# A System Dynamics Approach to Feedback Processes in Project Scheduling

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## ABSTRACT

**Projects, as catalysts for proactive transformation, offer a temporary and adaptable framework that effectively handles complexities (or uncertainties) within a competitive corporate landscape. Hence, the use of an effective project management framework, such as Dynamic Project Scheduling (DPS), is a method to handle intricacies in order to accomplish organizational objectives. DPS refers to a triangle interaction involving baseline scheduling, schedule risk analysis, and project control while supporting schedule adjustment in response to changes and uncertainties. However, there is a lack of information regarding studies that have investigated the feedback mechanisms among DPS components. This study was designed to examine the counterintuitive relationships between these components using system dynamics. The quantities within the DPS system were identified and defined. A causal loop diagram was used to illustrate the interactions among these quantities. Subsequently, a Stock and Flow Diagram (SFD) was created to identify the inputs, states, and flow mechanisms within the DPS. Using the SFD, a system dynamics expression was generated which was then employed to compute the rate of change of the Budgeted Cost of Work Remaining (BCWR) for two projects at different time intervals. The results properly indicated the period of idleness during project execution. The use of BCWR rather than schedule variance provides a more effective visual representation for evaluating performance and tracking progress. The BCWR and planned value exhibit contrasting trends, highlighting the importance of earned value quantities in project control. The use of system dynamics in project management can enhance the planning and scheduling phase, allow project managers to monitor pertinent performance measures, and optimize project outcomes through informed decisions.**

***Keywords-project scheduling; system dynamics; dynamic project scheduling; project performance measures; budgeted cost of work remaining***

## I. INTRODUCTION

Nowadays, technological advancements, innovative business strategies, collaborations, and worldwide integration have contributed to the increasing complexity of undertaken projects. Apart from traditional projects like construction and engineering, significant interest in a management-by-projects strategy for business operations is due to the advent of new business endeavors (or applications). These new endeavors, such as the development of a new product, research and development, the acquisition of new certifications, operational process enhancement, novel information technologies deployment, system improvement, etc. [1-4] are called modern projects. The criteria for determining the success of a project may vary across different stakeholders [5]. A project is deemed successful if it is finished within the designated timeframe and financial constraints, while meeting the client's expectations in terms of stated standards [4, 6]. The issues that result in project failure frequently arise from the intricacy, unpredictability, and ever-changing characteristics of project execution. Some projects may incur cost overruns between 100 and 200% and can be delayed beyond the anticipated market delivery date [7]. According to prior research, 70% of projects were unsuccessful because they lacked a clearly defined objective, whereas 55% of project managers identified budget overruns as a contributing factor to failure [8].

Complexity is considered a characteristic of a program, a project, or its environment that is difficult to manage due to human or system behavior or ambiguity [9]. On system behavior, a project can be viewed as a system or sub-system depending on the project structure. Invariably, the interactions between project components may result in complex situations. These interrelationships include dependencies between the project and the environment, interactions among project activities, and the resulting system dynamics. The effect of dynamism is the counterintuitive relationships and behavior among components in a project system [10]. Therefore, to navigate through the expected complex situation, a good understanding of the components and their resulting connections will enhance project performance. Also, to avoid negative consequences, a rigorous qualitative description of the processes, boundaries, and strategies of the project management process can be achieved using system dynamics.

System Dynamics (SD) has been applied in various fields including social sciences, economics, and strategic management [11-15]. SD is a widely employed methodology for modeling and simulating complex systems, which helps in making informed decisions and gaining a deeper comprehension of these systems [14, 16-18]. Project management has greatly benefited from the application of SD [19, 20]. Authors in [21] examined the interrelationships and linkages among the initial stages of construction projects utilising Stock and Flow Diagrams (SFDs) and Causal Loop Diagrams (CLDs). Authors in [22] determined that SD has the capacity to detect and establish links between risk elements, as evidenced by their study on the influence of risk analysis in construction projects. However, the methods of structural decomposition and Delphi risk analysis did not possess this potential. Authors in [23] investigated the root cause of rework in construction projects executed in southwest Nigeria, and proposed strategic interventions to improve project performance. However, the study did not consider modelling approach, which provides a deeper comprehension of the challenges related to project activity rework. Authors in [24] created a model that integrated SD and earned value management to track changes in the distribution of staff histograms and problematic project behaviour in real-world scenarios. Similarly, in [18] it was concluded that a SD model possesses the capability to comprehensively assess the impact of risk factors in building projects.

