DESIGN OF A 4D DELIVERABLE FOR CONSTRUCTION SCHEDULE UPDATES

by

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ABSTRACT

SAVANNAH DEWITT. Design of a 4D deliverable for construction schedule updates. (Under the direction of DR. JOHN HILDRETH)

Advancements in digital technology within the construction industry have significantly impacted the way in which the built environment comes to fruition. The use of 4D technology provides enhanced communication of the plan of action established by the contractor through visualization. 4D animations are created by combining 1D schedule activities and 3D geometries in order to visually depict the entire construction sequence, eliminating the need to be versed in the practice of construction scheduling. While the practice of implementing 4D technology is a common occurrence prior to the start of construction, application decreases greatly once construction begins. Information regarding project status is conveyed through traditional schedule updating methods due to the lack of an appropriate 4D update deliverable and limited technological capabilities.

This research has identified the informational and technological needs for the integration of 4D technology into the schedule updating process. Specific objectives were established in order to achieve this goal, beginning with a comprehensive review of the function of a schedule update. Various update users were identified, along with their individual reasons for consulting the update. Information gathered was then used to design an applicable deliverable for 4D construction schedule updates. The result focuses on visual representation of project status through graphical attributes applied to 3D geometries, as well as the ability to digitally navigate within the 4D deliverable. Visual output can be modified by the user to allow for a more in depth analysis of schedule update information.

Following the design of the 4D update deliverable, the current 4D technology was assessed to determine capabilities and functionalities. Comparisons were then made between the current capabilities and the proposed design in order to identify discrepancies relating to the ability to produce the desired deliverable. Issues found primarily related to the ability to use status information generated by the update in order to dictate the visual appearance of 3D geometries. While the necessary information is present within the 4D application, functionality necessary to display that information in a visual manner is needed. There is also a need to modify output functionalities that allow the proposed deliverable to be exported from the 4D application and distributed to various users.

The results of this research indicate the feasibility of implementing 4D technology into the scheduling updating process via the proposed deliverable. With the addition of the aforementioned functionalities, current 4D technology will be capable of producing a 4D schedule update and will significantly impact the construction industry. The ability to visualize progress will positively alter the way users understand project status and improve the communication between all parties involved.

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TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Advancements in digital technology within the construction industry have significantly impacted the way in which the built environment comes to fruition. Utilization of new tools, such as 4D construction scheduling, has allowed owners, designers, and contractors to better visualize the construction process and communicate the desired intent. This drive for visualization and clarity has influenced the development and application of 4D models, but the full range of benefits that can be realized through 4D techniques has yet to be determined.

Currently, 4D models are being created at the beginning of projects, alongside the baseline construction schedule. This initial 4D model easily allows all parties involved to understand the timeline of the 1D construction schedule through visualization of a 3D model. The final product is typically an animation that graphically depicts the construction sequence, meaning no prior knowledge of construction or project scheduling is required in order to comprehend the procedure.

For contractors, this 4D tool is multifunctional. During the actual scheduling process, the implementation of 4D can aid in the identification of sequencing issues, space limitations, safety hazards, and conflicts between various trades. Even the most experienced schedulers can overlook details that could affect future project elements. 4D modeling can alert the contractor to potential issues long before construction even begins, allowing sufficient time to create an alternate plan of action. If design changes would allow for increased constructability or greater worker safety, the visual display of the construction sequence that creates such risks can better inform architects and engineers of the necessity, reducing the chances of resistance. In addition, once the 4D model has been fully integrated with the construction schedule, the final product can be presented to owners to clearly communicate the plan of action established by the contractor. Rather than attempting to verbally explain the sequencing to the various parties involved, some of which may be non-construction personnel, the 4D animation depicts a step by step process that is easy to comprehend and does not require an in-depth understanding of construction scheduling. Ultimately, the 4D model gives the entire project team a common basis of understanding, which allows the project to move forward smoothly.

1.1 Problem Statement

While the use of 4D modeling tools and techniques have proven extremely useful, they are primarily being implemented prior to the start of construction. Once construction begins, the 4D processes tend to be pushed into the background and the contractor returns to the more traditional methods of project communication. Information regarding project status is conveyed through schedule updates, narratives, emails, and word of mouth. However, the visual communication aid used previously has disappeared during the actual construction process. The issue surrounding this disconnect lies in the appropriate application of this new technology as it relates to construction schedule updating.

In order to determine the proper delivery format that this 4D technology should take in schedule updating, there are several preliminary questions that must first be answered. It is first necessary to understand the relevant personnel that utilize schedule updates and the reasons those individuals consult them. Different users will be seeking different information, depending on their level of involvement in the project. With the various users in mind, it is then necessary to analyze the function of a schedule update and understand its intended purpose for each of the previously determined users. Once the user functions have been identified, it is then essential to define when a schedule update should be performed and what information it should include. This information will be derived from the previously established needs of the various users.

Once the key players (who), their needs (what), and the update frequency (when), have been identified, the physical (or digital) delivery format of a 4D schedule update can be articulated and a suitable application determined. This research is aimed at providing a 4D schedule update deliverable, with intentions of bringing benefits experienced at the beginning construction throughout the entire life of the project.

However, the lack of an appropriate deliverable of 4D updates is but one portion of the overall issue. While an ideal format can be articulated as a theory, there are currently limited technologies available for the production of 4D schedule updates. Therefore, in addition to the formulation of a suitable deliverable, there is a need to scrutinize current 4D technologies to gain an understanding of the limited capabilities in order to suggest new processes that enhance output abilities.

1.2 Research Objectives

This research examines current industry practices regarding construction schedule updating and presents a delivery format that allows for the integration of 4D technology to the updating process. The application focuses on the implementation of visualization aids that act as a supplement to the current updating practices. Following the development of an ideal deliverable, the research then seeks to understand the feasibility of realization via current technologies. These tasks were achieved by completing the following objectives:

1. Define the function of a schedule update
2. Design an applicable deliverable for 4D schedule updates
3. Assess the capabilities of current 4D technology in relation to updating
4. Compare the designed deliverable with current technological capabilities

A thorough review of current scheduling practices and processes provided the basic background information. In addition, current 4D uses are reviewed as they relate to the practice of construction scheduling. The understanding of basic scheduling processes and 4D technology lead to the realization of the numerous benefits experienced at the beginning of the scheduling process. This research considers the specific task of scheduling updating in tandem with the benefits of 4D technology and seeks to identify the informational and technological needs for the integration of 4D technology into the schedule updating process.

Objective 1: Define the Function of a Schedule Update

In order to incorporate 4D technology into the schedule update process, it was first necessary to understand the function that the schedule update serves. There are many end users that must be considered, as well as specific information being sought by each user. Full comprehension of the schedule update function allowed for the development of a cohesive deliverable that has the ability to enhance the desired output for each user.

Objective 2: Design an Applicable Deliverable for 4D Schedule Updates

This objective was directed at the formulation of a deliverable that allows for the implementation of 4D technology in the schedule updating process. Information gained in the previous objective played a crucial role in determining the parts and pieces necessary for creation. Specific items that required addressing included:

- Is the output digital or physical in nature
- Who produces the output
- What is the interaction mechanism
- What information is present
- How is the information represented
- Can the output be modified by user
- How is the usefulness of the output determined

Objective 3: Assess the Capabilities of Current 4D Technology in Relation to Updating

Upon the definition of the ideal deliverable format, an examination of the current capabilities of 4D technology was required. Although a suitable application has been determined, it was unknown if the desired output could be produced through the utilization of current 4D technologies. Therefore, an attempt to produce the desired output was simulated. Results of the simulation were directly utilized in the subsequent objective.

Objective 4: Compare the Designed Deliverable with Current Technological Capabilities

The precise delivery format defined in the second objective was not directly attainable through current 4D software. With knowledge obtained from simulated outputs, a gap analysis was used to determine the capacity of the current technology in comparison with the previously articulated deliverable. From the gap analysis, specific discrepancies were noted regarding software capabilities in relation to 4D updating functionality.

1.3 Scope and Limitations

The goal of this research was to design an appropriate deliverable that allows for the utilization of 4D technology in construction schedule updating. While numerous scheduling processes exist, the focus was placed on the process of updating due to the frequency in which the action is performed in industry. Although the research aimed at producing an applicable deliverable for 4D schedule update, the final result utilized the proposed deliverable to identify the needed capabilities of the current 4D technologies. Within the research scope, the following limitations apply.

1.3.1 Information Sources

The completion of this research was accomplished through the use of scholarly articles, journals, textbooks, construction contracts, and construction specifications. When deemed necessary, opinions from industry professionals were solicited in order to provide feedback regarding the accuracy and relevance of the generated information.

1.3.2 Construction Scheduling Techniques

In terms of applicability, this research focused solely on projects utilizing the critical path method (CPM) for scheduling. It was assumed that projects using CPM were complex in nature and could therefore benefit from the application of 4D technology. Alternate scheduling methods, such as Gantt Charts, activity on arrow diagrams, activity on node diagrams, and linear scheduling techniques, were not considered relevant in terms of 4D technology implementation. While these practices still exist in industry, the complexity of projects utilizing these techniques do not typically compare with those projects utilizing CPM.

Additionally, current 4D technologies focus solely on schedules developed using CPM techniques. While CPM schedules can be developed within the 4D software or imported from outside programs, there is no ability to use alternate scheduling methods within the 4D environment. As such, only schedules using CPM techniques were considered in this research.

1.3.3 Existing Software

From a technology standpoint, digital applications utilized in this research consisted of Synchro Pro Software, Primavera P6 Professional, Adobe Acrobat Pro, Revit, Google SketchUp, and SolidWorks. Exploration of 4D capabilities and applications were limited to the capacity of the current software.

1.4 Research Benefits

Benefits of this research include the proposal of an applicable deliverable for the use of 4D technology in construction schedule updating. 4D project management software is becoming more widely used in the construction industry, but lacks key capabilities for use throughout the duration of the project. The 4D update deliverable described in this research has the ability to bring value to the construction industry by allowing for the expanded use of current technology. This expansion is made possible through the identification of gaps present between the proposed format and the current 4D capabilities.

1.5 Document Organization

Content of this thesis document is organized into six chapters. Chapter one contains introductory information pertaining to the purpose of the research, the problem statement, research objectives, and limitations. Chapter two provides background information relating to construction scheduling and the processes associated with the practice.

Chapter three focuses on the schedule update process and details specific information relating to the function of a schedule update. Chapter four takes information from chapter two and three in order to propose a schedule update deliverable for projects utilizing 4D technology.

Chapter five compares the proposed deliverable with current capabilities in the form of a gap analysis. Details of the gap analysis are provided in chapter six, along with conclusions pertaining to the research.

CHAPTER 2: BACKGROUND INFORMATION

This review of background information seeks to understand the current uses and processes associated with construction project scheduling. Definitions of key elements have been established for future reference, with emphasis placed on the schedule updating process. The interaction between current scheduling practices and 4D technology has also been further detailed. It is necessary to comprehend the purpose and capabilities of this advanced technology so that further implementation can occur.

2.1 Scheduling Overview

Scheduling in construction can be defined as "…an application of special knowledge or judgment of the mathematical, physical, or engineering sciences to the conception or implementation of creative work" (O'Brien 2006). Perhaps in simpler terms, construction scheduling is a part of the overall construction planning process that specifically analyzes the timing and sequence of activities necessary to complete the project. The schedule is a direct reflection of the plan and identifies "when" the "what" will take place and "who" will carry out the "what" (Hinze 2008).

2.2 Schedule Uses

The primary purpose of a construction schedule is to document the plan of action set forth by the contractor for the completion of a project. However, the information present in the schedule identifies much more than the activities and their sequencing. Presence of a schedule inherently provides information on the total project duration, the critical path, selected means and methods, resource requirements, and cost information. These key items are known as soon as the initial schedule has been completed. Knowing how to analyze and understand these elements can aid the contractor in the identification of potential problems imposed by the current schedule. For example, if the current schedule has all MEP trades beginning their respective tasks on the same date, it may cause severe congestion on the job site, leading to loss in productivity and increased safety hazards. Analysis of the schedule prior to the beginning of construction would allow the contractor to amend the schedule and properly stagger the MEP trades to mitigate the aforementioned issues.

Once construction begins, the schedule becomes a tool that is used to monitor and control the progress of the project. Hinze (2008) describes that "Monitoring implies the recording of actual start and finish dates for activities while the project is underway, and control relates to the analysis of the impacts of any schedule deviations and evaluation of what remedial actions, if any, should be taken." If maintained properly, the schedule can serve as an effective management tool that has the ability to indicate if the project is ahead or behind schedule and if the project is over or under budget (Hinze 2008). Identifying and remediating potential issues early on is paramount to the success of a construction project.

2.2 Contractual Scheduling Processes

There are several steps associated with the development and maintenance of a construction schedule. As previously described, the contractor will usually create an initial schedule that details the entire scope of work, and then use that schedule to monitor progress during construction. The schedule can only help to measure progress if it is properly maintained throughout the life of the project. In some instances, the contractor may develop an initial schedule, only to completely disregard it once construction begins. This practice essentially defeats the purpose of creating a schedule and makes monitoring progress impossible.

To help ensure that the schedule is being properly utilized, there are usually required practices established through contractual agreements between the owner and the contractor. Specific requirements will vary by contract, but will typically include details for the following items: preliminary schedules, baseline schedules, schedule updates, schedule modifications, schedule revisions, recovery schedules, and as-built schedules. Each of these scheduling processes represent the various schedule forms and detail the proper steps to be taken should particular events occur.

2.2.1 Preliminary Schedules

The creation of a preliminary project schedule can be viewed as the jumping off point for the contractor for establishing a generalized work plan. Submission of a preliminary schedule is usually required with the initial bid documents and is expected to include the contractors plan for achieving major milestones, as well as an estimated total project duration.

Upon award of the project, the contractor must then work to further detail the preliminary schedule, usually encompassing the first 60 to 90 days of work in detail. Work to be completed after this time frame will temporarily remain at a summary level, consisting of major milestones or phases (VDOT 2011). Specifics regarding the level of detail will vary based on contractual requirements.

Submission of this version of the preliminary schedule typically occurs within two days of the scheduling conference or preconstruction meeting. Submittal elements typically include the schedule itself, along with a narrative that verbally describes the proposed plan. This type of workflow allows the project to begin, while also giving the contractor sufficient time to complete the details for the remainder of the schedule (Li and Carter 2005). The construction schedule will remain as a "preliminary schedule" until the entire scope of work has been properly detailed and accepted by the owner as the baseline schedule.

2.2.2 Baseline Schedules

Within a short period of time (usually 30 days) following the notice to proceed (NTP), the contractor is generally required to submit a baseline schedule. The baseline "… encompasses the entire project, including all subcontracted work, and provides an overall snapshot of the project scope" (Sears 2008). To properly showcase the entire scope of work, the baseline schedule submittal will typically contain the schedule itself, the project narrative, and the earnings curve proposed by the contractor.

As mentioned previously, the owner must accept the contractor's plan of action before the schedule can officially be deemed the baseline. Upon submission, the owner (or the owner's representative) will review the schedule to ensure compliance with the contract. Items of interest will typically include: sequence and workflow, constructability, timing and phasing, resource usage and balance, ease of understanding, ease of updating and maintaining, and constraints (Winter 2007). In most cases, the first submittal will not fully meet the terms of the contract documents and alterations will be necessary (Li and Carter 2005). Figure 2.1 gives an example of the baseline development/submission process, where the terminology "Initial Schedule" corresponds directly with the previous section, "Preliminary Schedules."

