the CPI concerning the number of employees and the probability of advancing. It shows that the number of employees and the advancement also affect the cost performance index (CPI). The table shows high CPI values when the probability is high and low values when the probability is low but does not vary much with the number of employees involved.

Table 4. CPI sensitivity analysis results. The employees' number versus the probability of advance. The darker color in the table means a higher CPI value.

Probability-of-Advance Employees-Number	0.000000	0.100000	0.200000	0.300000	0.400000	0.500000	0.600000	0.700000	0.800000	0.900000
1	0.548008	0.609541	0.685730	0.783219	0.915103	1.106740	1.377564	1.846275	2.740608	5.611477
2	0.550267	0.607176	0.685457	0.787587	0.913403	1.104403	1.372748	1.817562	2.782771	5.635066
3	0.550096	0.612313	0.685667	0.787730	0.910915	1.101636	1.378627	1.841838	2.756855	5.674607
4	0.551275	0.609906	0.689134	0.788121	0.916298	1.103034	1.365377	1.839154	2.807393	5.481482
5	0.549912	0.610428	0.685860	0.779776	0.913223	1.111374	1.368596	1.828576	2.770266	5.411466
6	0.550164	0.610680	0.686776	0.785780	0.921015	1.104609	1.365208	1.859988	2.772758	5.578888
7	0.548133	0.611021	0.686966	0.785835	0.923714	1.109246	1.376516	1.819473	2.795025	5.434565

Table 5 shows the results of the sensitivity analysis of the CPI concerning the number of employees and the probability of delay. It shows that the number of employees and the delay also affect the cost performance index (CPI). The table shows high CPI values when the probability is low and low values when the probability is high but does not vary much with the number of employees involved.

Table 5. CPI sensitivity analysis results. The employees' number versus the probability of delay in task execution. The darker color in the table means a higher CPI value.

Probability-of-Delay Employees-Number	0.000000	0.100000	0.200000	0.300000	0.400000	0.500000	0.600000	0.700000	0.800000	0.900000
1	2.923209	2.697309	2.356683	2.081919	1.788999	1.462714	1.165987	0.881181	0.575454	0.290812
2	2.986358	2.658718	2.394938	2.021872	1.749269	1.494834	1.172753	0.885583	0.597050	0.295065
3	2.993954	2.679616	2.397810	2.044512	1.760310	1.498649	1.168188	0.878099	0.584551	0.294594
4	2.953739	2.633249	2.347091	2.043536	1.743552	1.478904	1.176356	0.892230	0.587110	0.295405
5	2.950445	2.638388	2.290606	2.013881	1.761984	1.465932	1.158620	0.873110	0.583534	0.292974
6	3.003698	2.675100	2.340356	2.055888	1.762180	1.451223	1.187985	0.892449	0.576981	0.290005
7	2.896081	2.611585	2.321156	2.056459	1.793138	1.491311	1.171935	0.872740	0.581986	0.294104

Table 6 shows the results of the sensitivity analysis of the CPI concerning the number of tasks assigned to an employee simultaneously and the probability of performing tasks quickly. It shows that the number of tasks and the progress also affect the cost performance index (CPI). The table shows high CPI values when the probability is high and low values when the probability is low but does not vary much with the number of tasks involved.

Table 6. CPI sensitivity analysis results. The assigned tasks to employees versus the probability of advance in task execution. The darker color in the table means a higher CPI value.

Probability-of-Advance Assigned-Tasks-Employee	**0.000000**	**0.100000**	**0.200000**	**0.300000**	**0.400000**	**0.500000**	**0.600000**	**0.700000**	**0.800000**	**0.900000**
1	0.550079	0.610386	0.686651	0.785175	0.915242	1.107459	1.374933	1.840992	2.750297	5.618992
2	0.549219	0.610502	0.688131	0.786606	0.916836	1.103004	1.370400	1.834234	2.794441	5.531616
3	0.549782	0.609569	0.684757	0.784525	0.916638	1.107127	1.370940	1.833146	2.780553	5.489771

Table 7 shows the results of the sensitivity analysis of the CPI concerning the number of tasks assigned to an employee simultaneously and the probability of being late in performing the tasks. It shows that the number of tasks and the delay also affect the cost performance index (CPI). The table shows low CPI values when the probability is high and high values when the probability is low but does not vary much with the number of tasks involved.