Scheduling is a vital aspect of project management that involves assigning resources to tasks in order to ensure efficient processing of the project [25-26]. Scheduling is an optimization problem with the primary goal of optimizing one or more criteria. The significance of scheduling lies in its ability to effectively handle interdependencies, foster team synergy, provide a clear project implementation plan, and monitor progress toward achieving project goals [25, 27-29]. However, researchers have acknowledged the constraints of conventional scheduling techniques and, as a result, have implemented dynamic scheduling [29-30]. Dynamic Project Scheduling (DPS) takes into consideration the effects of several elements, such as modifications in project requirements, availability of resources, and external influences on the project schedule [29-31]. Furthermore, project data may be consistently reviewed, and if needed, schedule adjustments can be implemented to guarantee the accomplishment of project objectives [32]. The DPS refers to a triangle interaction involving Baseline Scheduling (BS), Schedule Risk Analysis (SRA), and Project Control (PC) [33]. The interactions among these components may have complex impacts, despite their apparent simplicity [10, 26, 33-34]. Therefore, a project manager must have a good understanding of the interconnectivity and interrelationship among the DPS components and their associated metrics. Numerous businesses and project managers have adopted the utilization of performance metrics to monitor project advancement for efficient decision-making.

Performance measurements encompass metrics that facilitate decision-making and evaluate the efficient utilization of resources in accomplishing strategic objectives [35]. Nevertheless, relying on a single metric across several scenarios may prove to be inefficient. For instance, while a metric can reveal the impact of the critical path on the total time, it may offer limited insights into its influence on cost, quality, and other factors crucial for project success. Therefore, in the DPS system, it is possible to explore holistically the counterintuitive relationships among the metrics. However, information is sparse on studies that explored the feedback mechanisms among DPS components. Hence, in this research, the counterintuitive relationships among the components of DPS will be investigated using SD.

## II. METHODOLOGY

In this section, DPS components were defined, and a CLD was used to aggregate the interrelationships between the elements. Thereafter, the mathematical relationship between these elements was developed using the SFD. The applicability and effectiveness of the mathematical equations were validated with two project datasets. The datasets were obtained from the operation research and scheduling group dynamic scheduling library [36].

### *A. Identification of Quantities in DPS*

Table I presents the quantities in the DPS system. A full definition of these quantities is beyond the scope of the current research.

TABLE I. QUANTITIES IN DPS

| | BS | SRA | PC |
|---|---|---|---|
| 1 | Activity id | Criticality index | Planned value |
| 2 | Activity name | Cruciality index | Earned value |
| 3 | Actual duration | Significance index | Actual cost |
| 4 | Precedence relations | Schedule sensitivity index | Actual start |
| 5 | Successors | | Schedule variance |
| 6 | Baseline start | | Cost variance |
| 7 | Baseline finish | | Budget at completion |
| 8 | Activity cost | | Tine at completion |
| 9 | Total project cost | | Performance factor |
| 10 | | | Percentage of project completed |
| 11 | | | Schedule performance index |
| 12 | | | Cost performance index |

The quantities presented in Table I were further categorized into four types, namely rates, state, inputs, and auxiliaries, as shown in Table II.