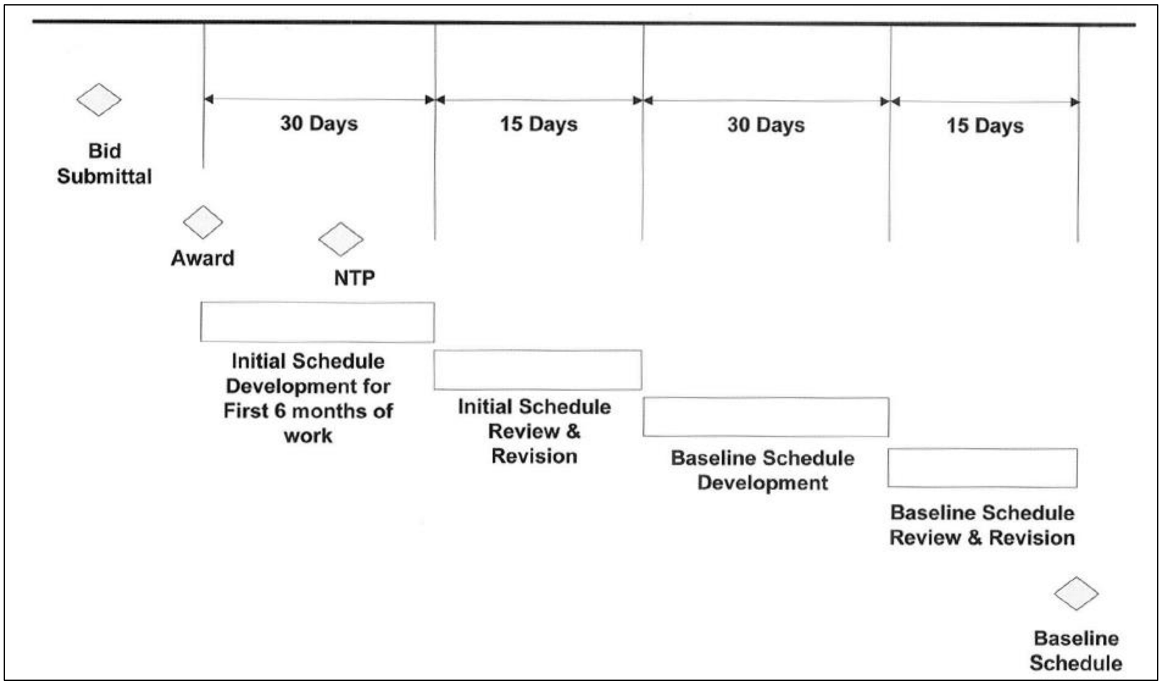


FIGURE 2.1: Baseline submittal timeframe (Li and Carter 2005)

Development of an accurate and useable baseline schedule is crucial for project success. Not only does it allow the contractor to communicate the plan of action and properly coordinate with others involved, it acts as a datum for assessing impacts to the schedule. Once accepted, the baseline schedule will serve as the reference for measuring and controlling project progress. This schedule is referred to as the Schedule of Record (SOR). Throughout the life of the project, it is necessary to maintain the schedule to ensure an accurate reflection of true project progress. Details regarding the maintenance of the construction schedule can be found in subsequent sections.

2.2.3 Schedule Updates

After a baseline schedule is created and accepted, it is then necessary to maintain the construction schedule throughout the life of the project. Hinze (2008) states “It’s important to have a schedule, but it’s more important to use it.” And in order to properly utilize a project schedule, it must accurately reflect the current project progress. This is where the act updating the schedule becomes relevant.

"The purpose of an update is to record past performance and to determine the impact of past performance upon expectations for the future" (O'Brien 2006). In a shorter phrase, schedule updating can be thought of as "bringing the schedule current." To carry out this task, the contractor must implement methods of monitoring work taking place on the job site and then use that information to physically update the schedule. Items of interest for each activity typically include: actual start dates, actual finish dates, and remaining duration (Winter 2007). When looking at the entire network, elements to be considered include: activity logic, data date, total float, unexpected delays, and resource usage (VDOT 2011). The primary monitoring method is direct observation. On smaller, less complex projects, this can be carried out by an individual at a management level. For larger, more intricate projects, it is usually more beneficial to receive status updates from the various foremen on the job. This is mostly easily accomplished by generating a report of activities within the timeframe of the update, and then giving the report to the foremen to complete. Figure 2.2 shows an example of such a report, where the columns "Activity" and "Scheduled" would contain the activities in question, and the remainder would be filled in by the various foremen. To supplement direct observation, the use of photographs or time-lapse photography may be employed to monitor progress (Hinze 2008).

Upon completion of the monitoring process, the contractor can then use the gathered information to generate status reports and make assumptions regarding the remainder of the project. Performing an update allows the contractor to look back and gauge if the project is meeting the planned expectations, exceeding the expectations, or falling behind the expectations (O'Brien 2006). It depicts exactly how the project has progressed thus far, and gives a snapshot of where the project stands, both in terms of time and money. With actual information regarding start dates, finish dates, and remaining duration, the contractor can analyze and determine which activities tended to take longer, which activities consumed more resources than expected, which activities were eliminated, and which activities have become critical or near critical. In addition, knowledge of actual construction sequence could reveal a more efficient work flow in regards to means, methods, and logic. These alterations are typically based on unforeseen site conditions or project constraints that were not easily identifiable during the development of the baseline schedule. Recognizing such elements can allow the contractor to make appropriate shifts in the schedule to ensure that the completion date can still be met and that the project will stay within the budget.

Activity		Scheduled		Actual/Expected		Status	Notes
ID	Description	Start	Finish	Start	Finish	%	

FIGURE 2.2: Sample updating report form (Hinze 2008)

An example of such an instance can be describe as follows. Suppose the masonry crew has taken two extra days to install brick veneer on section A of a project. Because of this, the contractor may assume that the brick veneer on section B will also require two extra days because the conditions of both section A and B are very similar. The contractor can make this minor adjustment to the duration of the activity and continue to analyze the remainder of the schedule for further impacts. With larger, lengthier projects, a loss of two days will not likely impact the remainder of the job. However, identifying and resolving these slight shifts early on can help to prevent small issues from becoming unmanageable in the future.

With only minor shifts performed in the update, the original baseline schedule will continue to be the SOR against which remaining progress will be measured. Should a more significant change be required, the contractor would then need to submit either a modified schedule or a revised schedule. Specific requirements for when a modification or revision are required versus just an update are typically detailed in the contract.

In terms of frequency, schedule updates typically occur on a monthly basis. The contract will specify the exact frequency, as well as the timeframe required for submittal. In general, the update should be submitted to the owner within five days of the monthly progress meeting and will typically include the updated schedule, the updated project narrative, and the updated earnings curve (VDOT 2011). Often times, payments due to the contractor will not be disbursed until the updated schedule has been received and reviewed. This allows the owner to ensure that progress is indeed being made and holds the contractor accountable (Winter 2007).

2.2.4 Schedule Modifications

Upon completion of the schedule update, the contractor must analyze past progress and make assumptions regarding the remaining work. If progress is proceeding as planned, the updated schedule will then be utilized to generate progress reports. However, if the schedule update reveals slight deviations from the baseline schedule, it may be necessary for the contractor to create a modified schedule.

Slight deviations might include: shifts in activity durations, minor logic shifts, or minor resource usage shifts. These elements will not create a need for a new baseline schedule, but will show how the work was actually performed and the contractor's plan for handling future work based on the minor shifts. Final project completion date will not be shifted due to the minor schedule modifications.

The submission of a modified schedule will proceed in a manner similar to a schedule update. It will typically consist of the schedule itself, a modified narrative describing the minor changes, and a modified earnings curve. Once submitted, it will be necessary to measure progress and ensure that the modified schedule accurately represents the actual construction sequence. Reports regarding overall job status and progress may then be generated.

2.2.5 Schedule Revisions

Occasionally, the schedule update will reveal that the project has significantly deviated from the SOR and the work plan in place for the remainder of the project no longer represents reality. In this instance, a schedule revision will be necessary. Its purpose is to "… insert deliberate changes to the existing 'plan of execution,' either to account for changes to the project or to improve upon the previously ‘means and methods’ chosen” (O’Brien 2006).

Specific elements that constitute a schedule revision will be detailed in the contract between the owner and the contractor. In most cases, a schedule revision will be necessary if changes occur in one of the following three areas: scope, conditions, or approach. For example, if a change order is issued by the owner that requires the addition of new work (or removal of existing work) it is considered a significate change in the scope and a revision will be required (Woolf 2007). In this case, the owner is responsible for the change and the contractor may be entitled to a time extension. On the other hand, if the project has shifted because the contractor altered the previously specified means and methods, an extension of contract time is usually not in order.

Regardless of who is at “fault”, a schedule revision contains alterations that are significantly different from the baseline schedule. Therefore, the original baseline schedule is no longer relevant, meaning the revised schedule will become the new SOR upon review and acceptance by the owner. This is also known as “rebaselining” (Woolf 2007). Submission of a revised schedule is similar to the initial process used in the creation of the baseline. The contractor will usually produce a revised narrative, a revised schedule, and a revised earnings curve. All revised information will be reviewed by the owner, and the contractor will make changes as directed by the owner. Once the revised schedule is accepted as the new SOR, all future progress on the job will be measured against the revised schedule.

2.2.6 Recovery Schedules

A recovery schedule may be viewed as a more severe version of a schedule revision. However, the purpose of a recovery schedule is to "… modify the current plan because the schedule slipped for whatever reason, with the goal of regaining whatever time was lost" (O'Brien 2006). The primary difference between a revised schedule and a recovery schedule is that a recovery schedule makes an attempt to make up for lost time. The contractor has fallen behind in an inexcusable manner, and is typically required by contract to create a plan to get the project back on track. It is still expected that the contractor meet the original completion date, or face any liquidated damages specified in the contract.

In order to achieve this goal, the recovery schedule must show the contractor's planned efforts to make up for lost time on the project. Typically, this will include the hiring of additional crews, working longer hours, working weekends, or adding larger equipment (O'Brien 2006).

Once the owner requests that the contractor submit a recovery schedule, the contractor will follow the same procedures utilized in the development of the original baseline. This will usually include the submittal of the recovery schedule, a detailed recovery narrative, and other requirements laid out in the contract documents. The owner will then review the contractor's recovery plan and determine if it is acceptable. Similar to a schedule revision, the acceptance of the recovery schedule establishes a new SOR and renders the original baseline useless. All subsequent progress will be measured against the newly created recovery schedule.

2.2.7 As-Built Schedules

The final scheduling process is known as the as-built schedule. This schedule is exactly what its name implies. It details actual start dates, finish dates, and durations for each activity on the project. Any changes pertaining to logic, means and methods, delays, or change orders will also be noted in the as-built schedule. This may even include information regarding specific weather events or extra work incurred due to unforeseen circumstances (Sears 2008).

It is important to complete the as-built schedule to reflect the actual occurrences on a project. From this, the contractor can analyze issues that could have been mitigated, and log them as a type of "lessons learned" for future projects. In addition, the as-built schedule may be of use should a delay claim arise. Having an accurate record of actual project process can potentially aid the contractor in legal disputes (Hinze 2008).

2.3 4D Technology and Scheduling

The practice of construction scheduling has remained fairly constant over the past several years. In general, schedules are developed as 2D diagrams on paper, such as CPM networks or a Gantt charts. However, these 2D methods do not provide construction planners with any spatial information regarding the actual construction process. Schedulers must use their experience and intuition in order to decide the appropriate means, methods, and sequencing of construction, which will then produce the construction schedule (Mahalingam et al. 2010; Karshenas and Sharma 2010; Wang et al. 2004).

With advancements in digital technology, 4D modeling has continued to grow and develop, making it more relevant in the realm of construction. In essence, a 4D model (or 4D schedule) is generated by linking elements within a 3D model to activities in the construction schedule (Fischer and Kunz 2004). The 3D model contains digital geometries that correspond with physical elements to be constructed on a project, while the schedule contains all activities necessary to construct the project. Attaching time information to traditional 3D elements allows the schedule to also be displayed in the 3D environment (Wang et al. 2004).

2.3.1 Current Uses

The implementation of 4D models in the construction industry has been primarily geared towards enhancing the visualization of the construction process (Castronovo et al. 2014). Thus far, these advancements are only being employed in the early phases of construction projects. In scheduling terms, the creation of the 4D model typically coincides with the development of the baseline schedule. The final product generated from the 4D is usually a video animation that can be viewed digitally. Typical controls such as video speed and zooming can be manipulated in order to focus on specific areas.

During the creation of the baseline, 4D technology allows planners and schedulers to visually coordinate various aspects of the project and identify issues that a traditional schedule would overlook (Dang and Bargstädt 2016). However, once the baseline has been completed, it is rare that the initial 4D model moves forward with the project and becomes integrated into the other scheduling processes such as updates and modifications.

2.3.2 Benefits

This ability to visualize provides benefits such as: improved communication, time-space conflict detection, identification of missing activities, identification of incorrect logic, and project constructability (Allen and Smallwood 2008; Dang and Bargstädt 2016; Koo and Fischer 2000; Staub-French et al. 2008). In addition, should any issues arise when evaluating the items listed above, the planner can then perform "what-if" scenarios in efforts to seek out a solution (Wang et al. 2004).

In order to have a successful construction experience, excellent communication is required between all parties involved. 4D modeling is a tool that can be utilized by the contractor to more clearly communicate the plan of action that has been developed for the project (Dang and Bargstädt 2016). Rather than simply submitting a 1000 activity schedule to the owner, a 4D model can serve as a visual representation of the schedule, allowing the owner to more easily understand the contractor's intent (Castronovo et al. 2014). Interactions between the contractor and the subcontractors can also benefit from the use of a 4D schedule. Subcontractors can gain a sense of the space that they will be working within and potential constraints, allowing them to better prepare for the upcoming job. The use of 4D technology provides a platform for consistency, allowing for clear lines of communication.

Another secondary benefit gained from the ability to visualize is the detection of time-space conflicts. Project planners must ensure that all trades working on the job have sufficient space to perform their necessary activities. Scheduling multiple trades at the same time, in the same place, can significantly reduce productivity, and potentially, quality (Koo and Fischer 2000). 4D modeling can alert the scheduler to these overlaps, allowing appropriate changes to be made before construction begins.

Viewing a construction schedule within a 3D environment can also aid in determining the accuracy and completeness of the schedule. In terms of accuracy, the planner needs to ensure that all activities proceed in a logical manner that represents the selected construction method. But, the planner must also be working with a complete schedule that is not missing any activities necessary for project completion (Koo and Fischer 2000). Analyzing a 4D model can instantly pinpoint missing activities because each 3D element ought to be tied to a discrete schedule activity. Similarly, work elements should appear within the 4D in the order of how they would be constructed. The planner would be able to visually identify errors within the logic, which can be difficult when only utilizing 2D network diagrams.

In addition to accuracy and completeness, 4D modeling can aid in evaluating the overall constructability of the project at hand (Boton et al. 2013). As mentioned previously, schedulers and planners must use their experience to determine the best course of action for a project. When utilizing hand drawn methods, it leaves time for only one physical iteration. But, with 4D modeling, numerous options can be tested to ensure optimum constructability (Staub-French et al. 2008). The amount of "what-if" scenarios are virtually unlimited, allowing the planning team to create the most ideal schedule that considers each of the previously mentioned aspects.

2.3.3 Shortcomings

Although there are clearly many benefits that can be realized through the utilization of 4D technology, the application is currently limited. Planners and schedulers are only implementing 4D models at the beginning of the construction project. Of course, the initial visualization process serves as a tremendous aid during the development of the baseline schedule and provides numerous benefits. However, the benefits experienced are limited to the early phases of the project and are not carried through the entire life. The schedule is a tool that should be constantly utilized and consulted to ensure proper project progression. Implementing 4D visual aids into all scheduling processes could further aid the contractor in this task, particularly with schedule updates. Updating the schedule is the most frequently performed process, and it is the update that indicates the status of the project at a particular point in time. Employing 4D technology into the updating process could reveal more information regarding project status, which would in turn offer supplementary assistance to the contractor when considering the plan of action for the remainder of the project.

In addition, the current presentation format of 4D technology only takes the form of video animations. While this is useful for displaying the sequencing for the entire project, it typically only captures the “big picture” by showing the general progression of work, which is necessary when considering a large project. Although animations are very clear in their intent, alternate forms of information delivery could be investigated. It could be that a static depiction derived from the 4D animation would better suit the needs of the viewer. Regardless, having more methods of conveying information from the 4D model could potentially benefit all users.

2.4 Summary

Construction scheduling and the associated processes are extensive in nature, and most frequently a product of contractual requirements. While they may seem cumbersome for some contractors, the requirements in place for all of the scheduling processes benefit all parties involved. It is crucial for the contractor to have a plan of action in place that can be clearly communicated to everyone involved.

With the utilization of 4D technology, communicating the contractor’s plan becomes much easier. Issues amongst interested parties can be worked out well before construction begin, making 4D scheduling a powerful tool in the beginning stages of the project. However, there are many other scheduling processes described in previous sections that do not take advantage of 4D scheduling technology. In particular, the act of updating a schedule occurs rather frequently and serves as the primary means of informing the client of the project status. Bringing the 4D model forward from the initial baseline schedule into the schedule update could provide the many benefits listed above throughout the entire life of the project.

CHAPTER 3: SCHEDULE UPDATE FUNCTION

When considering schedule update function at an overview level, it generally allows parties involved to understand the current status of a project at a specific moment in time. Progress documented at the time of the update is measured in comparison with the baseline schedule developed prior to the start of construction. This comparison details project progression and communicates delays, unforeseen issues, or positive impacts, which allows informed decisions to be made regarding remaining work.