Table 7. CPI sensitivity analysis results. The assigned tasks to employees versus the probability of delay in task execution. The darker color in the table means a higher CPI value.

Probability-of-Delay Assigned-Tasks-Employee	**0.000000**	**0.100000**	**0.200000**	**0.300000**	**0.400000**	**0.500000**	**0.600000**	**0.700000**	**0.800000**	**0.900000**
1	2.978426	2.663062	2.362711	2.046665	1.772522	1.479867	1.173713	0.888923	0.580200	0.294114
2	2.988602	2.658812	2.314510	2.069138	1.740356	1.477683	1.173824	0.882516	0.585297	0.294250
3	2.907608	2.646968	2.372195	2.020511	1.784022	1.475407	1.167531	0.875158	0.585931	0.291476

Table 8 shows the results of the sensitivity analysis of the CPI concerning the probability of being ahead of schedule and the probability of being late in performing the tasks. It shows that overtaking and delay affect the cost performance index (CPI). The table shows that, when the probability of advancing is high and the probability of delay is low, then performance increases. Conversely, when the probability of advance is low and the probability of delay is high, then performance drops. There is a strong relationship between these two input variables and the output variable CPI.

Table 8. CPI sensitivity analysis results. The probability of delay versus the probability of advance in task execution. The darker color in the table means a higher CPI value.

Probability-of-Advance Probability-of-Delay	**0.000000**	**0.100000**	**0.200000**	**0.300000**	**0.400000**	**0.500000**	**0.600000**	**0.700000**	**0.800000**	**0.900000**
0.000000	1.000000	1.108873	1.250670	1.424626	1.662969	2.030450	2.467776	3.331564	5.110659	10.194536
0.100000	0.901227	0.991782	1.126371	1.282113	1.493521	1.806010	2.257168	3.012464	4.621043	9.071108
0.200000	0.801303	0.891224	0.996478	1.148412	1.339701	1.606832	1.991850	2.699662	4.007647	8.014947
0.300000	0.697102	0.779057	0.873445	0.999431	1.166258	1.405789	1.750664	2.314024	3.465186	7.003424
0.400000	0.602836	0.666494	0.746477	0.857062	1.000851	1.202470	1.490557	1.995534	3.001171	6.092882
0.500000	0.497076	0.552568	0.622811	0.714094	0.830579	1.004919	1.256750	1.665710	2.559082	5.072936
0.600000	0.397853	0.445080	0.499436	0.571599	0.666491	0.806707	1.009625	1.332263	1.995027	3.992812
0.700000	0.301044	0.331156	0.373308	0.426633	0.499541	0.596892	0.754331	1.003200	1.497278	3.038604
0.800000	0.198708	0.224264	0.250335	0.287390	0.335720	0.399535	0.495143	0.672126	0.993766	1.981109
0.900000	0.099786	0.111024	0.125797	0.142994	0.166754	0.199028	0.247045	0.334692	0.500109	1.005570

Finally, we tested the model's structure and robustness using the nonlinear search algorithm, designed to break the model's implications actively (active nonlinear tests

(ANTs) [22]). BehaviorSearch is a software tool (included in the latest Netlogo versions) to help automate the exploration of agent-based models (ABMs) by using genetic algorithms and other heuristic techniques to search the parameter space [26].

We aim to explore the necessary reflections in the simulation structure and thereby begin to approach complexity. So, we configure the tool and search in the CPI parameter space to identify the max fitness of employees-number, assigned-tasks-employee, probability-of-delay, and probability-of-advance combinations using the 2100 tests' results dataset (we want to maximize the CPI-related space parameters that influence the project performance). In the same way, to compare, we configure the tool and search in the "step" parameter space to identify the min fitness of employees-number, assigned-tasks-employee, probability-of-delay, and probability-of-advance combinations (we want to minimize the "step"-related space parameters that influence the project duration). Table 9 shows an assortment of fitnesses in the search parameter space related to "CPI" in comparison with Table 10, which shows a similar fitness in the search parameter space related to "step" (project duration).

Table 9. "CPI" active nonlinear tests final bests fitness.