TABLE II. FLOW DIAGRAM NOTATIONS

| | Quantity type | Quantity | Notation |
|---|---|---|---|
| 1 | Rates | Planned value rate | $PV_{rate}$ |
| | | Earned value rate | $EV_{rate}$ |
| 2 | State | Budgeted cost of work remaining | BCWR |
| | | Planned value | PV |
| 3 | Inputs | Performance factor | PF |
| | | Actual cost | AC |
| | | Percentage of project completed | %PC |
| | | Actual duration | AD |
| | | Planned duration | PD |
| | | Budget at completion | BAC |
| 4 | Auxiliaries | Earned value | EV |
| | | Schedule variance | SV |
| | | Cost variance | CV |
| | | Schedule performance index | SPI |
| | | Cost performance index | CPI |
| | | Estimated time at completion | $EAC_{time}$ |
| | | Estimated cost at completion | $EAC_{cost}$ |

## B. *Causal Loop Diagram (CLD) for DPS*

The relationship between the quantities defined in Table I is described by the CLD in Figure 1. In a CLD, the relationships between the factors that influence the cost and duration of a project activity are described.

## C. *Flow Diagram for DPS*

In Table II, the BCWR is defined as a state. The value of BCWR can be determined from the difference in the rate of inflow and outflow represented by Planned Value rate ($PV_{rate}$) and Earned Value rate ($EV_{rate}$), respectively. The $PV_{rate}$ is estimated from the value of budget at completion and planned duration. The Schedule Variance (SV) is the difference between the earned value and the planned value at time t expressed in monetary value. Similarly, the $EV_{rate}$ can be calculated using the budgeted cost of work performed at time t. The budgeted cost of work performed, also known as the Earned Value (EV) is determined using the values of Budget At Completion (BAC) and percentage project completion. The SFD for DPS is presented in Figure 2.

## D. *Formulation of System Dynamics Equations for DPS*

The SD model for DPS was developed based on the following assumptions.

1. At the start of the tracking process, the BCWR is equal to the total budgeted cost of work scheduled.
2. The planning phase precedes project tracking and monitoring.
3. The planned duration and total budgeted cost of the project are constant.
4. Project activity rework is not permitted.
5. Resource cost is assumed to be a part of the budgeted cost for each activity.
6. The baseline scheduling and schedule risk analysis information is assumed to be available and accurate.

## E. *Rate Equations*

Equation (1) is the Rate Of Change (ROC) or the budgeted cost of work remaining.

$$\mathrm{ROC} = \text{inflow - outflow} = \frac{\mathrm{BCWR}}{\mathrm{dt}} = \mathrm{PV_{rate}} - \mathrm{EV_{rate}} \quad (1)$$

Equation (2) gives the $PV_{rate}$, from assumption 3, with BAC and PD being constant:

$$\mathrm{PV_{rate}} = \frac{\mathrm{BAC}}{\mathrm{PD}} \quad (2)$$

Equation (3) gives the $EV_{rate}$:

$$\mathrm{EV_{rate}} = \frac{\mathrm{EV}}{\mathrm{AD}} \quad (3)$$

Equation (4) can be derived by inserting (2) and (3) into (1):

$$\mathrm{ROC} = \mathrm{K} - \frac{\mathrm{EV}}{\mathrm{AD}} \quad (4)$$

By differentiating (4), change in ROC can be expressed as a function of time (t) as presented in (5):

$$\Delta\mathrm{ROC(t)} = -\,\Delta\mathrm{EV(t)} \quad (5)$$

## F. *Auxilliary Equations*

The auxiliary equations are stated from (6)-(10).

Earned value:

$$\mathrm{EV} = \%\mathrm{PC}*\mathrm{BAC} \quad (6)$$

Schedule variance:

$$\mathrm{SV} = \mathrm{EV}-\mathrm{PV} \quad (7)$$

Cost variance:

$$\mathrm{CV} = \mathrm{EV}-\mathrm{AC} \quad (8)$$

Estimated time at completion:

$$\mathrm{EAC_{time}} = \mathrm{PD} - \frac{\mathrm{SV}}{\mathrm{PV_{rate}}} \quad (9)$$

where $\frac{\mathrm{SV}}{\mathrm{PV_{rate}}}$ is also known as the time variance.