However, a more precise function of the schedule update will vary based upon the end user and the specific information they are seeking. In order to gain an understanding of the many facets present within a schedule update, it was first necessary to identify end users and assess their rational for consulting the update. This assessment produced a comprehensive understanding of the various informational elements being sought by each user and allowed for the compilation of an essential capabilities list.

Once the essential schedule update capabilities were compiled, a review of the current communication methods was conducted. Understanding the ways in which information is presented to the various users allowed for the identification of effective processes in place, as well as gaps and areas that require improvement. The capabilities previously identified as essential were used in tandem with current communication methods when defining an applicable deliverable for 4D schedule updates.

3.1 Key Schedule Update Users

For the process of construction schedule updating, three key end users have been identified: General Contractors, Subcontractors, and Owners. While there are other potential users of the update, those identified represent those who will consult and utilize the update regularly in order to monitor and maintain project progress. These three users will be concerned with the schedule update for a variety of reasons and will seek to gain various information contained within the update. The following sections examine each user and identify their specific needs regarding a construction schedule update.

3.1.1 General Contractors

The general contractor will often be the party that is most concerned with the schedule and the various scheduling processes that occur throughout the project. In the early project phases, it is the contractor who develops the baseline schedule to represent the overall plan of action for completing the work. To ensure that the project is progressing as planned, it is necessary for the contractor to perform periodic schedule updates. This allows the contractor to analyze current project performance and determine if previous performance will have an effect on the remainder of the project (O’Brien 2006).

Contractors being by identifying the following items: actual start (AS) dates, actual finish (AF) dates, and remaining activity durations (RD). This information will be used to evaluate project status and compute various schedule metrics that inform the contractor if the project is behind schedule, on schedule, or ahead of schedule. The various metrics can be used to detail the status of the entire project or perhaps a set of activities within a particular project phase or milestone. Metrics of interest to the contractor include but are not limited to:

- Budgeted Cost of Work Scheduled (BCWS) – estimated value of the work *planned* to be completed to date
- Budgeted Cost of Work Performed (BCWP) – estimated value of work completed to date
- Actual Cost of Work Performed (ACWP) – cost incurred of work completed to date
- Budgeted Cost at Completion (BAC) – original estimated value of the total project
- Estimated Cost at Completion (EAC) – current estimated cost for the total project based on actual cost performance to date and estimated cost of future work
- Planned Percent Complete (PPC) – percentage of total work *planned* to be completed to date
- Percent Complete (PC) - percentage of total work completed to date based on estimated costs
- Schedule Variance (SV) – deviation from the schedule
- Schedule Performance Index (SPI) – ratio of work performed to work planned, based on estimated costs
- Cost Variance (CV) – deviation from the budget
- Cost Performance Index (CPI) – ratio of actual to estimated costs, based on the work completed to date

Calculation of the metrics listed above can be computed by utilizing the updated schedule. These items transform project progress into a numerical format that can quickly inform the contractor of project status.

However, numerical representation of status may not always depict the complete nature of the events occurring on site. Additional information can be derived from the update process that speaks to larger issues that may have impacted the project. Examples of such include the analysis of the critical activities through the network. At the beginning of construction, a set of activities are deemed critical, meaning shifts in their planned start and finish dates will influence the completion date of the overall project (Dunn 2005). Creation of new critical paths due to float usage on previously non-critical activities could be an indication of major issues that may continue to occur as the project progresses (O'Brien 2006). On the contrary, activities may have started or finished late, but that does not necessarily put the entire project behind. If those activities that were late are not on the critical path, then the likelihood of overall project delay is slim. At first glance, metrics can be very informative, but it is crucial that all details are taken into consideration when utilizing an update.

Contractors also use the schedule update to gain an understanding of activities and their intended start and finish dates. For example, reports can be produced that include activities that have started but have not yet finished, activities that started and should have been finished, and activities that should have been started but were not. Items such as these could lead the contractor to conclude that a specific crew is continuously late on their designated tasks, in turn causing delays in the project. Similarly, a specific type of work could be causing problems due to the nature of the site or surrounding environment. On the other hand, the contractor can view activities that started on time but finished early, those that started early and finished early, or those that started late but finished early. Understanding tasks that finish early could identify crews that performs their tasks efficiently, which may constitute reward for excellent work. Generation of various activity reports is virtually unlimited and gives the contractor the ability to sort, filter, and view activities of interest. This can produce a schedule update that allows the contractor to pinpoint the root of the issue and work to formulate solutions to maintain intended project progress.

The updating process is equally as useful for understanding the scope of the upcoming work. While meeting the final completion date is the overall goal, contractors must also focus on the work in progress and the work immediately upcoming. Contractors can view activities due to begin within the next week, the next two weeks, or even the next month. The ability to look ahead allows the contractor to prepare for the specific tasks that are actually upcoming, rather than those that might have been expected to be upcoming during the initial creation of the schedule. On a much larger scale, the contractor may also have to consider future jobs that have already been awarded. In order to keep up with the work demand established, the contractor must complete all duties in a timely fashion to avoid delaying current projects in addition to future projects.

Different contractors will be drawn to different methods of viewing project status, but the overall goal remains the same; utilize the update to evaluate past project performance, understand the current status, and determine an appropriate strategy for the remainder of the project. The contractor is responsible for the overall plan of action, and using an accurately updated schedule allows the plan of action to be shifted, if necessary, to control project completion.

3.1.2 Subcontractors

The second major party of concern is that of the subcontractors. Subcontractors utilize a schedule update in a similar manner to the general contractor, but their focus is placed solely on their individual scope of work and its relation to the entire project. As the project progresses, the master schedule will be updated to reflect current status, which could potentially alter the timing of the responsibilities held by subcontractors.

Consideration must be taken in order to understand the implications of the master schedule on the individual scope of the subcontractor. This is done by looking specifically at tasks that precede and succeed the tasks of the subcontractor. The overall schedule update will indicate any delays in prerequisite work, therefore notifying the subcontractor of potential issues. This could mean that the subcontractor cannot physically begin their portion of work, or they could be forced to work around the previous task that should have been completed. On the other hand, work may be progressing more rapidly than originally expected, which might allow the subcontractor to begin their tasks early. This type of occurrence gives more flexibility to the subcontractor and eases the pressure of performing within a limited time frame. No matter the situation at hand, it is the duty of the subcontractor to plan and coordinate their specific work within the context of the overall project.

In addition to timing conflicts, subcontractors might also be concerned with the coordination of multiple ongoing projects. If this is the case, the subcontractor has more than likely made arrangements regarding the allocation of resources such as manpower, machinery, materials, and money. Specific resources may be limited, especially for smaller companies, and will dictate when work may be performed. For example, suppose a small concrete subcontractor owns two concrete pumps. The subcontractor has three jobs on the books, two of which are ongoing, and one that is upcoming. One of the ongoing projects, Job A, is due to be complete in one week, meaning that one of the concrete pumps will be available for the upcoming job. The new project, Job C, is slated to begin just after the completion of Job A. But, if a delay occurs on Job A, it will require the use of the concrete pump for additional time, in turn delaying progress that should have been made on Job C. While this example is very simplistic in nature, the consequences experienced by the subcontractor could be devastating.

The accurate update of the overall schedule will allow for proper arrangements to be made by each of the subcontractors present on the jobsite. A comparison between the master schedule and the individual plan laid out by the subcontractors could identify and mitigate conflicts before they arise, preventing negative effects on the overall project completion date (Dossick and Schunk 2007).

3.1.3 Owners

The last party identified with a specific interest in schedule updates is the owner. While their concern may not be focused on specific project metrics, numbers, or activities, they will be seeking information regarding overall project status. Status could be representative of the entire project or of particular milestones, depending on the specific goals of the owner.

Owners are typically considering a much larger picture when inquiring the status of a construction project. Whether it is a 20-story high rise or a roadway repair, owners will normally be analyzing status in terms of impact to their overall strategy. Updates are useful in this case because they allow owners to consider the effect of a particular occurrence and compare potential outcomes. Such outcomes could relate to future business endeavors that hinge on successful completion of the project. An update will allow the owner to make informed decisions regarding upcoming tasks relating to their personal commitments.

In addition to long term planning for personal purposes, the owner uses an update to understand the timing of their obligations to the current project. Examples of such obligations might include reviews to shop drawings, submittal approvals, provision of equipment, or payments to the contractor. It is important that the owner understands the potential shift in the timing of their duties to avoid unnecessary delays.

Owners will also utilize the information generated in an update to determine if past progress is sufficient and if the remainder of the work complies with contractual requirements. If current progress is not adequate, or if the proposed plan for future work violates the contract, the owner may direct the contractor to modify the schedule or produce a recovery schedule. No matter the circumstance, the owner will utilize the schedule update and determine the actions needed, if any, to meet their previously defined goals.

3.2 Summary of Required Elements

From reviewing the three identified end users, it is clear that a fully functional schedule update provides various informational elements to users. While the previously identified elements are wide spread in terms of specific informational goals, it is possible to condense the various concepts into a more concise list of discrete capabilities. These capabilities represent the elements required for the functionality of a schedule update. Ideally, each of the three users mentioned previously could gain their desired information if the schedule update provides and identifies information pertaining to the following:

- The data date and update period
- Planned activity start dates
- Actual activity start dates
- Remaining duration for activities in progress

- Planned activity finish dates
- Actual activity finish dates
- Planned activity logic
- Actual activity logic
- Critical activities
- Newly critical activities
- Near critical activities
- Cost incurred by each activity
- Resources used by each activity
- Float usage
- Anticipated completion date of overall project or milestone
- Activities due to start in the next update period
- Activities that should have been due to start in the next update period
- Activities due to finish within the next update period
- Activities that should have been due to finish in the next update period
- Activities that finished late
- Activities that finished early
- Activities that utilized the exact duration estimated
- Activities that utilized more duration than estimated
- Activities that utilized less duration than estimated

Capabilities listed here would provide an update user with information needed to make informed decisions, no matter their individual goals. Within the identified capabilities, a secondary filter can be applied to rank the importance of individual elements and their overall contribution to the update. Understanding which capabilities are essential versus supplemental allows for a more thoughtful creation of informative deliverables. Therefore, the previously identified capabilities have been subdivided into three distinct categories: those essential for an update, those recommended for an update, and those supplemental to an update.

3.2.1 Essential Capabilities

Items listed in the essential category describe capabilities necessary to fulfill the minimum function of a schedule update. Users can analyze the elements within this category and eventually derive answers for any lingering question. Without these key capabilities, the update would not exist. Essentials capabilities are as follows:

- The data date and update period
- Planned activity start dates
- Actual activity start dates
- Remaining duration for activities in progress
- Planned activity finish dates
- Actual activity finish dates
- Planned activity logic
- Actual activity logic

3.2.2 Recommended Capabilities

Items listed in the recommended category describe capabilities that would facilitate further analysis of the schedule update. While these items could eventually be derived from the information included in the “essentials” category, providing the recommended capabilities would give the user additional information from the beginning and allow for a greater ease of understanding. Recommended capabilities are as follows:

- Critical activities
- Newly critical activities
- Near critical activities
- Float usage
- Anticipated completion date of overall project or milestone
- Activities due to start in the next update period
- Activities due to finish within the next update period
- Activities that finished late
- Activities that finished early

3.2.3 Supplemental Capabilities

Items listed in the supplemental category represent items that bring additional value to the schedule update but are not necessary to fulfill the primary function. Supplemental items provide a backdrop and allow the user to gain insights into details surrounding the schedule update. Supplemental capabilities are as follows:

- Cost incurred by each activity
- Resources used by each activity
- Activities that should have been due to start in the next update period
- Activities that should have been due to finish in the next update period
- Activities that that utilized the exact duration estimated
- Activities that utilized more duration than estimated
- Activities that utilized less duration than estimated

3.3 Current Communication Methods of Required Elements

Typically, the act of updating the schedule warrants the submission of progress evidence to the owner or client. This submission documents work that has been completed, provides information pertaining to the plan of action for remaining work, and allows progress to be measured against the baseline schedule (Hildreth 2006). While this process is typically mandated by the contract, the act of updating the schedule is key in communicating and informing all parties of the current situation. Specific submission requirements will vary based on the contract, but will most often include: the updated schedule (digital file or hard copy), updated earned value reports, updated project narrative, and an updated look ahead schedule. Of course, countless documents can be produced in order to convey project status, but those listed represent the most common forms of communication between the contractor, the subcontractors, and the owner.

Each update item listed contains specific information related to the status of the project. The format of the deliverable differs based on the type of data being conveyed. Therefore, it is necessary to consider the relationships between the data portrayed in each item in order to understand the overall status of the project.

3.3.1 Update Schedule

One of the primary elements required in the submittal of a schedule update is the actual schedule itself. The update schedule is usually presented in a digital format, but may also be viewed physically. Field personnel may benefit from a large scale physical schedule that allows for easy review in the construction office.

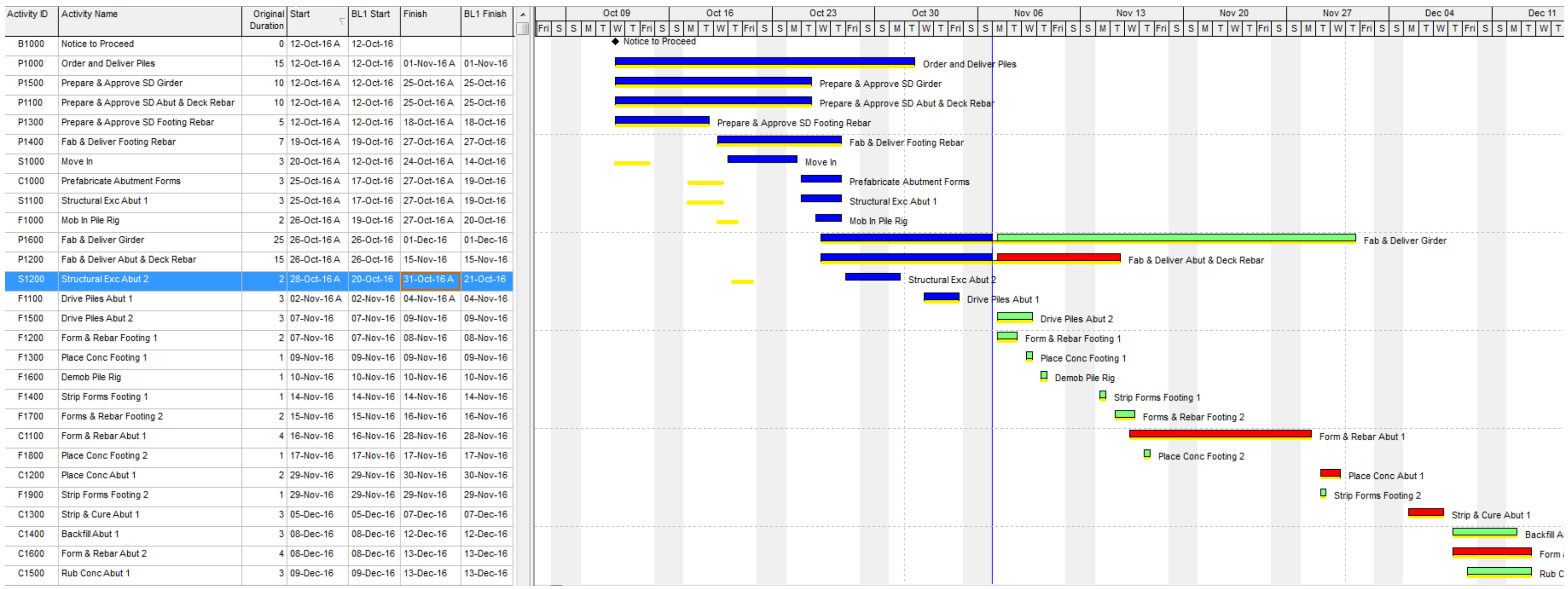


FIGURE 3.1: Basic baseline display

Content is traditionally displayed in list format in combination with a time scaled Gantt chart. Figure 3.1 shows an overview of the display format, which contains list style elements, known as an activity table, on the left and a Gantt chart on the right. Color is used to aid in the visualization of the Gantt chart, where bars in blue represent work that has been completed, green bars represent non-critical work that has not been completed, and red bars represent critical work that has not been completed. The thin yellow bars represent the planned activity dates.

As expected, this deliverable contains the data relating to the activities and logic that make up the schedule. Activity items in the update schedule include actual start dates and actual finish dates for completed tasks, actual start dates and remaining durations for tasks in progress, and projected start and finish dates for future tasks. Additionally, the update schedule has the ability to convey actual logic sequence followed during the construction process and can display anticipated logic for future activities.