Search-Number	Evaluation	Employees-Number	Assigned-Tasks-Employee	Probability-of-Delay	Probability-of-Advance	Num-Replicates	Best-Fitness-so-Far
1	500	6	2	0.2	0.9	10	8.125806944
2	500	5	1	0.2	0.9	10	7.92122959
3	500	3	1	0	0.6	10	2.571417207
4	500	3	2	0	0.9	10	10.18728451
5	500	4	1	0	0.9	10	10.35474418
6	500	1	3	0.4	0.9	10	5.902861442
7	500	1	2	0	0.8	10	5.015753468
8	500	7	3	0.3	0.9	10	6.719011184
9	500	5	3	0	0.9	10	10.22730573
10	500	3	1	0.3	0.9	10	6.764397903

Table 10. "step" active nonlinear tests final bests fitness.

Search-Number	Evaluation	Employees-Number	Assigned-Tasks-Employee	Probability-of-Delay	Probability-of-Advance	Num-Replicates	Best-Fitness-so-Far
1	500	7	2	0	0.7	10	163
2	500	6	2	0.2	0.1	10	223.6
3	500	4	3	0	0.9	10	180
4	500	5	2	0	0.6	10	198
5	500	7	3	0	0.1	10	146
6	500	6	3	0	0.2	10	155
7	500	6	3	0	0.3	10	155
8	500	5	3	0	0.1	10	163
9	500	6	2	0.1	0.7	10	197.5
10	490	6	3	0	0.5	10	155

The model could describe the project duration linearly, but the CPI shows uncertain behavior. In the case of the search parameter space related to "CPI," the model is very predictable when the probability of delay and advance is close to 0. However, when close to 1, the sequence and time of execution could vary away from the estimation. We consider complexity to hide behind the tasks executed by agents that express a probability of delay or advance in an active project. In other words, the project execution could leave us in a different final stage, starting from the same initial project parameter values that are a feature of complex systems behavior.

5. Discussion

The objective of this research was to create an agent-based model that allows the exploration of different explanation alternatives to specific problems in agile project management through earned value management. Therefore, we presented a model of EVM where employees work on a task backlog in a characteristic project execution process to approach the agile development process. The to-do jobs are visually represented in a typical task board to show how the task path to completion happens. At this level of representation, the results show that the model behaves as expected: the model simulates the employees attending tasks, and the EVM metrics show the assessment.

Further to this first approach, studies related to the dynamism of project management, which seek to explain behavior and results using the fundamentals of complexity theory, are becoming more frequent [27,28]. In this context, project management gains importance among the complex sciences by studying the relevant variables involved [27,28]. Regarding the multidisciplinary character of project management, research in innovation and technology management that considers the different theoretical frameworks is perhaps the most influential emerging discipline [29,30].

So, to overcome the limitations of traditional project management, the cultural agency theory would allow the representation of the internal and external factors involved during the development of stakeholder scenarios [31]. This theory's holistic perspective considers the cultural, personality, and operational systems. In a business context, the cultural system integrates values and beliefs (knowledge management and market orientation); the personality system considers cognitive capabilities (goals, ideology, self-schema); and the operating system integrates structural components (operational performance and self-organization) [10].

Therefore, we could go beyond a simple system design where the EVM performance result could hide the causes linearly [32]. So, we could represent the EVM as an operational subsystem according to Yolles's cultural agency theory [33–35] in a complex system context. From this point of view, the EVM agency could establish the gameplay rules for the other agents in the system that constrains or motivates their behavior. Within these conditions, other stakeholder agents should negotiate and develop agreements to self-organize and accomplish their goals.

How do the agents' conditions affect the design of complex production systems? As a result of our experience modeling EVM and operating different scenario simulations, we observed that EVM, as an agency in a complex production system, concerns the operative game rules where other agencies should persist. In this circumstance, the play rules determine the other agents' behavior (for example, employees), execute assigned jobs, and earn value for the project following the production constraint. So, different initial conditions pre-determine the whole system's behavior; thus, making real-time corrections would help the project to succeed.