Estimated cost at completion:

$$\mathrm{EAC_{cost}} = \mathrm{AC} + \frac{\mathrm{BAC}-\mathrm{EV}}{\mathrm{PF}} \quad (10)$$

## G. *State Equations*

From the SFD presented in Figure 2, the BCWR is a stock that is subject to change over time. Therefore, the value of BCWR can be estimated using Euler solution method [10]. The state variable (S) can be replaced by BCWR at different time intervals. If i represents intervals of time, then:

$$\mathrm{S}\,(\mathrm{t_{i+1}}) = \mathrm{S}\,(\mathrm{t_i}) + \Delta\mathrm{ROC}(\mathrm{t_i}) \quad (11)$$

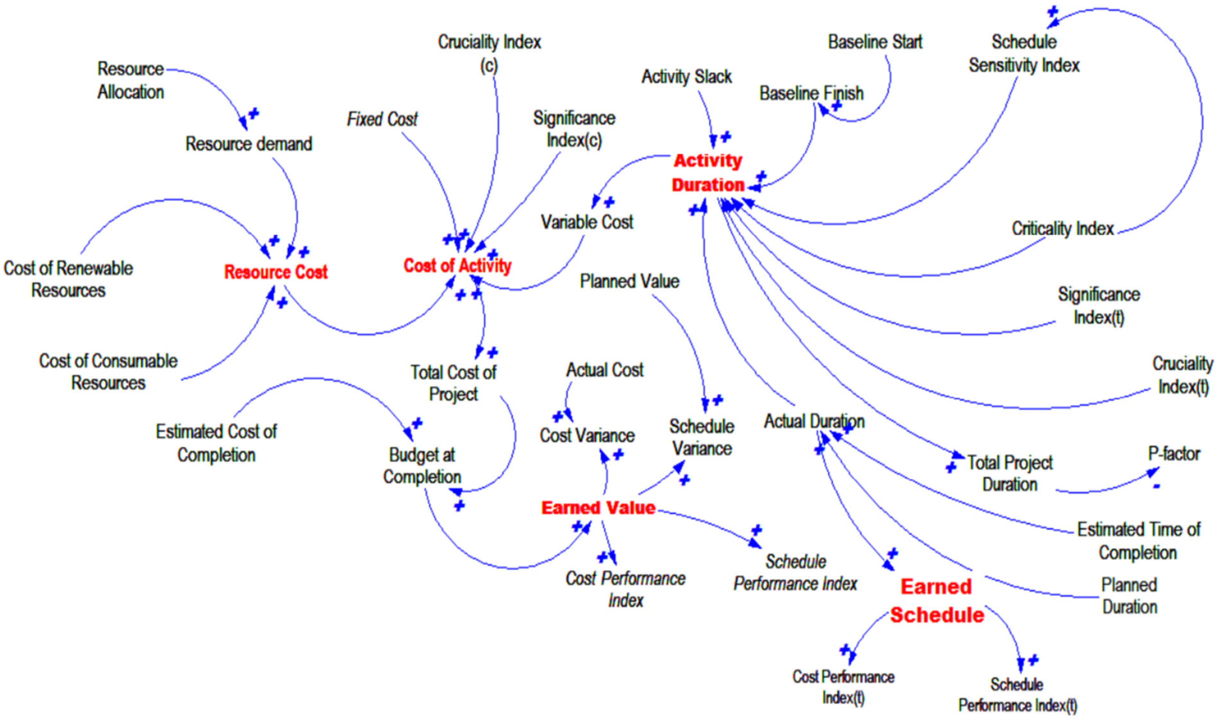


Fig. 1. CLD showing the relationship between the quantities of DPS.