Activity ID	Activity Name	Original Duration	Start	BL1 Start	Finish	BL1 Finish	Predecess	Successors
P1400	Fab & Deliver Footing Rebar	7	19-Oct-16 A	19-Oct-16	27-Oct-16 A	27-Oct-16	P1300	F1200
S1000	Move In	3	20-Oct-16 A	12-Oct-16	24-Oct-16 A	14-Oct-16	B1000	S1100, F1000, C1000
C1000	Prefabricate Abutment Forms	3	25-Oct-16 A	17-Oct-16	27-Oct-16 A	19-Oct-16	S1000	C1100
S1100	Structural Exc Abut 1	3	25-Oct-16 A	17-Oct-16	27-Oct-16 A	19-Oct-16	S1000	F1100, F1000, S1200
F1000	Mob In Pile Rig	2	26-Oct-16 A	19-Oct-16	27-Oct-16 A	20-Oct-16	S1000, S1100	F1100
P1600	Fab & Deliver Girder	25	26-Oct-16 A	26-Oct-16	01-Dec-16	01-Dec-16	P1500	D1000
P1200	Fab & Deliver Abut & Deck Rebar	15	26-Oct-16 A	26-Oct-16	15-Nov-16	15-Nov-16	P1100	C1100
S1200	Structural Exc Abut 2	2	28-Oct-16 A	20-Oct-16	31-Oct-16 A	21-Oct-16	S1100	F1500
F1100	Drive Piles Abut 1	3	02-Nov-16 A	02-Nov-16	04-Nov-16 A	04-Nov-16	F1000, P1000,	F1200, F1500
F1500	Drive Piles Abut 2	3	07-Nov-16	07-Nov-16	09-Nov-16	09-Nov-16	F1100, S1200	F1600, F1700
F1200	Form & Rebar Footing 1	2	07-Nov-16	07-Nov-16	08-Nov-16	08-Nov-16	F1100, P1400	F1300

FIGURE 3.2: Sample update schedule, list form

Figure 3.2 shows a portion of the activity table within an update schedule. In this instance, the column “Start” refers to the actual start date for activities that have started and the planned start date for those that have not started. A date with an "A" indicates that the activity has started. The column "BL1 Start" refers to the start date listed in the baseline schedule. The same logic applies to the column "Finish" and "BL1 Finish." In Figure 3.2, it can be seen that activity S1000 "Move In" was planned to begin on the 12th of October but did not actually begin until the 20th of October. Similarly, the planned finish was to be the 14th of October but it did not actually finish until the 24th of October. This example also shows the columns "Predecessors" and "Successors", which details the logic of the construction process. Various column headings can be added or removed based on submission requirements or user preference.

Figure 3.3, on the other hand, depicts the same portion of data in Figure 3.2, but in the form of a Gantt chart. While specific dates cannot be seen in this view, a general timeline can be understood. Graphically, the vertical blue line that divides activities "Fab & Deliver Girder" and "Fab & Deliver Abut & Deck Rebar" is known as the Data Date and represents "The date used as the starting point for schedule calculations" (Hinze 2008). Bars within the chart correspond directly to activity duration, with colors correlating to work that has been performed (blue), non-critical work that is upcoming (green), and critical work that is upcoming (red). The Gantt chart also provides a graphic depiction of the baseline schedule in thin yellow bars below each activity. The baseline can be visually compared with the update to easily gain a sense of the planned timing versus actual timing. For instance, the activity "Move In" was previously describe using actual dates in list format. However, in Figure 3.3, it can be graphically determined that "Move In" occurred later than originally planned. The same can be noted for several other activities shown. Logic between activities is represented through black lines and arrowheads, however, it can be difficult to decipher on a larger schedule. Therefore, it is key to utilize the activity table, as well as the Gantt chart when considering the schedule update.

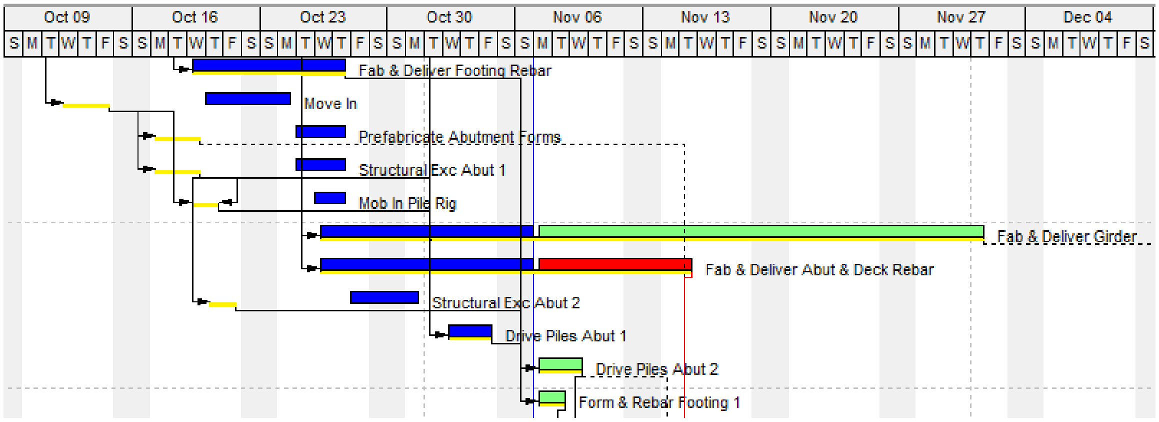


FIGURE 3.3: Sample update schedule, Gantt chart

3.3.2 Update Earned Value Report

In addition to the update schedule submission, an additional item that is required is an earned value report. Earned value can be defined as "… the determination of how much work has been performed on the basis of what was budgeted for the work that has actually been completed. The idea is that a contractor has 'earned' whatever amount was budgeted for the work that has in fact been completed" (Hinze 2008). Using earned value essentially considers cost data in addition to schedule data to aid in the determination of overall project status (Hinze 2008).

Figure 3.4 illustrates the general concepts of an earned value analysis. Key pieces of information needed for the analysis include: budgeted cost of work scheduled (BCWS), budgeted cost of work performed (BCWP), and actual cost of work performed (ACWP). In Figure 3.4, "Earned Value" refers to BCWP, "Planned Value" refers to BCWS, and "Actual Cost" refers to ACWP. In this sample graph, comparisons are made between the listed variables to determine both schedule variance (SV) and cost variance (CV). These two metrics indicate if the project is (or is not) on budget and on schedule and aids in forecasting for future work.

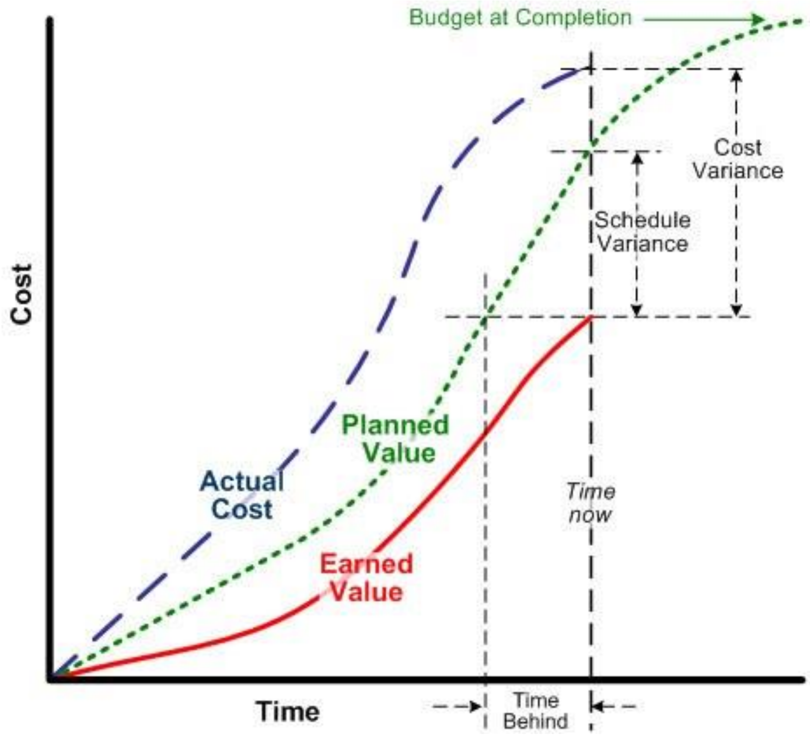
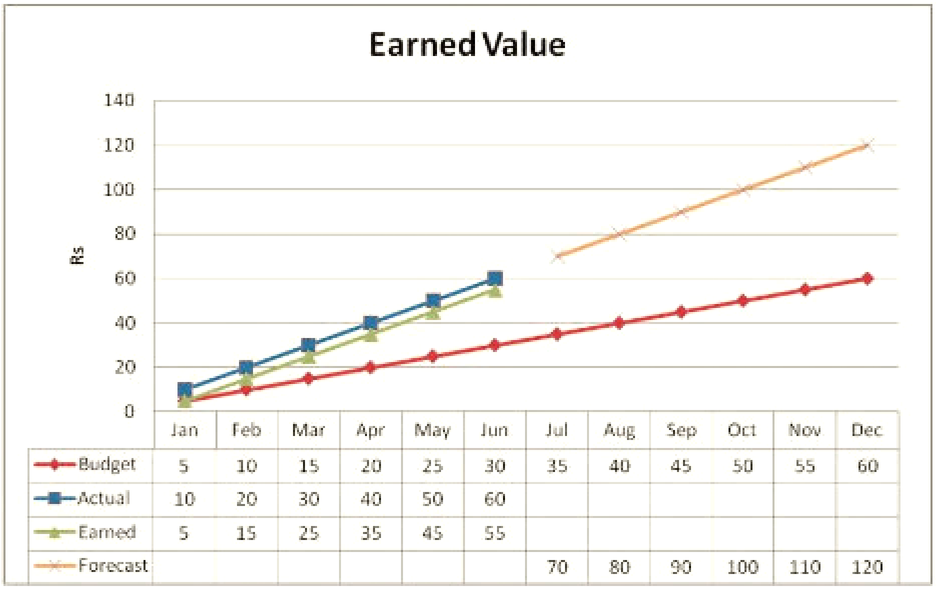


FIGURE 3.4: Typical earned value graph (Williams 2016)

In addition to earned value curves, data may be represented in tabular format. Exact submission requirements are typically detailed in the contract documents, and may require the use of a specific form or document style (VDOT 2011). Figure 3.5 shows a very simple example of an earned value analysis using tabular data at the bottom and graphical data at the top.

Another example format can be seen in Figure 3.6, which displays various calculations and variables of interest. In this case, the term planned value is synonymous with BCWS, earned value with BCWP, and actual cost with ACWP. Calculations seen in the bottom portion of the report show metrics such as cost variance, schedule variance, and estimate at completion for each week of the project. Constant tracking of cost information adds an additional layer for examining overall project performance.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Budget	5	10	15	20	25	30	35	40	45	50	55	60
Actual	10	20	30	40	50	60						
Earned	5	15	25	35	45	55						
Forecast							70	80	90	100	110	120

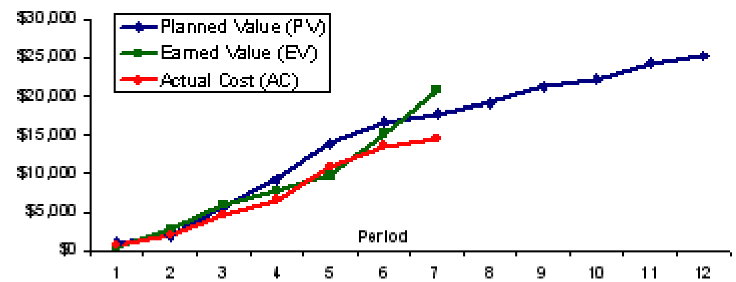
FIGURE 3.5: Basic earned value report (Gaur 2012)

Earned Value Analysis Report

Prepared By: [Manager's Name]
Date: [Report Date]

For Period: Week 7

Summary:
[Use this space to write a brief summary or to record specific observations or notes]



Planned Value (PV) or Budgeted Cost of Work Scheduled (BCWS)

WBS	Task Name	TBC	1	2	3	4	5	6	7	8	9	10	11	12
1.1	Task 1	3500	1000	500	2000									
1.2	Task 2	4200		500	800	900	2000							
1.3	Task 3	4500			700	2000	1000	800						
1.4	Task 4	3300			200	600	1000	1500						
1.5	Task 5	3000					700	500	1000	800				
1.6	Task 6	6700								700	2000	1000	2000	1000
		0												
		0												
		0												
		0												
		0												
		0												
Insert new rows above this one														
	Total Budgeted Cost	25200	1000	1000	3700	3500	4700	2800	1000	1500	2000	1000	2000	1000
	Cumulative Planned Value (PV)		1000	2000	5700	9200	13900	16700	17700	19200	21200	22200	24200	25200

Actual Cost and Earned Value

	1	2	3	4	5	6	7	8	9	10	11	12
Cumulative Actual Cost (AC)	800	1950	4550	6550	10800	13600	14500					
Cumulative Earned Value (EV)	525	2800	5885	7820	9725	15170	20770					

Project Performance Metrics

	1	2	3	4	5	6	7	8	9	10	11	12
Cost Variance (CV = EV - AC)	-275	850	1335	1270	-1075	1570	6270	-	-	-	-	-
Schedule Variance (SV = EV - PV)	-475	800	185	-1380	-4175	-1530	3070	-	-	-	-	-
Cost Performance Index (CPI = EV/AC)	0.66	1.44	1.29	1.19	0.90	1.12	1.43	-	-	-	-	-
Schedule Performance Index (SPI = EV/PV)	0.53	1.40	1.03	0.85	0.70	0.91	1.17	-	-	-	-	-
Estimated Cost at Completion (EAC)	38400	17550	19483	21107	27986	22592	17593	-	-	-	-	-

FIGURE 3.6: Detailed earned value report (Wittwer)

3.3.3 Update Narrative

To create a more cohesive submission, the update schedule and earned value report will almost always be supplemented with an update narrative. The update narrative is a verbal description of project progress and provides insights that are not readily apparent by simply viewing tabular reports. Narratives give consideration to owners and those who are not trained in the construction industry. While contractors can gain a sense of status from viewing the actual update schedule and numerical reports, the information understood by the contractor must be transposed into verbal explanations that can be easily understood.

Content included in a narrative is usually dictated by the contract documents, but will more or less detail the following: general status of the project, changes that occurred during construction, why those changes occurred, identification of issues and problem areas, current factors causing delay, anticipated sources of delay for future work, the estimated impact of potential delays, and the work plan proposed to mitigate future issues (DVA 2012).

Of course, items listed represent an example of minimum requirements. The narrative is the opportunity for the contractor to provide additional rational for occurrences on the project, particularly those with negative impacts. For example, suppose an owner views the update schedule and notices that the excavation work began on time but is overdue to finish by a week. The owner might assume that the contractor is at fault, especially if no other knowledge is available to the owner. The contractor has the ability to defend the delay by including the occurrence of a weeklong rain storm in the narrative. The description could explain that the storm flooded the majority of the project site and required additional time to remove the water and resume excavation. It could also be explained that the excavation work in progress was for the parking area, which is not a critical activity. Although delay was experienced within a specific activity, there were no negative impacts to the entire project.

In the instance that large scale delays were caused, the narrative also provides the opportunity to explain the revised plan of action for the remainder of the work. The background information offered by the update narrative is crucial in comprehending overall project status.

3.3.4 Update Look Ahead Schedule

The last piece of information that is typically included in an update submission is a look ahead schedule. This element differs from the update schedule in that it only focuses on a short period of time immediately following the update. A look ahead schedule will usually detail the work upcoming in the next week or two week period. Producing a look ahead schedule allows the contractor to clearly understand the scope of the immediate work upcoming and plan to accomplish all tasks in a timely manner.

The format of a look ahead may be similar to examples seen in the Update Schedule section using both Gantt charts and tabular data. However, rather than viewing all future activities, only those upcoming within the designated time frame will be shown. The look ahead will also include those activities that were ongoing during the update period. Again, contract requirements will usually determine specific submission requirements.

3.4 Communication Improvements

As described in the previous sections, desired information pertaining to project status is currently communicated through four major deliverables. Each of these items serves a different role in conveying project status to the viewer. It is crucial that each user considers all of the deliverables present when reviewing a schedule update to ensure an accurate understanding of progress on the project.

In terms of formatting and representation of items produced for the schedule update, all documents are 2D representations, viewed on paper or digital monitor. Each item is an individual, static depiction of the project in the form of a schedule, chart, or table. End users are not able to manipulate the deliverables, nor combine them into a single representative form. Furthermore, the lack of three dimensional representation creates difficulties in the visualization of project progress, especially for those who are not accustom to viewing construction schedule documentation.