Beyond this embryonic project management representation, we consider that there are several advantages to using this prototype for more elaborated modeling:

1. We provide a simulation tool to explore the relationship between task planned and performance conditions and the effect in the EVM metrics observations. Additionally, the model shows a typical task board tool to visualize the job backlog processing as most managers used to. This experimentation could help EVM learners and managers explore scenarios to understand how the metrics perform in different conditions.
2. The model is inspired by agency theory, specifically by Yolles's cultural agency theory. Under this theoretical perspective, the model could have sense in the rationale of complexity. As the theory proposed, we can consider new features to add individual behavior and cultural factors.
3. We defined the model according to the ODD protocol. The ODD is a protocol recommended by the social simulation scientific community to overview the model and describe design concepts and implementation details to communicate agent-based models.
4. We programmed an agent-based model in a freely available tool. Netlogo is friendly for unskilled programmers and easily adaptable for new purposes.
5. The PMI considers the EVM a standard in project management.

However, we consider that the most significant weaknesses of this proposed model are as follows:

1. The tool has limitations to building high-performance simulations.
2. The implicit systematic EVM limitations to assess other aspects of agile development management.

3. It is limited to the execution and control processes of the tasks where the promoting and executing agents have direct participation.

Nevertheless, the current proposed model may only be able to answer some of the questions it could raise, and future expansion of the model could prove helpful.

6. Conclusions

The proposed model is a valuable tool for quantifying the operating system in project management. In particular, it makes it possible to quantify earned value management. Future research could propose a model that considers the sequentially of tasks, the organization of these tasks in work subteams, and the inclusion of the underlying systems of the cultural agency theory: the cultural system and the personality system [10]. In the cultural system, variables could be included at the organizational level (practices, corporate policies, and managerial leadership), and in the personality system, variables at the team level would be included (skills, coordination, cooperation, communication, cognition, leadership, and internal conditions) [36].

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Actual Cost
ABM	Agent-Based Model
CPI	Cost Performance Index
EV	Earned Value
EVM	Earned Value Management
ODD	"Overview, Design Concepts, Details" protocol
PV	Planned Value
PM	Project Management
PMB	Performance Measurement Baseline
PMBOOK	Project Management Body of Knowledge
PMI	Project Management Institute
SPI	Scheduled Performance Index
WBS	Work Breakdown Structure

Appendix A. The Earned Value Management Model

In this appendix, we described the earned value management [7] model according to the ODD [17–19]. We followed "S1: ODD Guidance and Checklists" for guidance and checklists for writing ODD descriptions of simulation models, based on the ODD version published in [17].

Appendix A.1. Overview

Appendix A.1.1. Purpose and Patterns

This model illustrates how EVM provides an approach to measure a project's performance. Our model's instance performs a project execution and calculates the EVM performance indexes according to a performance measurement baseline (PMB), as detailed below.

Appendix A.1.2. Entities, State Variables, and Scales

Entities

We include the following entities in the model: agents representing employees (i.e., developers, architects, stakeholders, etc.), tasks, and the global environment representing the workspace (i.e., physical or virtual spaces).

The following entities are included in the model:

1. The employee-agent, representing the developers (i.e., team leaders, team members, architects, and stakeholders);
2. The task-agent, representing the tasks (i.e., the work breakdown structure and tasks);
3. The employee-task-link, representing the employee-task assignations (i.e., the tasks backlog);
4. The global environment, representing the task board and the workspace (i.e., the Kan-ban board).

State Variables

An *observer* is an individual that commands global variables and submodels. Therefore, *observer* state variables are global variables that may alter over time. In Table A1 we show the entities' state variables.

Table A1. Entities' state variables

Entity	Variable Name	Variable Type	Meaning
Task	status	Integer	The task status
	task-number	Integer	The task number
	task-description	String	The task description
	priority	Integer	The task priority
	planned-start	String	A planned task start date
	planned-finish	String	A planned task finish date
	planned-hours	Integer	Planned task execution hours
	complete-hours	Integer	Complete task execution planned hours
	actual-hours	Integer	Real/actual task execution hours
Employee	employee-number	Integer	The employee ID number
	status	Integer	The employee status
	role	String	The employee role

Scales

Our model's temporal scale is set as hours because for project duration we often counted working hours. So, a tick in this agent-based model (ABM) means an hour. We set up the simulation time as long as the work breakdown structure (WBS) requires because the term of most projects is different, and simulating according to the backlog retrieved from the WBS can adequately contain the usual operations of a short project-based organization.