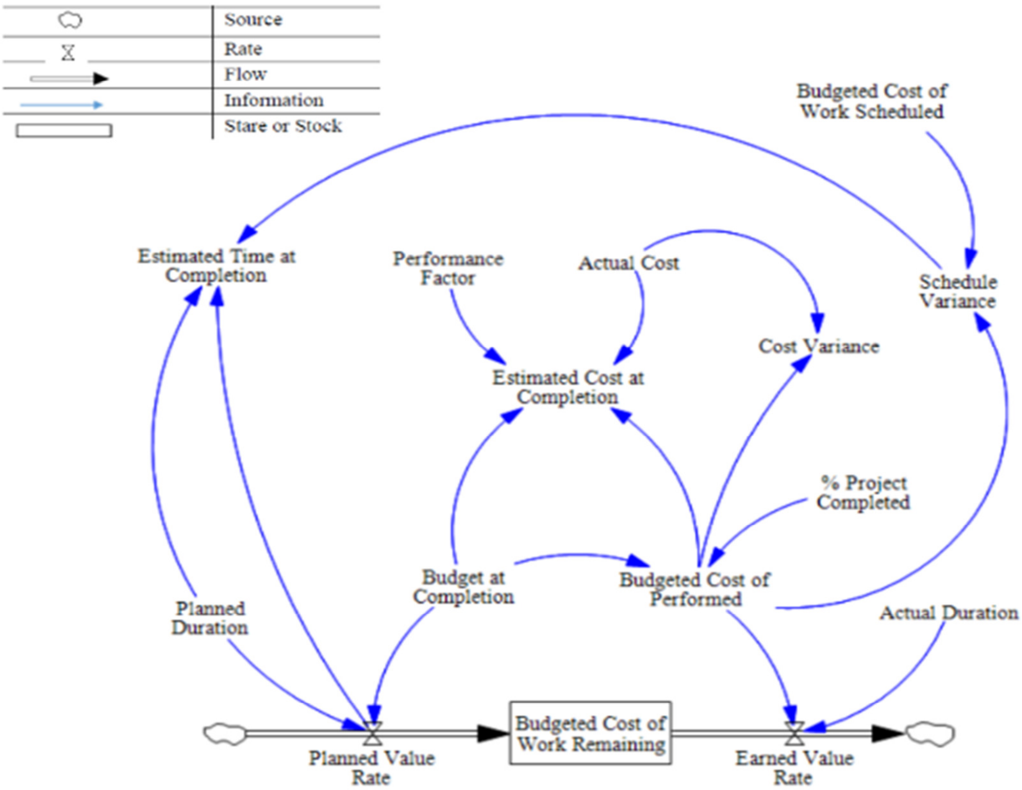


Fig. 2. The SFD for DPS

The state variable in (11) is replaced with BCWR as shown in (12):

$$\mathrm{BCWR}(t_{i+1}) = \mathrm{BCWR}(t_i) + \Delta\mathrm{ROC}(t_i) \quad (12)$$

Equation (5) can be inserted in (12). Thus, we get:

$$\mathrm{BCWR}(t_{i+1}) = \mathrm{BCWR}(t_i) - \Delta\mathrm{EV}(t) \quad (13)$$

Equation (13) can be used to simulate the BCWR.

### *H. Model Application*

From the dynamic scheduling library (DSLIB), two datasets regarding projects, namely (i) Christmas Market Project (CMP), and (ii) Tournament Infrastructure Project (TIP) were obtained to test the validity and applicability of the developed model. These projects were selected based on the detailed tracking information available. From the datasets, relevant project metrics were extracted such as planned duration, budget at completion, actual duration, percentage of project completed, planned value, actual cost, cost variance, SV, schedule performance index, and cost performance index.

## III. RESULTS AND DISCUSSION

To verify the applicability of the model, several additional metrics were estimated to enhance the analysis. The estimated metrics include: (i) planned value rate, (ii) earned value rate, (iii) estimated cost of completion, and (iv) estimated time of completion. The BCWR at each project tracking point is the output of the model.

### *A. Christmas Market Project (CMP)*

The Actual Duration (AD) and the simulated budgeted cost of work for CMP are 185 days and €58900, respectively. There is a five-day interval between tracking updates. The tracking pattern allows for a comprehensive understanding of the project's status and aids in the evaluation of the amount of work remaining in terms of monetary value using (13).

#### *1) Relationship between SV and ROC*

The relationship between the SV and the ROC of the budgeted cost of work shown in Figure 3 is essential for performance evaluation and project progress tracking.