While the current communication methods have sufficed thus far in conveying necessary information to schedule update users, techniques could be improved through the use of 4D technology. Incorporating 4D technology into a deliverable for schedule updates would allow for enhanced communication regarding project status and enable all users to fully understand the exact implications of issues, regardless of their construction knowledge. Rather than sorting through separate reports and documents to gain a complete picture of the progress, a 4D deliverable can combine all necessary elements and create a more cohesive presentation of required information. A 4D schedule update deliverable would by no means replace the current communication methods, but rather supplement their contents by providing a visual aid for understanding project progress.

CHAPTER 4:4D SCHEDULE UPDATE DESIGN

As mentioned previously, 4D technology has the ability to bring visualization benefits into the realm of the construction schedule updating. However, an ideal deliverable and format for implementing this advanced technology does not yet exist. From studying construction scheduling and the updating processes, it was clear that in order to determine and design an ideal deliverable, a comprehensive investigation of the updating processes must first occur.

Results yielded the “who”, the “what”, and the “how” of current updating practices. That is, who uses schedule updates, what knowledge is desired from the update, and how that knowledge is currently presented. Understanding current communication methods allowed for the identification of efficient processes that work as intended, as well as the identification of processes that could be improved upon. It was found that each of the deliverables mentioned (update schedule, narrative, earned value report, and look ahead schedule) worked well on their own to convey specific bits of information regarding project progress. However, the lack of visual aids forces the viewer to mentally translate numerical values into tangible progress that can be understood within the physical environment. Difficulty also arose when attempting to consider the deliverables in conjunction with each other, which is necessary in order to fully understand the true status of the project.

The approach taken in formulating the aptitudes of a schedule update deliverable using 4D technology works to directly address the aforementioned issues. Capabilities necessary to fulfill the function of a schedule update, which were identified in the previous section, were used as the basis for content creation. Delivery of the content focused on the implementation of visualization aids, which caters to all end users and does not require extensive knowledge of the construction process.

Specifically, the proposed deliverable suggests an informational display in the form of a digitally interactive document that gives users predetermined functionalities for accessing schedule update information. Presentation centers on the visualization of project metrics and status via 3D geometries alongside time indicating elements. Configuration of the displayed data allows the user to quickly view 3D elements in relation to numerical data, eliminating the need to mentally synthesize information from various sources and documents. Additionally, the 4D environment can be navigated through manipulation of the view of the 3D model and various time settings.

To aid in the development of the proposed deliverable, several sources were consulted as precedents to understand current applications of 4D technology within the construction realm. Chau et al. (2004) and Hartmann et al. (2008) discussed 4D visualization as a beneficial project management tool and suggested various means for implementation. These suggestions were considered when determining the appropriate presentation platform for the 4D update deliverable. Additional literature was consulted regarding methods used for visually representing project performance on 3D geometries. Song et al. (2005) presented numerous techniques for representing status through graphical attributes, while Chang et al. (2009) discussed ideal color schemes for use in 4D models. Principles established and utilized within the aforementioned literature provided an existing basis that aided in the formulation of the presented 4D update deliverable.

4.1 Deliverable Overview

This proposal is a representation of the many iterations conducted in order arrive at a viable 4D schedule update deliverable. The primary purpose of the deliverable is to provide a visual aid for viewing and understanding construction schedule update information. As with the traditional communication methods, the deliverable is a product of the updating process. While visible content and viewing preferences of the deliverable can be manipulated by the user, informational attributes contained within the deliverable cannot be modified, altered, or removed.

Before presenting specific details and capabilities, it is first necessary to discuss the proposed platform of the 4D schedule update deliverable. The deliverable contains elements that represent project status through both 3D geometries and written data. This information is produced and displayed in the form of a 3D PDF file, which is digital in nature and can be viewed with a computer, tablet, or smart phone device. PDF files are a standard file type for exchanging information. The 3D aspect of the file refers to the ability to interact with embedded file elements. Producing necessary elements in the form of a 3D PDF allows the user to manipulate and navigate through 3D model elements in a "view-only" environment. Users are not required to possess the software used to create the original 3D model or the original construction schedule. PDF files can be viewed with Adobe Reader, which is a widely available free software.

4.1.1 Content Layout

In terms of content layout, the configuration can be modified by the schedule update creator based on preference and workflow. For the purpose of this research, a default layout display has been established and will be used throughout the remainder of this document. Figure 4.1 shows a schematic layout for the proposed deliverable.

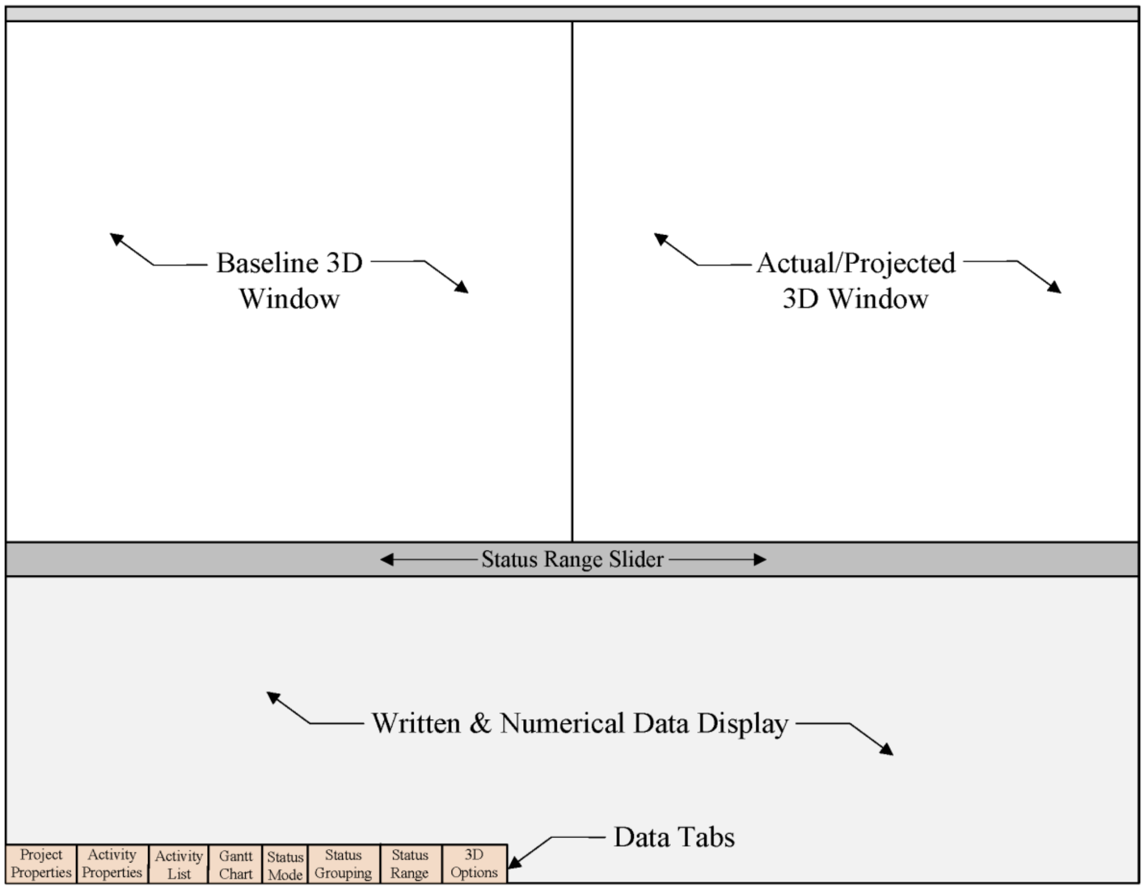


FIGURE 4.1: Schematic layout of 4D deliverable

Three main windows are used to display information pertaining to the schedule update. As seen in Figure 4.1, there are two windows dedicated to the display of the 3D model elements and one dedicated to the display of written and numerical data. 3D models seen in the “baseline” window correspond to the baseline schedule and serve as the point of reference for visually assessing progress. Model elements in the “actual/projected” window represent actual progress, or projected progress, as recorded in the schedule update. The “written & numerical data” window at the bottom of the display consists of various tabs for data display pertaining to project status. An options tab is also included, which allows the user to maneuver through various modes and display styles. Specifics of each window will be detailed further in subsequent sections. Note that the layout shown in Figure 4.1 represents the intended way to view and understand the schedule update within the design of this 4D update deliverable.

4.1.2 Illustrative 3D Geometry

To aid in the explanation of the proposed 4D update deliverable, a basic 3D model was created with various components and levels. The overall geometry is a rectangular prism, comprised of four levels, which can be seen in Figure 4.2. The entire rectangular prism is considered the "project" while the component geometries are considered "activities".

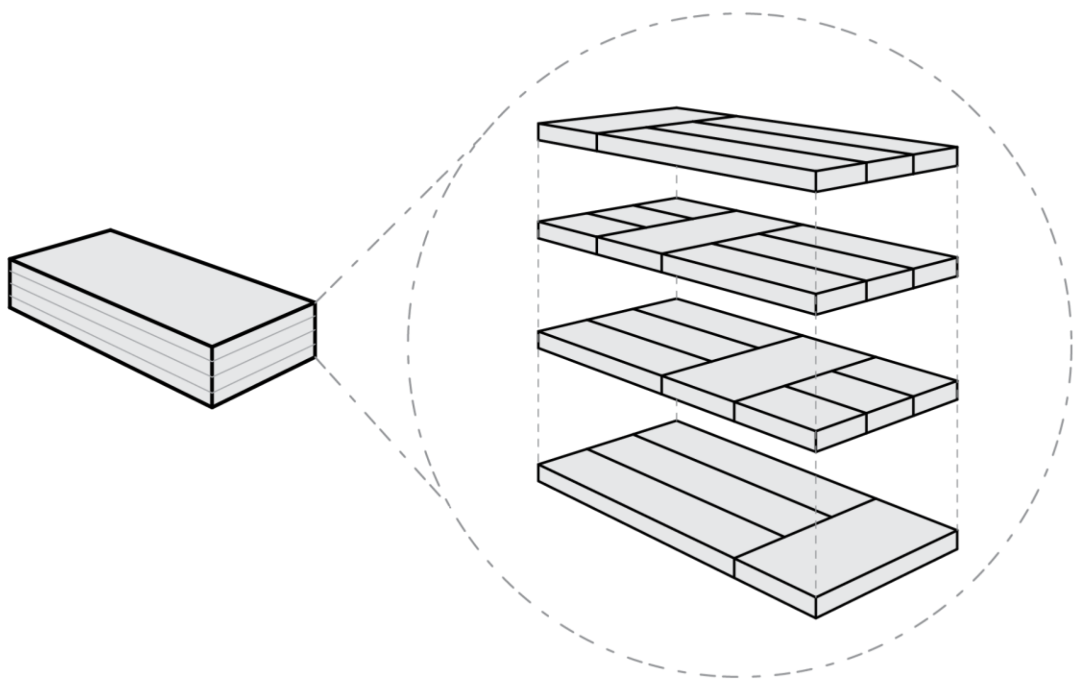


FIGURE 4.2: Rectangular Prism and its component levels

Each of the four levels consists of several geometries. For the purposes of this research, each of the component geometries has been assigned an identifying label. The label refers to the geometry itself as well as its corresponding activity. Figure 4.3 shows each component and its title, which will be referenced throughout the remainder of this document.

Particular capabilities of the proposed 4D update deliverable require the knowledge of activity sequencing for the rectangular prism. Figure 4.4 illustrates the steps taken in order to “construct” the rectangular prism.

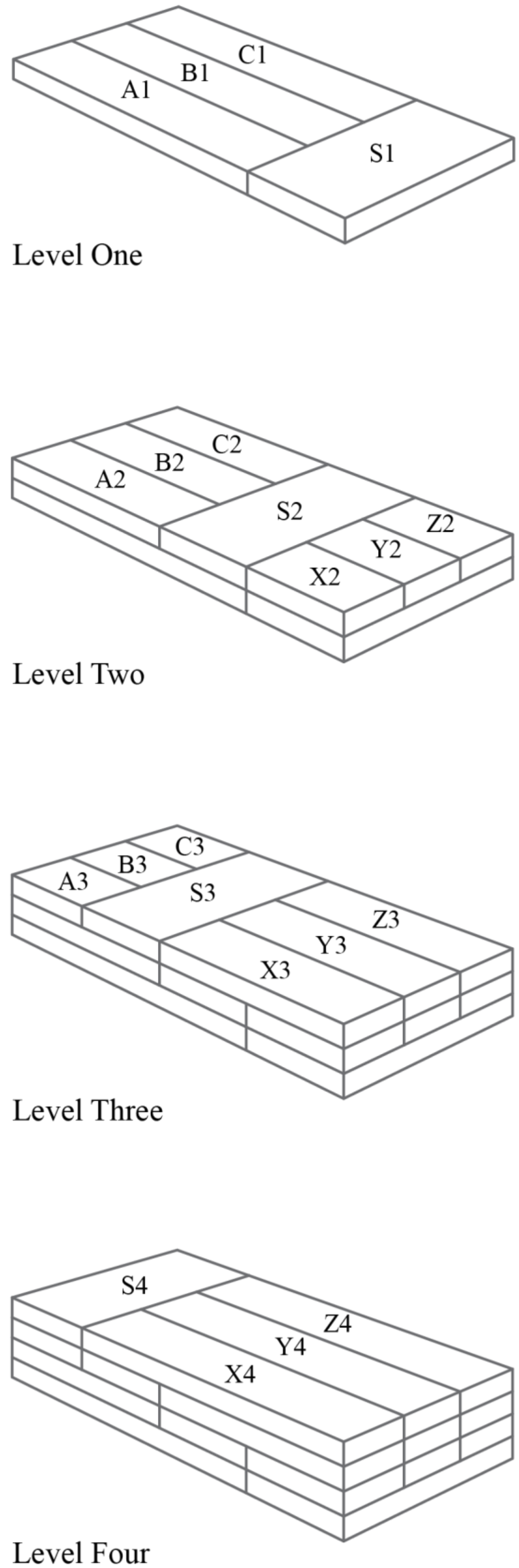


FIGURE 4.3: Component geometries and corresponding titles

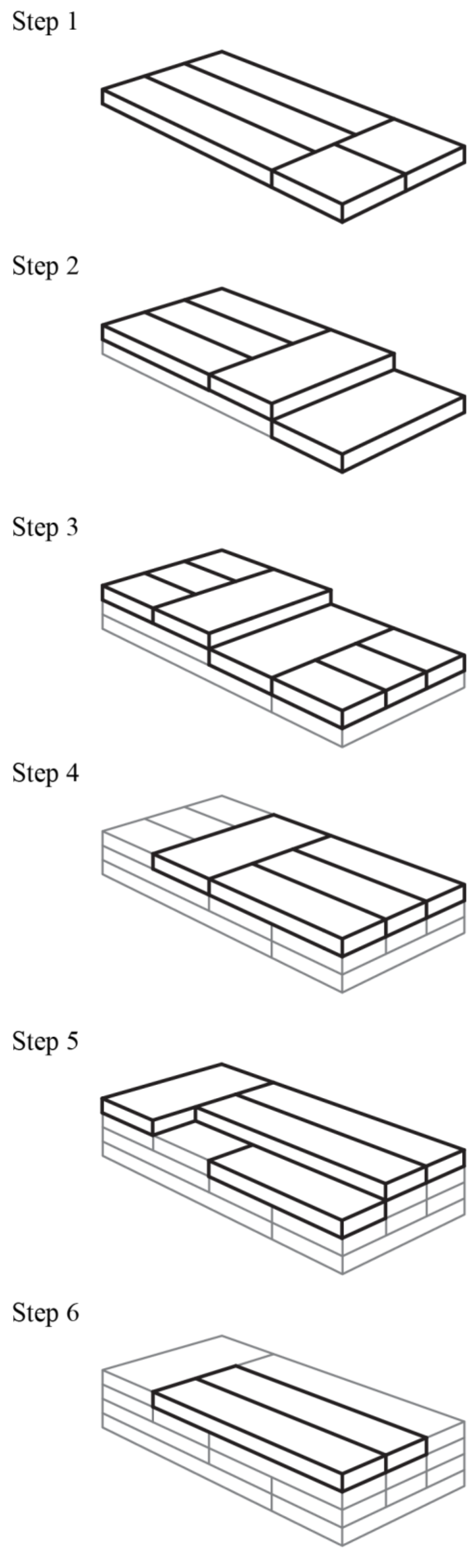


FIGURE 4.4: Assembly sequence for Rectangular Prism

4.2 Content Navigation

As mentioned, a 3D PDF gives the user the ability to interact with informational elements present within the file. This specifically pertains to the geometries in the 3D model windows. When activated, the 3D windows provide basic navigation functions that allow the 3D model to be manipulated and viewed in various ways. Basic functions include panning, orbiting, and zooming and are accomplished respectively: left mouse click and drag, middle mouse click and drag, and middle mouse scroll. Standard views, such as top, bottom, left, right, front, back, and isometric are available within the 3D options tab. By default, manipulation within either 3D window will simultaneously apply the same manipulation to the other 3D window. This option, called "Link 3D Models", can be toggled on and off within the 3D options tab, allowing the user to maneuver each 3D window independently.