In Table A2, we show the environmental scales.

Table A2. Scales.

Scale	Values	Meaning
Grid	16 × 32	The task board and color tags.
Grid	16 × 32	The workspace and employees.
Ticks	0–n	The working hours

Appendix A.1.3. Process Overview and Scheduling

First, we create a random task backlog according to the maximum number of jobs specified in the initial configuration. We also indicate how many workers will form the work team. Finally, we indicate how many tasks we will delay and how many will be advanced.

The workers then process the tasks. First, each worker chooses tasks from the backlog and moves the task to the in-progress column. Tasks can last in this state depending on the time specified in each task. We could delay some tasks or complete them early. Eventually, the tasks are tagged again with a done mark when the employee entirely performs them.

We continue processing the tasks in a loop until all jobs in the backlog have passed the done state on the board.

Figure A1 shows the process of executing the tasks.

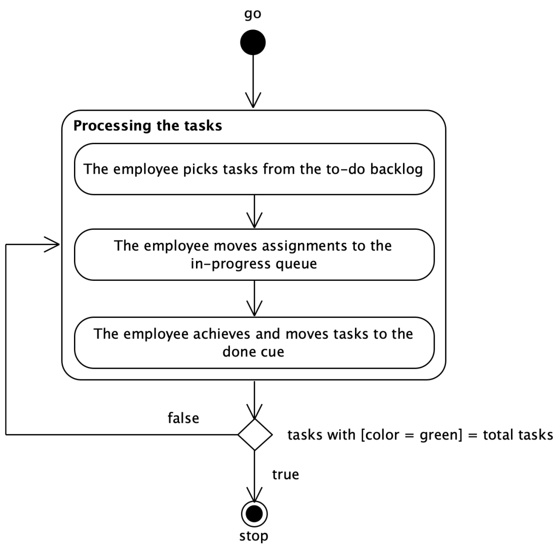

Figure A1. The employee processing the chosen tasks.

Each tick represents a unit of time in the schedule. Each task has an estimated time to complete and a real completed time.

In this model, tasks have no predecessors, and the hourly cost is the tick cost. So, the project's total cost is equal to the total sum of the planned hours of the tasks or the total sum of ticks.

Appendix A.2. Design Concepts

Appendix A.2.1. Basic Principles

This model addresses a classic problem of project management (PM). This problem involves the risk of delay in execution and cost and schedule estimation failure. There is an extensive literature on earned value management to handle project behavior, mainly founded on cost levels and performance metrics. Our model executes a task board with workers assigned to complete a task backlog, where workers may delay or advance task execution. We calculate performance using the *earned value management* approach, basing our model design on five fundamental ideas:

- A task backlog: a task backlog (to-do column) requires individuals to complete it.
- A task board: task states are portrayed on a task board to visualize the project's advancement.
- Players: players must take as many tasks as permitted from the "to-do" queue and deliver them to the "done" cue in the panel. While a player is working on an assignment, he must keep the assignment tag in the "in-progress" column.
- A cost and schedule: the task has a planned cost in hours and start–finish time, but the worker could delay or advance in completing the job, or environmental situations could increase and decrease the final cost.
- Performance metrics: the earned value management metrics estimate the project performance.

Appendix A.2.2. Emergence

The key outcomes of the model are earned value management impacts—mainly how suitable the entire system is; these outcomes emerge from how the task executions respond to delays and advance probabilities in tasks, backlog size, players number, and tasks assigned per person.

Appendix A.2.3. Adaptation

The project management behavior of employee agents is to re-estimate the task cost or schedule: the employee characterizes the decision to reduce or increase the actual hours (actual cost) in contrast with planned hours (planned cost) by the probability of affecting each task. Each decision (conscious or unconscious, rational or emotional) directly impacts the project performance (cost or schedule performance).

Appendix A.2.4. Objectives

The objective measure used by project managers to decide whether to take course-correcting action on a project is the cost–schedule performance ratio. Workers reduce their chances of failing to perform or estimate a task if they are motivated. However, the project manager can take analytical actions, such as increasing the number of workers, the number of assignments per person, etc. The project course will immediately reflect any manager's activity on the fly in the earned value management metrics observation.