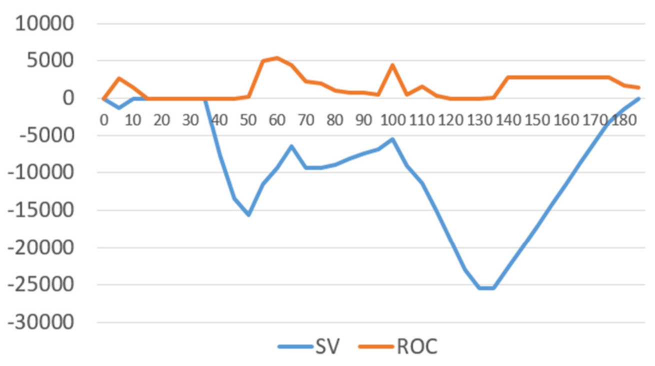


Fig. 3. Relationship between SV and ROC for CMP.

The SV considers the difference between the planned and actual progress, but it ignores periods of project stagnation. On the other hand, ROC is a helpful metric to determine whether project work is finished. Project modifications are clearly shown with ROC, giving a clearer picture of whether work is completed or whether there are delays and interruptions. A period of zero activity can be seen in Table III from AD = 15 to AD = 45 and from AD = 120 to AD = 130. From a tracking perspective, Figure 3 illustrates the dynamic nature of ROC, there was no project activity between Project Tracking ID (PTID) 10 to 35, and PTID 120 to 135 as indicated by the ROC.

#### *2) Relationship between BCWR and PV*

An important aspect of good budget management is the alignment with planned values, as demonstrated by the relationship between BCWR and PV which have opposing trajectories and intersect at project tracking ID 18 as shown in Figure 4. This is equivalent to AD of 90 days. The intersection between BCWR and PV data indicated the point at which the planned value of the remaining work aligned with the budgeted cost. With the opposite trajectories and eventual convergence between budgeted costs and planned values, ongoing monitoring and analysis are necessary to detect and address potential budgetary concerns. By closely tracking these metrics, project managers can ensure financial control and make informed decisions to optimize project outcomes.

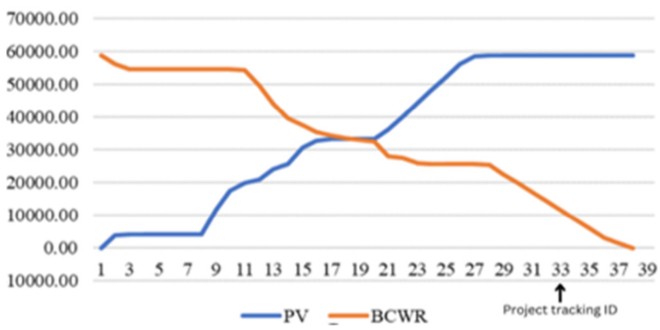


Fig. 4. Relationship between BCWR and PV for CMP.

### *B. Tournament Infrastructure Project (TIP)*

The planned duration of the project is 27 days while the actual duration is 23 days. The budget at completion was estimated to be € 126,955.30 while the actual cost at the end of the project summed up as € 124,502.30.

#### *1) Relationship between SV and ROC*

In Figure 5, the maximum value for ROC was obtained at AD = 20. The rate of change between AD=5 and AD=20 can be compared to a batch-tub scenario. This implies that between AD=5 and AD=9, there was a decline in the BCWR, which remained unchanged between AD=9 and AD=17, and increased between AD=17 and AD= 20. However, the SV remains unchanged between AD=9 and AD=13. In reality, an SV with zero value denotes that the project is on time (i.e. the earned value equals the planned value). This explains why the value of BCWR was zero between AD=9 and AD=13. Also, this could be explained from a steady natural rhythm of work maintained among team members [37].