Content within the written and numerical data window is navigated by a series of selections to display desired information. Data tabs along the bottom of the window contain various information, which is described in a subsequent section.

4.3 3D Content Display

As mentioned, the primary purpose of this deliverable is to utilize visual aids to convey schedule update information. While all necessary information is present within the 3D PDF file, the 3D content can be visually modified based upon the users knowledge requirements. Three primary capabilities have been given to the user in order to modify the display of the 3D model elements. These include how project status is represented, how status is applied to 3D objects, and which 3D objects are visible. Capabilities have been titled "Status Mode", "Status Grouping", and "Status Range", respectively. Secondary options within each of these categories will further refine the informational display and allow users to customize their visual output. The following sections detail the three primary capabilities.

4.3.1 Status Mode

The Status Mode option gives the user the ability to view project status in two primary ways; in terms of time or in terms of money. In this instance, time refers to using dates, durations, and criticality to determine status. Monetary terms, on the other hand, refers to using the metrics of schedule performance index (SPI) and cost performance index (CPI) to determine project status. These two Status Modes have been deemed “Time Mode” and “Cost Mode.” The user can move between Time Mode and Cost Mode by selecting their preference in the Status Mode tab, located in the Written and Numerical Data window.

The selected mode determines the graphical attributes applied to visible 3D model elements. Attributes assigned by Status Mode include color and transparency. Each mode is represented through a distinct combination of color and transparency, allowing the user to easily differentiate between Status Modes. If the user wishes to view 3D objects without visual attributes representing status, the “None” selection can be made within the Status Mode tab.

4.3.1.1 Status Mode: Time

When viewing status in terms of time, color is used within the 3D environment to indicate start and finish timing (early, on time, or late), and transparency is used to indicate the remaining work. In this instance, “on time” refers to the exact dates within the baseline schedule. A date is considered “early” if the activity begins earlier than the date specified by the baseline. Similarly, dates are considered late if they begin after the date specified in the baseline.

Colors used in this mode include green, blue, and red, where green corresponds with early dates, blue corresponds with on time dates, and red corresponds with late dates (Figure 4.5). When an activity begins, its coloration will be determined by comparing its actual start date with baseline. The 3D geometry that represents that activity will appear in the determined color, with the opaque portion proportional to percentage completed of the activity. The remaining portion of the 3D geometry will appear at a 25% transparency level, with the color corresponding to the projected finish timing.

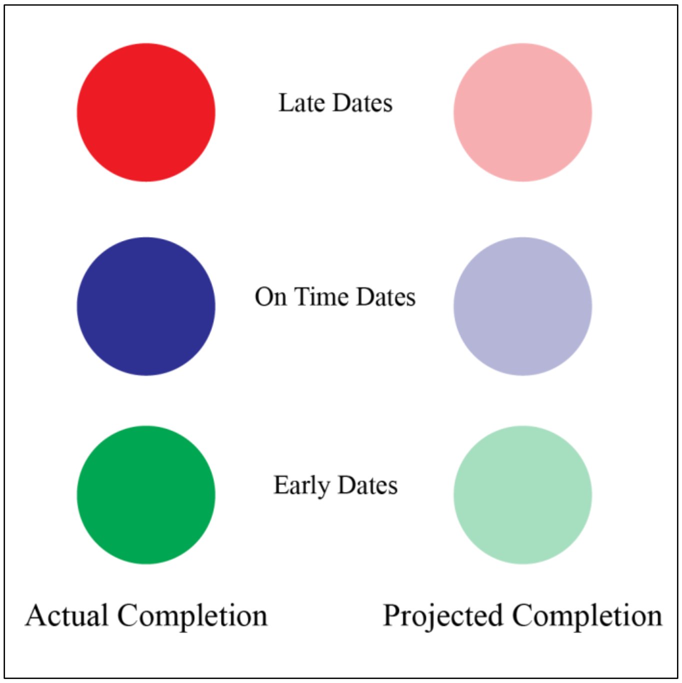


FIGURE 4.5: Time Mode colors

This concept is best explained through illustration of the graphical attributes. Referring back to Figure 4.3, suppose activity A3 was scheduled to start within the most recent update period. Not only was it scheduled to begin, it was also expected to be 30%

complete at the time of the update. This describes the baseline for activity A3 and would have graphical attributes shown on the left side of Figure 4.6. It can be seen that the coloration of the opaque portion is blue, indicating that the activity is planned to begin on time. Additionally, the entire 3D geometry is only 30% opaque, which directly corresponds to the planned percent complete. The transparent portion of the geometry is also blue, indicating that the activity is planned to finish on time.

When the update is performed, actual information regarding activity A3 is used to generate the appearance seen on the right side of Figure 4.6. From this graphic, we can deduce the following:

- The activity began on time (opaque portion is blue)
- The activity is approximately 50% completed (opaque portion covering half of the object)
- The activity is projected to finish early (transparent portion is green)

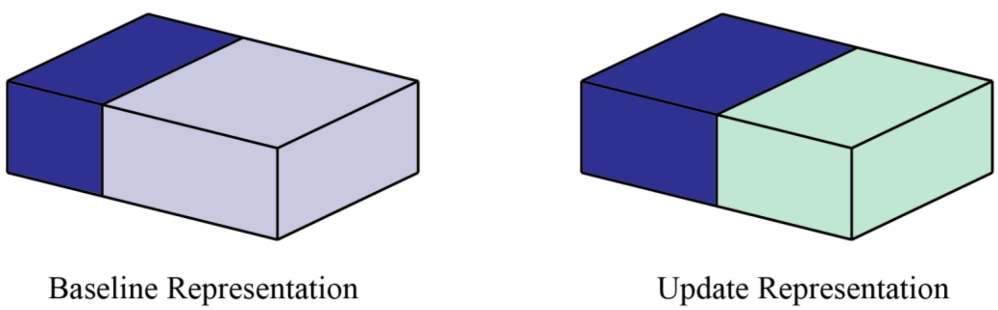


FIGURE 4.6: Basic concept used in Time Mode

When considering the layout of the previously described elements in the 4D deliverable, the left portion of Figure 4.6 would be displayed in the "baseline" 3D window, while right portion would be seen in the "actual/projected" 3D window. This allows for a very easy comparison between the baseline schedule and actual performance on the project. Colors allow users to make quick inferences regarding general project status. An abundance of green coloration in the “actual” 3D window would inform the user that progress is ahead of schedule. Likewise, numerous amounts of red objects would indicate that the project is falling behind schedule.

Of course, display of 3D geometries will vary from activity to activity. Figure 4.7 uses activity A3 to depict several potential status representations. The left side of the Figure 4.7 represents the baseline for activityA3. The blue opaque portion indicates that the activity is due to begin on time and be 50% complete within the update period, while the blue transparent portion projects that the finish date will be on time. On the right side of Figure 4.7, various update statuses are represented graphically, along with brief explanation of status.

The Time Mode Status concept has also been applied to the illustrative example described in Section 4.1.2. Each step of the defined sequence has been illustrated in Figure 4.8, with the left portion of the diagram representing the baseline and the right portion representing the schedule update. During step one, progress appears to be slightly ahead of schedule. However, by step four, progress is definitely behind schedule in comparison to the baseline. Contractors can visually assess progress in this manner and determine if further investigation is needed.

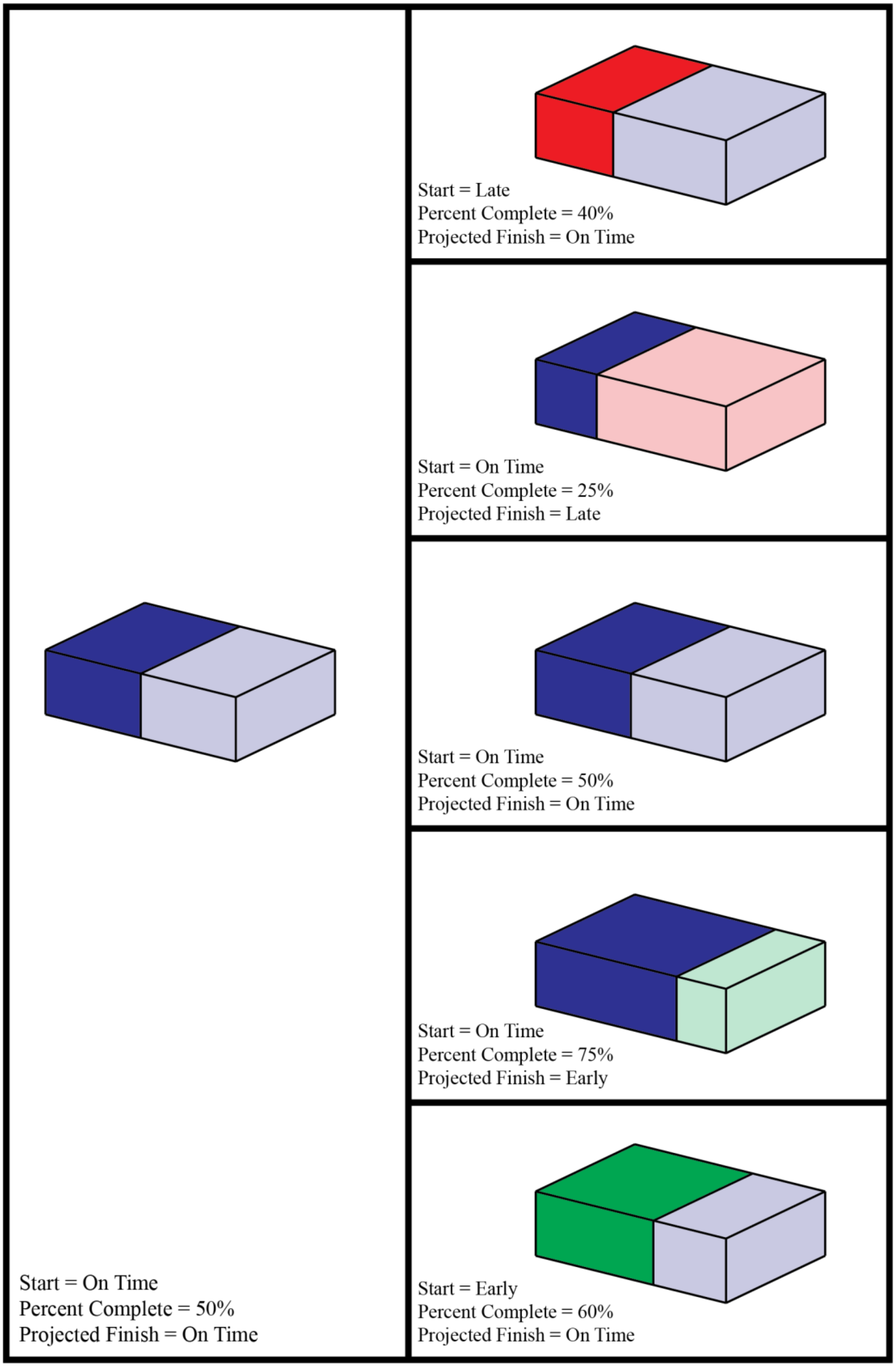


FIGURE 4.7: Various Time Mode status representations

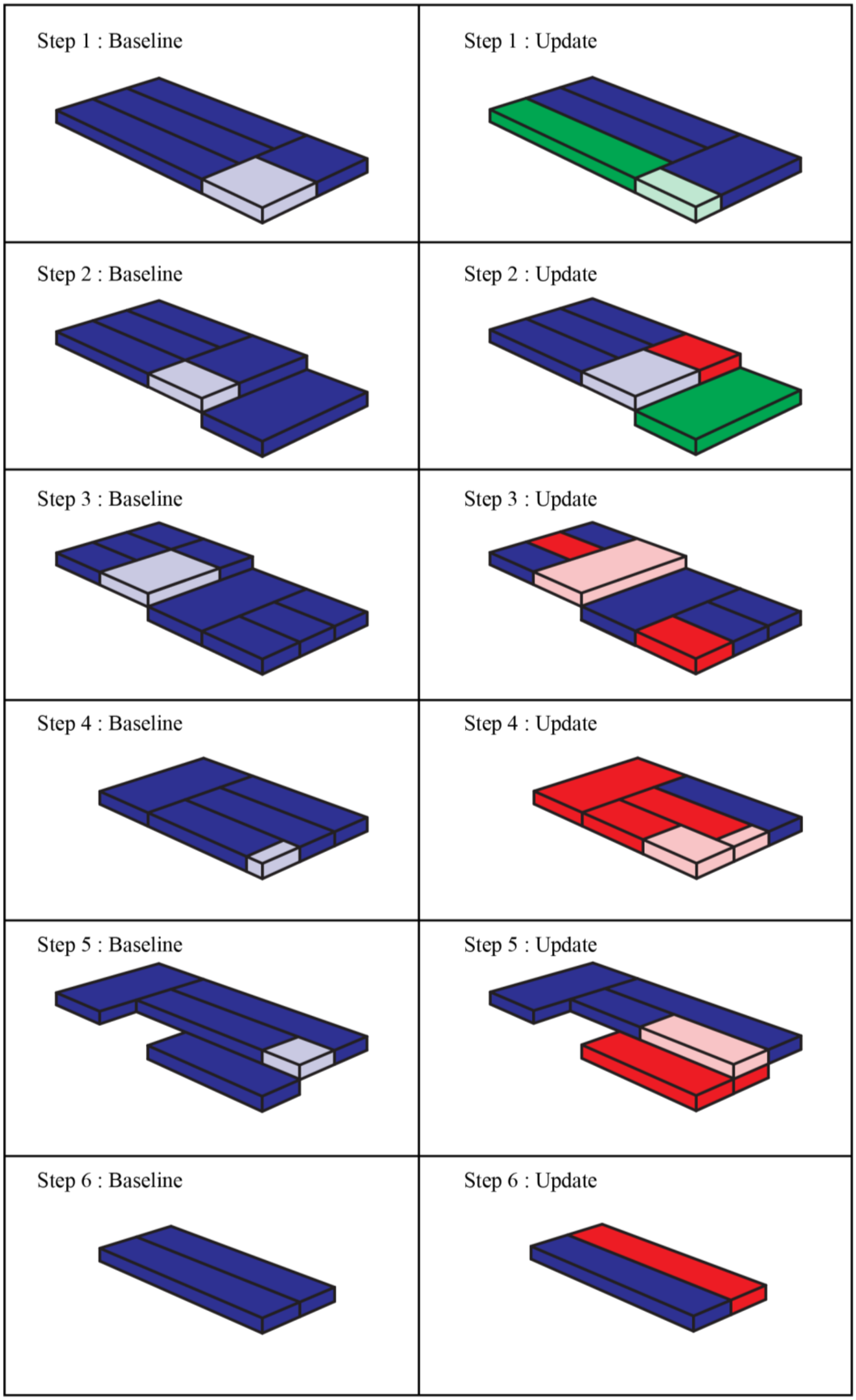


FIGURE 4.8: Illustrative example steps using Time Mode

4.3.1.2 Status Mode: Cost

The alternative method for viewing and understanding status is cost mode. Rather than using time as a basis of performance, cost is used to analyze project status, specifically the metrics of schedule performance index (SPI) and cost performance index (CPI). These metrics can be computed with information from the updated schedule. SPI values greater than one indicate that the project is ahead of schedule in terms of estimated costs. Likewise, CPI values greater than one indicate that the project is under budget based on work completed to date. Figure 4.9 illustrates the different statuses based on SPI and CPI values.