Appendix A.2.5. Prediction

The project managers can observe project course predictions by cost and schedule to finish estimations beyond the cost–schedule performance ratio. For example, earned value management metrics figure the cost performance index at conclusion (CPIAC) or time estimate at completion (EACt) to help managers to have a future idea about the project.

Appendix A.2.6. Stochasticity

We used stochasticity in two ways. First, we initialize the model stochastically to establish the planned cost and duration task randomly. These initialization methods are stochastic so that the model can be assumed unsegregated at the start of a simulation and that each model run produces different results. Second, when an employee decides to delay or advance in task execution, its choice of the new cost or duration is stochastic. The latest actual cost of finish when the employee performs is stochastic because modeling the details of the decision is unnecessary for this model.

Appendix A.2.7. Collectives

Our model encompass two types of collective groups of tasks that affect the employees and are likewise powerfully affected by the individuals. Such groups are represented as model entities, with state variables and behaviors. These task and employee group entities have their state variables defined above at entities, state variables, and scales, naturally. Our model includes these groups due to employees having several cooperative behaviors, making decisions critical to the project's performance that depend on their collective choices. Tasks may clearly have diverse connections, establishing key constraints to the project's performance. We have found that it is much easier to model cooperative behavior and linkage conditions as *collective entity behaviors* than *individual entity behaviors*.

Appendix A.2.8. Observation

The model aims to study how potential management alternatives affect project behavior. One measure of simulated project management is the probability of failure within certain conditions. We can estimate this probability of failure as the fraction of replicate simulations in which employees never completed some task at the end. Arbitrary observation decisions are how many tasks or workers or how long are the delays that we execute. Here, we estimate the project performance as the fraction of 100 replicate simulations with a probability of high cost and schedule delays so high that the performance index is so low that the project never ends.

Appendix A.3. Details

Appendix A.3.1. Initialization

We initialize the state variable of each individual (planned-hours, probability-of-delay, probability-of-advance, etc.) from probability distributions that describe its variability. We randomly select the estimated scheduled hours from the following set of possible values: 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, and 233. The values match the first ten numbers in the series of Fibonacci, which mimics an agile Fibonacci estimation (AFE) method. AFE refers to a way of quantifying the effort needed to complete a development task.

Appendix A.3.2. Input Data

In this model, we do not use input data files from external sources by default (tasks and assignments to employees). Instead, we generate observer-predetermined task sets with random estimates for each simulation. But the model has an example of loading data from a file. The data file could be a set of tasks from an existing or fictitious source in an excel file in CSV format. In Table A3 we show the initialization setup variables.

Table A3. Setup variables.

Input Variable	Data Type	Values
employees-number	Integer	0–100
number-of-tasks	Integer	1–n
probability-of-delay	Integer	0–1
probability-of-advance	Integer	0–1
assigned-tasks-employee	Integer	0–3

Appendix A.3.3. Submodels

Earned Value Management

In earned value management, unlike in traditional management, there are three data sources: planned value (PV), earned value (EV), and actual cost (AC). Figure A2 shows the graphic performance report and Table A4 shows the metrics description and calculations.

The PV is the budget (or planned) value of work scheduled, the EV is the "earned value" of the physical work completed, and the AC is the actual value of work achieved.

The tasks state determines PV, EV, and AC values and is the core of EVM performance indexes and estimations.