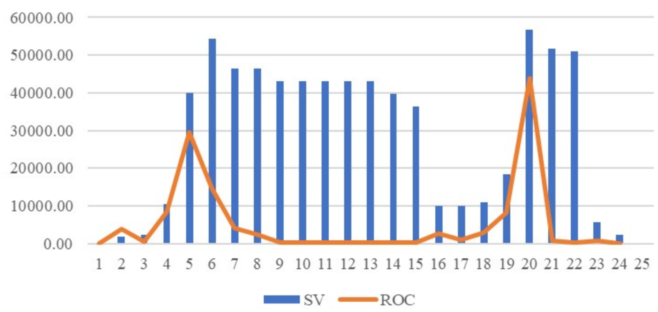


Fig. 5. Relationship between SV and ROC for TIP.

*2) Relationship between BCWR and PV*

In Figure 6, BCWR and PV follow opposite trajectories. Hence the need to monitor this relationship throughout the project lifecycle. Any significant deviation or consistent disparities between these metrics could signify potential budgetary issues or challenges in meeting planned targets.

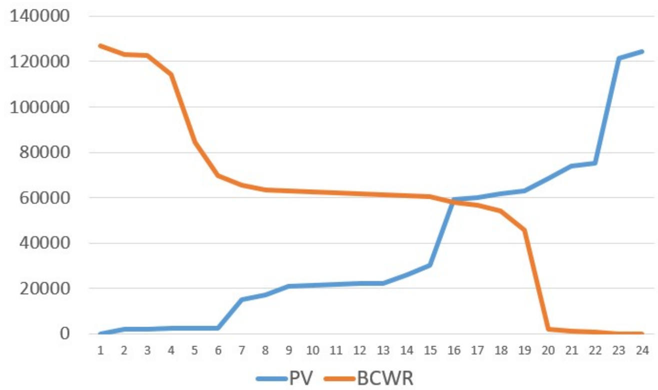


Fig. 6. Relationship between BCWR and PV for TIP.

## *C. Practical Implications of SD in DPS*

Within the project performance framework, baseline scheduling, schedule risk analysis, and project control are metrics available for monitoring the progress of a project. In this study, from the results obtained using the developed SD model, the assumed counterintuitive relationships among DPS components and their implications for project management practices were confirmed. Also, the herculean computational process associated with DPS was reduced. In addition, the project tracking system provided real-time data on project scheduling, activity sensitivity, and actual time/cost performance, facilitating a more comprehensive understanding of the project and enabling informed decision-making. Nevertheless, it is implicitly assumed that all other factors influencing the effective completion of a project are under control.

## *D. Discussion*

Scheduling project activities is a complex task and a key component of operational-level decision-making. While dynamic project scheduling establishes an inherent relationship among its components, a mathematical framework that aligns the interdependencies between the components is sparse. To achieve this, a quantitative structure was created utilizing SD to model the flow of inputs and outputs between different components of DPS. The project tracking opportunity provided by this method allows for the identification of actions that may not be deemed significant in the baseline schedule, but are nonetheless essential for the successful completion of the project. For example, activities which may not be critical (from baseline scheduling), could be crucial to the completion of the project as identified from the BCWR and SV indices. Therefore, our research differs from past studies by examining all three components, whereas earlier research only focused on the use of system dynamics on individual elements of DPS.

# IV. CONCLUSION AND FUTURE WORK

In this research work, system dynamics was used to explore the intricate interconnections among the various components of dynamic project scheduling. Through the development of a causal loop diagram, the underlying relationships between these quantities were revealed. Using a stock and flow model, a mathematical expression to calculate the Budgeted Cost of Work Remaining (BCWR) at each tracking period was derived. As highlighted in the literature, BCWR is relevant in the context of forecasting time and accuracy. The BCWR is a valuable indicator to monitor the completion of project activity and it serves as a tool to identify idle period. The modeling technique demonstrated how baseline scheduling and project control impacted the scope. However, quantities associated with schedule risk analysis focused on project activities rather than project scope.

This study examined the connections between the components of dynamic project scheduling at the macro level, with less focus on the relationships between activities. In future works, the system dynamics equations can be extended to capture activity level interactions, and the risk factors associated with project activities through schedule risk analysis. Furthermore, it is possible to model various scenarios of project activity rework and analyze how they impact DPS quantities and project outcomes.

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