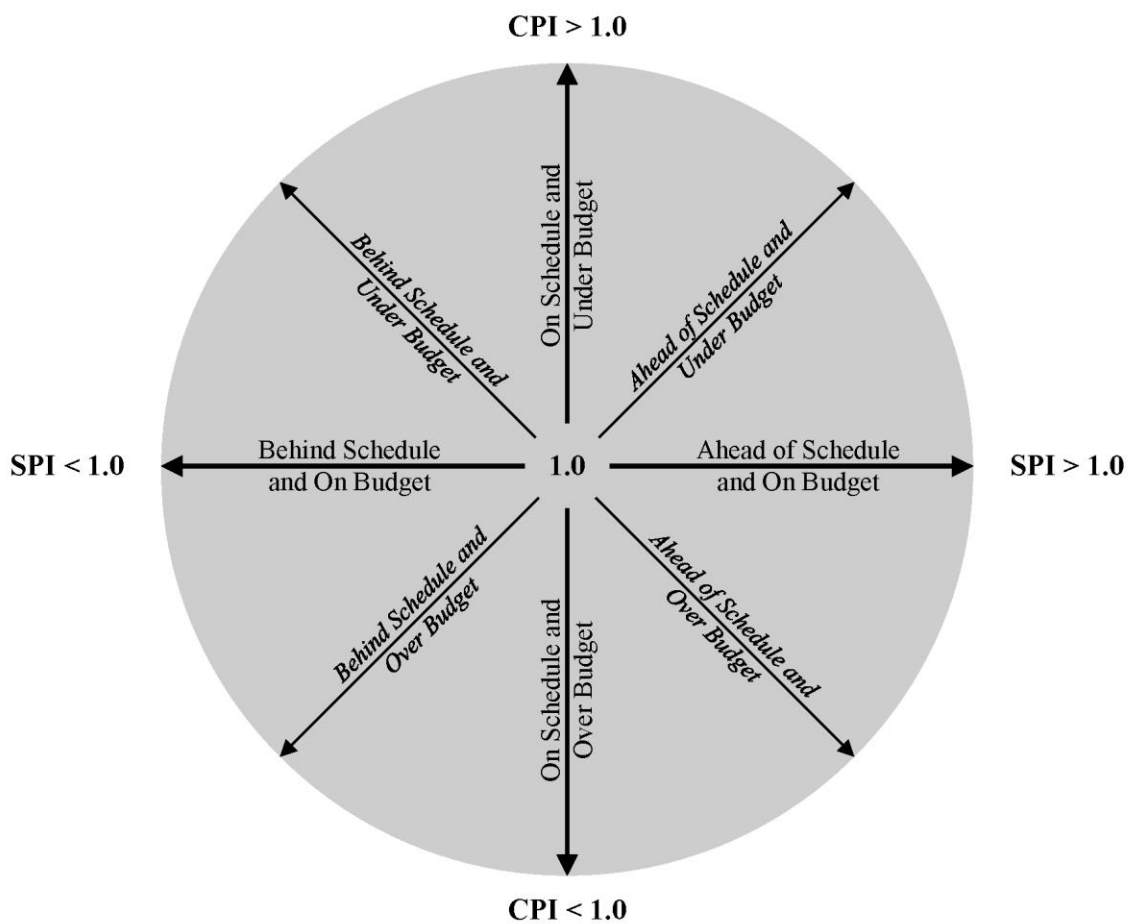


FIGURE 4.9: Project statuses using SPI and CPI

The primary attributes applied to 3D elements in Cost Mode are color and color value (also referred to as hue). Each color represents one of the statuses show in Figure 4.9 and the hue of that color indicates the distance from a value of one. Darker hues indicate a value further away from one, while lighter hues indicate a value closer to one. The absences of color indicates that the activity has an SPI and CPI of exactly one. Using the diagram shown in Figure 4.9, colors and hue ranges were assigned to each of the statuses, which can be seen in Figure 4.10.

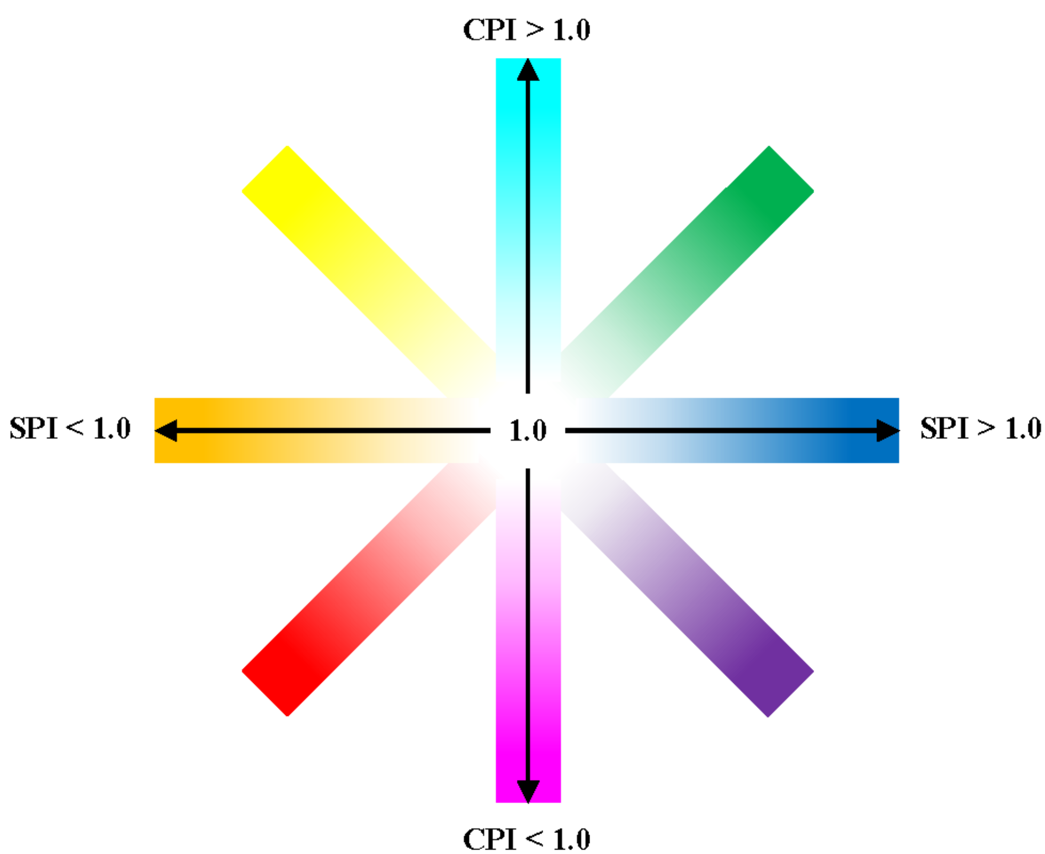


FIGURE 4.10: Color assignment for statuses in Cost Mode

Comparisons made between the baseline and actual performance in cost view mode can be done quickly by checking for the presence of color in the display. An abundance of warm colors, such as red and orange, indicate that progress is both behind schedule and over budget. However, abundance of cooler colors, such as green and blue, show that progress is ahead of schedule and under budget.

4.3.2 Status Grouping

The option of Status Grouping allows the user to alter the way that the selected Status Mode is applied to the visible 3D objects. Typically, users consider project status at the level of the entire project on work completed to date. However, it may be the desire of the user to consider the status of a particular group of activities, such as those completed by a specific subcontractor or those falling within a specific date range. The Status Grouping option gives the user four predetermined options, with the ability to create custom groupings as needed.

The first of the default options is called “Individual Activity” and refers to the ability to view the status of each activity as a separate entity. With this option selected, each object visible within the 3D window will be displayed with graphical attributes representing the status of that individual activity. The second default is the option called “All Activities” which groups visible 3D objects into one geometry and displays graphical attributes that represent the average status of all activities within that group.

The two basic options described above represent the extreme ends of the spectrum. To allow the user greater variability, two additional default options are available, titled “WBS” and “Activity Code.” WBS refers to grouping activities by work breakdown structure to assess status. If the schedule was developed with multiple WBS levels, the user is able to identify at what level they would like to group the activities. Visible 3D objects will be grouped based on WBS, with each group will displaying graphical attributes that represent the average status of the activities within the group.

The Activity Code option is the most flexible of these because it allows the user to group elements based on activity codes assigned during the original schedule creation. Activity codes are a common practice within the realm of scheduling because they allow schedulers to assign additional data parameters to each activity. Examples of common activities codes include the area of the site the task will take place, which subcontractor is responsible for the task, or which phase the task belongs in.

If the users prefers to view status by grouping a particular set of activities together, custom activity codes can be generated in the original schedule. These codes can then be transferred in the 4D update deliverable to allow the user to more grouping options.

Figure 4.11 illustrates the basic concept of the Status Grouping option. Items in the 3D Object Outline column represent the base geometry that receives graphical attributes. The geometry is determined based on the Status Grouping option. The option Individual Activity maintains the geometry of each 3D object. In the WBS option, each level of the rectangular prism represents a different piece within the WBS. Therefore, status is represented by level, in this case, activities S1 for level one and activities A2, B2, C2, and S2 on level two. Activity Code in this example is classified by activity type, where A2, B2, and C2 are the same type of activity and S1 and S2 are a different type of activity. Status representation is done so through the grouping of activity types. The last option of All Activities is simply an outline of all geometries. Status shown represents the combine average status of each of the component activities.

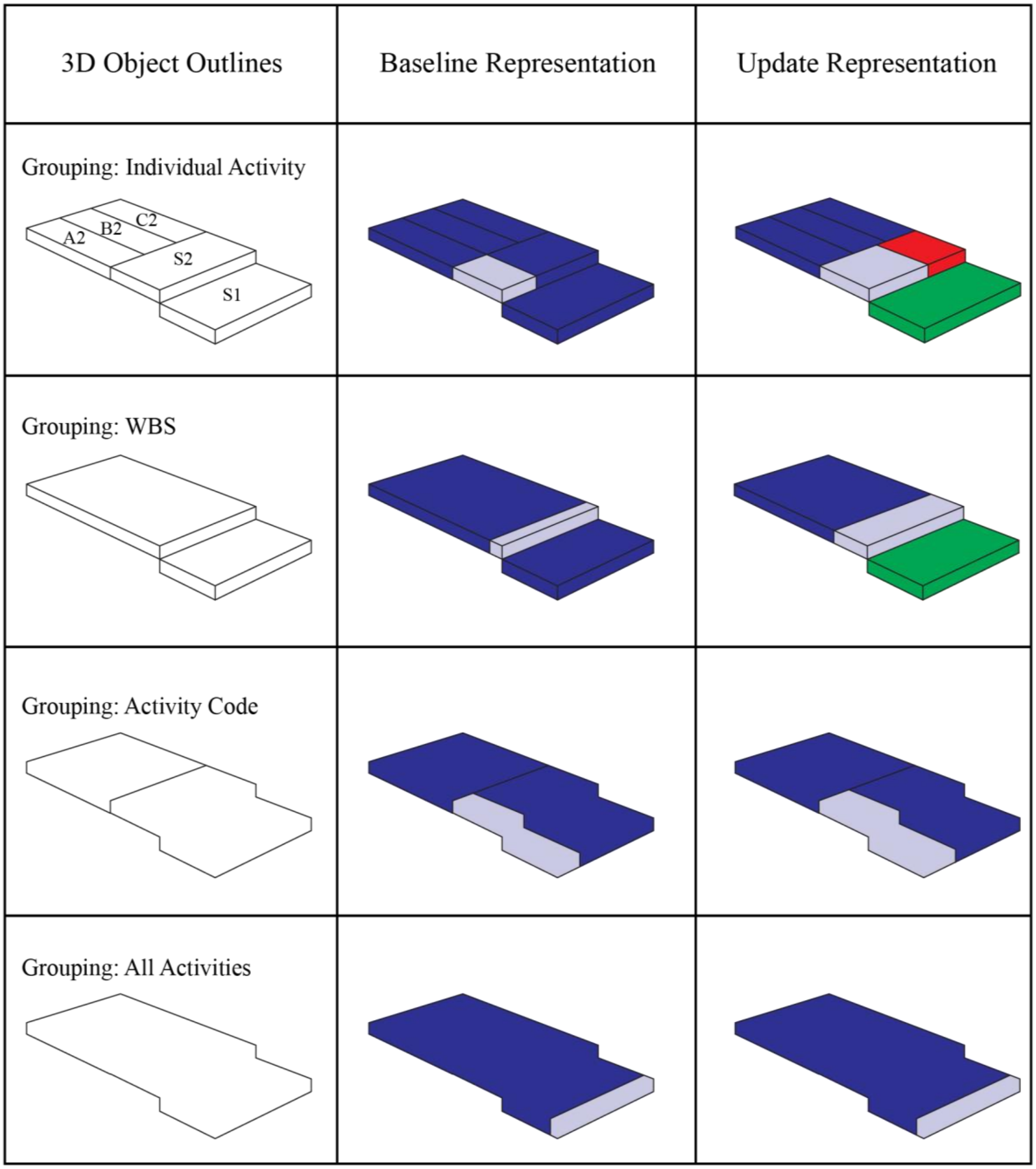


FIGURE 4.11: Status Grouping options

As seen if Figure 4.11, the ability to group objects into various categories could be beneficial to the update user. If analyzing the update at an overview level, the All Activities option would inform the user that activities within this update began on time overall, and are also expected to finish on time. However, using the Individual Activity option would allow the user to understand that activity S2 started late, but did not impact overall progress. Likewise, activity S1 finished early, but did not influence projected completion for this update period.

4.3.3 Status Range

The Status Range option refers to the range of project time that the user desires to view. Status Range settings correspond directly to the visibility of elements within the 3D model windows and the application of status indicating graphics. The user can elect to view either past performance or projected future performance, ranging between the current update period and the entire duration of the project. Settings are controlled through the use of a sliding bar, called the Status Range Slider, located beneath the 3D windows. Figure 4.12 shows a typical Status Range Slider for an ongoing project.

The current update is indicated by a thick black line, which separates previous updates on the left and future updates on the right. Previous and projected updates can be labeled by date performed, the number of working days at which it was performed, or a custom name determined by the user. A gray hatched region will appear in the Status Range Slider to indicate if past performance or projected performance is being displayed.

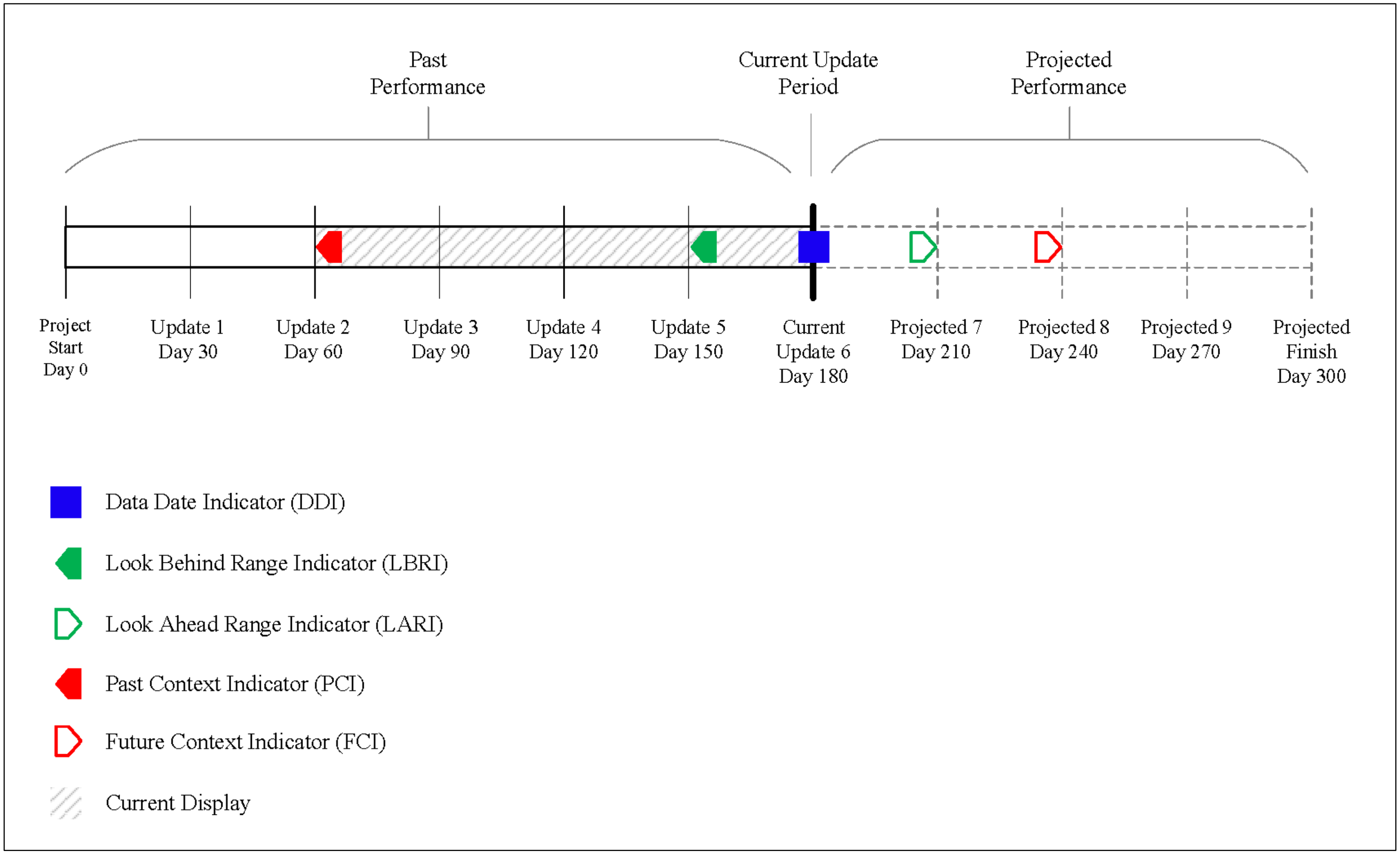


FIGURE 4.12: Status Range Slider

As shown in Figure 4.12, the Status Range Slider contains several components for adjusting the 3D objects that get displayed. The first item to note is the Data Date Indicator (DDI), represented by a blue square. By default, the data date is set to the most current update period, in this case the update at day 180. The data date is the "…date used as the starting point for schedule calculations" (Hinze 2008). Project status will be calculated and displayed in the 3D windows based on the location of the DDI. If the user wishes to view project status from a previous data date, the DDI can be moved to any update to the left of the current period. The DDI cannot, however, be moved past the most current update period.