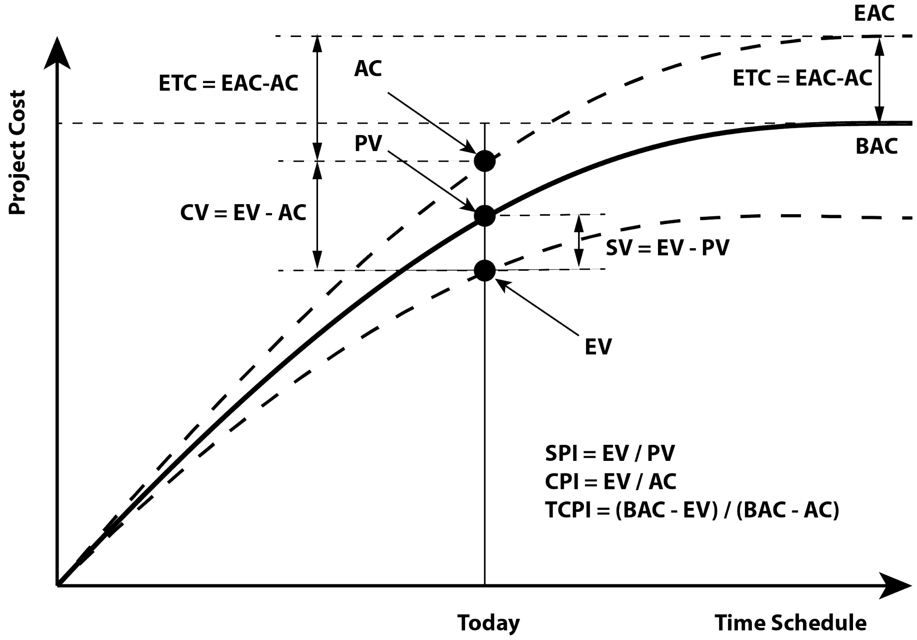

Figure A2. The earned value management (EVM) graphic performance report.

Table A4. Earned value management metrics description.

EVM Metric	Calculation and Description
Planned Value, PV	The budget (or planned) value of work scheduled
Earned Value, EV	The "earned value" of the physical work completed
Actual Cost (AC)	The actual value of work completed
Budget at Completion, BAC	PV% = PV / BAC EV% = EV / BAC AC% = AC / BAC
Schedule Variance, SV	SV = EV – PV SV% = SV / PV
Cost Variance, CV	CV = EV – AC CV% = CV / EV
Schedule Performance Index, SPI	SPI = EV / PV
Cost Performance Index, CPI	CPI = EV /AC
To Complete Performance Index, TCPI	TCPI = (BAC – EV) / (BAC – AC)
Estimate at Completion, EAC	EAC = BAC – SV EAC = BAC / CPI EAC = BAC / (CPI * SPI) EAC = AC + new estimate of remaining work
Estimate to Complete, ETC	ETC = EAC – AC
Variance at Completion, VAC	VAC = BAC – EAC VAC% = VAC / BAC
Cost Performance Index at Conclusion, CPIAC	CPIAC = BAC / EAC
Time Estimate at Completion, EACt	EACt = (BAC / SPI) / (BAC / PMB Duration) = PMB duration / SPI
Time Variance at Completion, VACt	VACt = PMB duration – EACt VACt% = VACt / PMB duration
Time Schedule Performance Index at Conclusion, SPIACt	SPIACt = PMB duration / EACt

Appendix B. Sensitivity Assessment

Table A5. Data description.

Variable	Mean	SD	Median	MAD	Min	Max	n
employees.number	4	2.00047636061173	4	2.9652	1	7	2100
assigned.tasks.employee	2	0.81669105433311	2	1.4826	1	3	2100
probability.of.delay	0.45	0.287296544411313	0.45	0.37065	0	0.9	2100
probability.of.advance	0.45	0.287296544411313	0.45	0.37065	0	0.9	2100
step	1116.98571428571	1603.01591793252	581	471.4668	146	15,980	2100
AC	2469.54904761905	2817.20670248899	1532	1245.384	125	15,939	2100
PV	1532	0	1532	0	1532	1532	2100
EV	1532	0	1532	0	1532	1532	2100
SV	0	0	0	0	0	0	2100
SPI	1	0	1	0	1	1	2100
CV	−937.549047619048	2817.20670248899	0	1245.384	−14,407	1407	2100
CPI	1.61839999350462	1.86235517369687	1	0.814674377613205	0.0961164439425309	12.256	2100

Table A6. Requirements verification.

Requirement	Specification	Number of Traces Where Requirement Is True	Total Number of Traces	Percent of Cases Where the Requirement Is True out of Total Cases	Assessment
employees.number >= 1	Always True	2100	2100	1	Requirement Is Met in ALL cases
employees.number <= 7	Always True	2100	2100	1	Requirement is Met in ALL cases
assigned.tasks.employee >= 1	Always True	2100	2100	1	Requirement is Met in ALL cases
assigned.tasks.employee <= 3	Always True	2100	2100	1	Requirement is Met in ALL cases
probability.of.delay >= 0	Always True	2100	2100	1	Requirement is Met in ALL cases
probability.of.delay <1	Always True	2100	2100	1	Requirement is Met in ALL cases
probability.of.advance >= 0	Always True	2100	2100	1	Requirement is Met in ALL cases
probability.of.advance <1	Always True	2100	2100	1	Requirement is Met in ALL cases

Table A7. Percent of "CPI" Cases within Range 0.0961164439425309 to 3.5 = 89.5238095238095, n = 1880.

Condition	Number of Traces Where Condition Is True	Total Number of Traces	Likelihood That Condition Appears Alongside "CPI" within Range 0.0961164439425309 to 3.5	Likelihood That "CPI" within Range 0.0961164439425309 to 3.5 Contains the Condition	Sensitivity Assessment
employees.number >= 0	1880	2100	0.895238095238095	1	0.944723618090452
assigned.tasks.employee >= 0	1880	2100	0.895238095238095	1	0.944723618090452
probability.of.delay >= 0	1880	2100	0.895238095238095	1	0.944723618090452
probability.of.advance >= 0	1880	2100	0.895238095238095	1	0.944723618090452
employees.number >0	1880	2100	0.895238095238095	1	0.944723618090452
assigned.tasks.employee >0	1880	2100	0.895238095238095	1	0.944723618090452
probability.of.delay >0	1713	1890	0.906349206349206	0.911170212765957	0.908753315649867
probability.of.advance >0	1670	1890	0.883597883597884	0.888297872340426	0.885941644562334
employees.number == 0	0	0	NA	0	NA
assigned.tasks.employee == 0	0	0	NA	0	NA
probability.of.delay == 0	167	210	0.795238095238095	0.0888297872340426	0.159808612440191
probability.of.advance == 0	210	210	1	0.111702127659574	0.200956937799043
employees.number <0	0	0	NA	0	NA
assigned.tasks.employee <0	0	0	NA	0	NA
probability.of.delay <0	0	0	NA	0	NA
probability.of.advance <0	0	0	NA	0	NA
employees.number <= 0	0	0	NA	0	NA
assigned.tasks.employee <= 0	0	0	NA	0	NA
probability.of.delay <= 0	167	210	0.795238095238095	0.0888297872340426	0.159808612440191
probability.of.advance <= 0	210	210	1	0.111702127659574	0.200956937799043

Table A8. Sensitivity Assessment. Percent of "step" Cases within Range 146 to 2720 = 92.0476190476191, n = 1933.

Condition	Number of Traces Where Condition Is True	Total Number of Traces	Likelihood That Condition Appears Alongside "Step" within Range 146 to 2720	Likelihood That "Step" within Range 146 to 2720 Contains the Condition	Sensitivity Assessment
employees.number >= 0	1933	2100	0.92047619047619	1	0.958591619142078
assigned.tasks.employee >= 0	1933	2100	0.92047619047619	1	0.958591619142078
probability.of.delay >= 0	1933	2100	0.92047619047619	1	0.958591619142078
probability.of.advance >= 0	1933	2100	0.92047619047619	1	0.958591619142078
employees.number >0	1933	2100	0.92047619047619	1	0.958591619142078
assigned.tasks.employee >0	1933	2100	0.92047619047619	1	0.958591619142078
probability.of.delay >0	1723	1890	0.911640211640212	0.891360579410243	0.901386345801726
probability.of.advance >0	1741	1890	0.921164021164021	0.900672529746508	0.910803034266283
employees.number == 0	0	0	NA	0	NA
assigned.tasks.employee == 0	0	0	NA	0	NA
probability.of.delay == 0	210	210	1	0.108639420589757	0.195986934204386
probability.of.advance == 0	192	210	0.914285714285714	0.099327470253492	0.179188054129725
employees.number <0	0	0	NA	0	NA
assigned.tasks.employee <0	0	0	NA	0	NA
probability.of.delay <0	0	0	NA	0	NA
probability.of.advance <0	0	0	NA	0	NA
employees.number <= 0	0	0	NA	0	NA
assigned.tasks.employee <= 0	0	0	NA	0	NA
probability.of.delay <= 0	210	210	1	0.108639420589757	0.195986934204386
probability.of.advance <= 0	192	210	0.914285714285714	0.099327470253492	0.179188054129725

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