The second items to note are the Look Behind Range Indicator (LBRI) and the Look Ahead Range Indicator (LARI), represented by a solid green arrow facing left and an outlined green arrow facing right, respectively. 3D model elements will be shown with the visual attributes of the selected Status Mode if their corresponding activities were impacted during the range set by the LBRI or the LARI. Activities are considered impacted if they started, finished, or remained in progress during the established range. The LBRI determines what 3D model elements are displayed when viewing past performance. Similarly, the LARI determines which 3D elements will be visible when viewing projected performance. The default location for the LBRI and the LARI is one update period behind and ahead of the current DDI.

The Status Range Slider also gives the user the ability to toggle the visibility of 3D objects that correspond to previously completed activities. This allows for the display of context items and gives the user a better understanding of the 3D elements currently being analyzed. The amount of surrounding context visible in the 3D window is controlled with the Past Context Indicator (PCI) and the Future Context Indicator (FCI), which are represented by a solid red arrow and an outlined red arrow, respectively. A gray outline is used to represent contextual 3D objects within the 3D display windows. Figure 4.13 shows the same progression seen in Figure 4.8, however in Figure 4.13, activities that occurred in previous update periods are shown within the 3D display as a gray outline. Contextual information within the 3D environment allows the user to easily understand the location of items within the current update period. The amount of context shown can be varied through the use of the PCI. In this example, the PCI would be positioned at the project start of the Status Range Slider, allowing all of the 3D objects associated with previously completed activities to be shown.

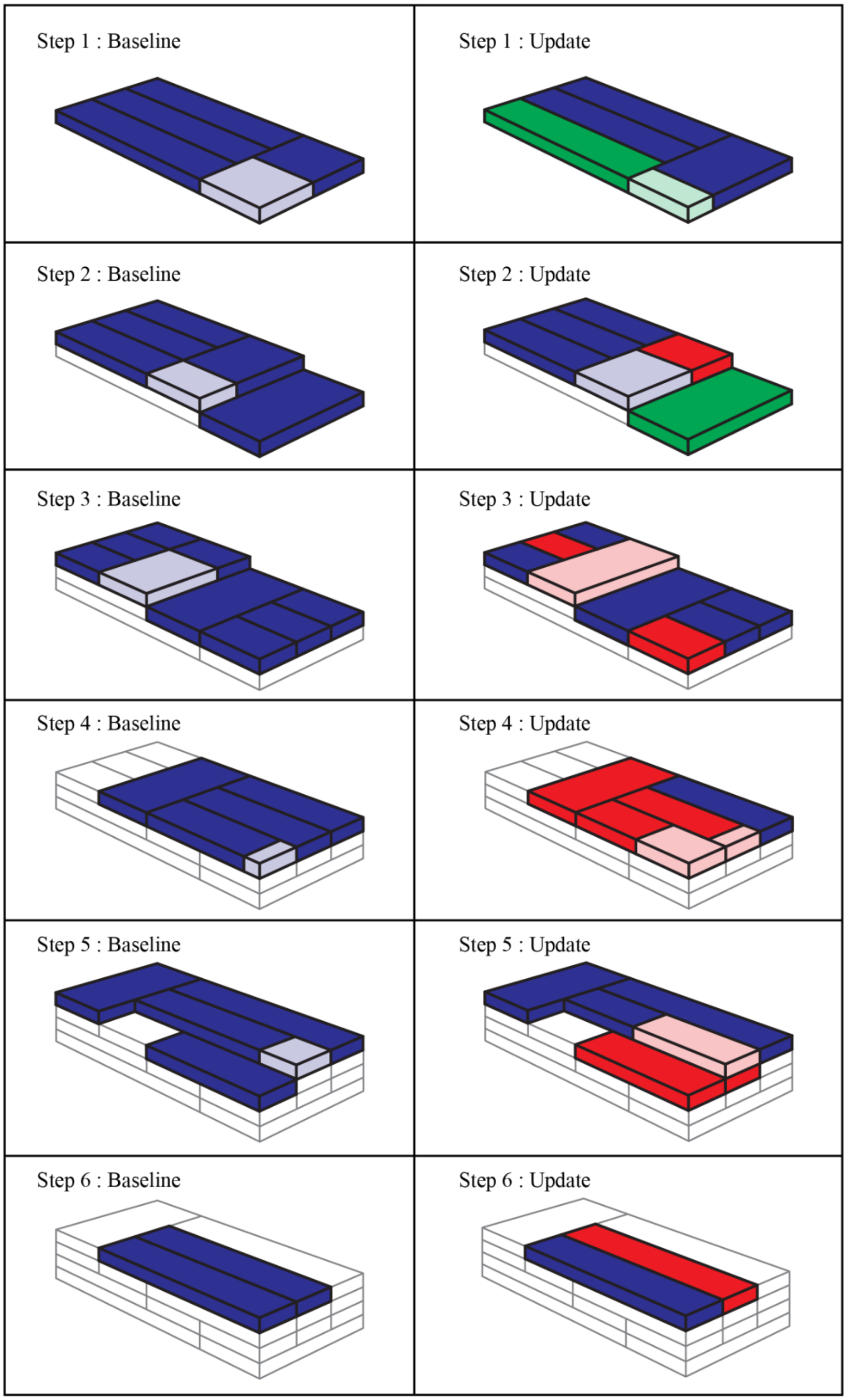


FIGURE 4.13: Illustrative example with 3D context

4.3.4 Additional 3D Capabilities

Descriptions provided in the sections above represent the primary capabilities present within the 4D update deliverable. However, there are additional options available that allow the user to further refine their 3D display. Toggles for these capabilities are found within the “3D Options” tab of the written and numerical display window.

The first of these options is called “Discrepancies.” This allows users to isolate 3D geometries based upon corresponding activity variability between baseline values and actual values. Meaning, activities that deviate from the baseline schedule, in either a positive or negative way, can be isolated to allow the user to easily identify variations. If this option is toggled, the user can filter the displayed items based upon early dates, late dates, projected dates, and remaining durations. This option can be applied within any Status Mode and with any Status Grouping.

Another secondary display option pertains to critical and near critical activities. By default, activities that fall along the critical path are not noted within the 3D display windows. However, should the user wish to view critical activities, the “Show Critical” option can be toggled, which applies a series of stripes to the surface of the 3D objects corresponding with critical activities. The pattern will correspond with the color scheme of the selected Status Mode. Similarly, the option “Show Near Critical” will allow the user to identify activities that are considered near critical, based upon free float values. The free float quaintly can be changed based on user preference. If activities fall within the established criteria, the surface pattern will display a series of thin crosses following the color scheme of the selected Status Mode. Examples of critical and near critical graphical attributes can be seen in Figure 4.14.

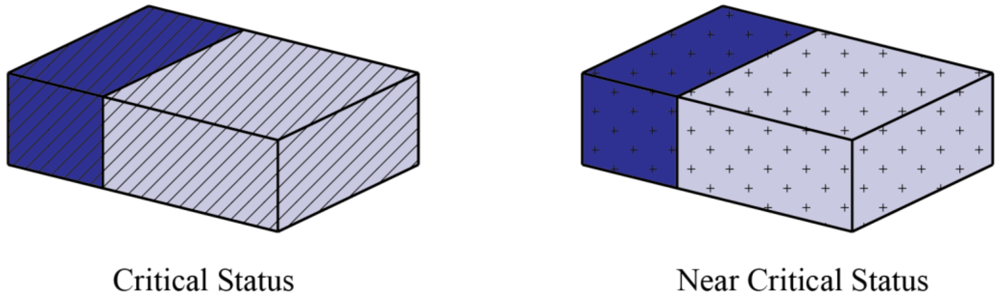


FIGURE 4.14: Critical and near critical representation

The final graphical attribute that can be applied to 3D elements deals with logic links and sequencing established within the schedule. Activity logic is defined in the baseline schedule by assigning predecessors and successors for each activity. In some instances, it is possible for activities to begin without their predecessors being 100% complete. Should the user wish to visually note logic discrepancies, the option “Modified Sequence” can be toggled. In the 3D windows, elements that correspond with out of sequence activities will flash slowly within the display.

Secondary capabilities described allow the user to easily identify 3D geometries that correspond with activities of interest. The ability to toggle these options on and off at will creates greater variability for users and allows for enhanced visualization.

4.4 Written and Numerical Content Display

While the primary focus of the 4D update deliverable is placed on visualization through the use of 3D geometries, additional information can be provided through the use of written and numerical data. Referring back to Figure 4.1, the bottom window is dedicated to the display of supplemental information pertaining to the schedule update, as well as options for 3D display settings. This window is populated with data tabs at the bottom of the display that allow users to cycle through information in an organized fashion.

Data tabs can be customized by the update creator, but several default tabs will always be present. These include: Project Properties, Activity Properties, Activity List, Gantt Chart, Status Mode, Status Grouping, Status Range, and 3D Options.

The last four data tabs listed pertain to options and settings for 3D elements display. Within these settings, color schemes can be customized, transparencies altered, date ranges modified, and secondary capabilities toggled. These data tabs will always be present within the 4D update deliverable. The display of supplemental information occurs within the Activity List, Gantt Chart, Activity Properties, and Project Properties tabs.

The Activity List tab is fairly straightforward in that it displays all activities within the schedule. This tab also details activity logic by listing all predecessors and successors for each activity. When the Status Range is modified, activities impacted within the specified range will be highlighted yellow in the activity list. This allows users to easily identify activities corresponding with 3D model elements appearing in the display. Similarly, if the user wishes to view the Gantt Chart, bars representing activities will be displayed with the same settings of the selected Status Mode and Status Range.

If the user is interested in information regarding a specific activity, it can be selected from the activity list and data will populate the Activity Properties tab. Information included can be altered by the update user, but will include the following by default (if applicable): planned start, actual start, planned finish, actual finish, planned duration, actual duration, and float values. Examples of additional activity information might include budgeted costs and assigned resources. Activity information can also be accessed by selecting 3D model elements from within the 3D windows. Selected geometries will be highlighted and their corresponding activity will be displayed in the activity list, the Gantt chart, and the activity properties tab.

The Project Properties tab will display standard information that aids in identifying the project being viewed. This includes the project name, location, involved parties, along with additional relevant items. The update creator can also include relevant notes and comments with the Project Properties tab. This is similar to explanations usually found within the update narrative that give users supplemental background information.

CHAPTER 5: INFORMATIONAL AND TECHNOLOGICAL GAP

Content discussed thus far represents the research efforts pertaining to the format of a 4D deliverable for construction schedule updates. Formulation of the deliverable was achieved through a comprehensive review of schedule update functionality, with emphasis placed upon users and their individual needs. While the proposed deliverable contains numerous capabilities that aid in the analysis and understanding of schedule updates, it is likely that current 4D technology is not able to support each of the defined capabilities in the preferred format. Therefore, a gap analysis has been performed to evaluate the current software system against the capabilities and format of the target deliverable.

The program utilized to evaluate current 4D software capabilities is Synchro Software, Pro Version 5.1. Synchro is a 4D construction project management software that provides construction professionals the ability to combine CPM project schedules and 3D models into a single platform. Specific details regarding the proposed format can be found in previous sections, but are referenced as need within this chapter. The approach taken to perform the gap analysis involved evaluating the software with respect to two primary areas. First, internal capabilities of the software were examined, particularly in regards to 3D object representation. The second step focused on output options, export format, and appropriate file type. Discrepancy descriptions are detailed in the following sections.

5.1 Internal Discrepancies

The gap analysis began by considering the process followed when working with Synchro, which aided in the identification of basic functionalities. Typical layout of the software interface can be seen in Figure 5.1, with key elements identified. Within the software, project schedules can be generated from scratch. Users can also import project schedules created in external programs, namely Oracle Primavera P6 and Microsoft Project. In terms of 3D objects, Synchro can import a wide variety of 3D file types, such as SAT, DWG, DWF, FBX, 3DM, STEP, SKP, RVT, and SLDASM (Synchro 2015b). While Synchro does allow for the creation of 3D elements within the program, modeling capabilities are limited and users are encouraged to import 3D geometries from external sources.

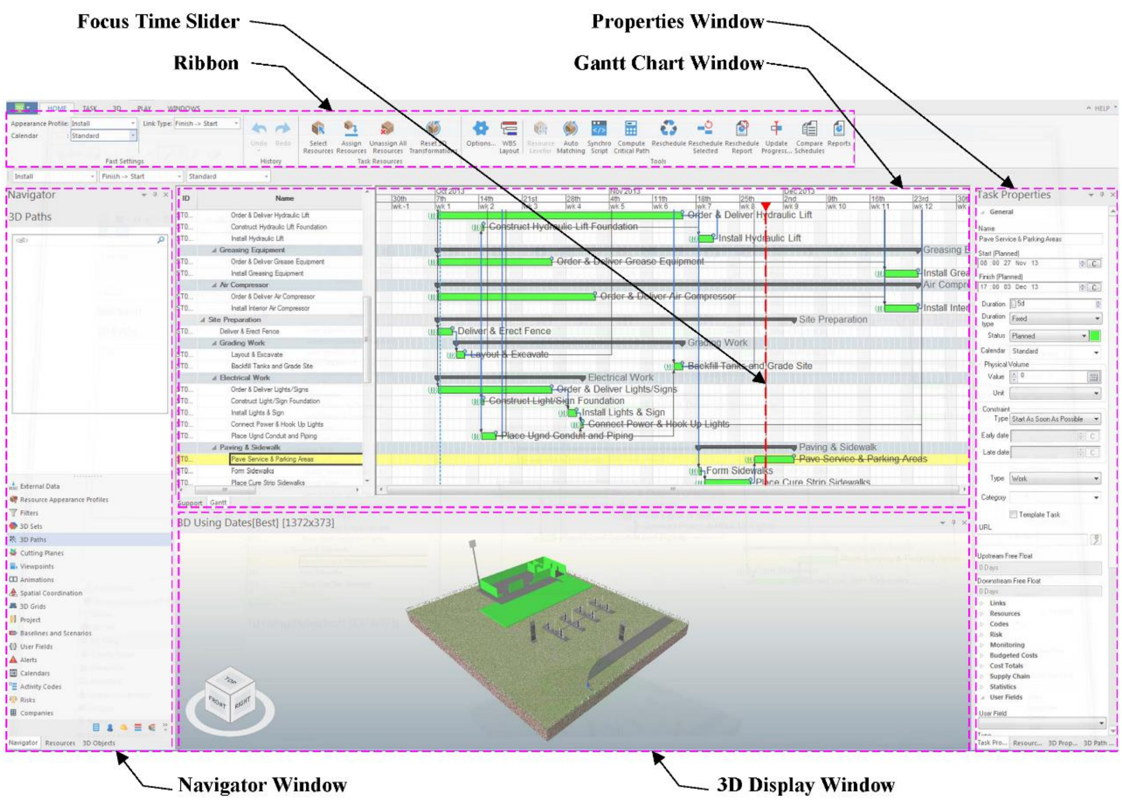


FIGURE 5.1: Synchro layout

Once both schedule data and 3D model data have been created or imported, links can be added between tasks and 3D objects, allowing for construction sequence visualization. When linked with corresponding tasks, each 3D object is assigned a Resource Appearance Profile. Resource Appearance Profiles "…dictate how the Resource is to behave before, during, and after the Task" (Synchro 2015a). Default Appearance Profile options include install, maintain, remove, and temporary, all of which are displayed in Figure 5.2. These default options only use color to indicate the selected action. To enhance the visualization process, custom Resource Appearance Profiles can be created to change appearance color, change transparency, and add growth simulations. Once the linking process is complete, the construction sequence can be viewed within Synchro or exported as an animation for external viewing.

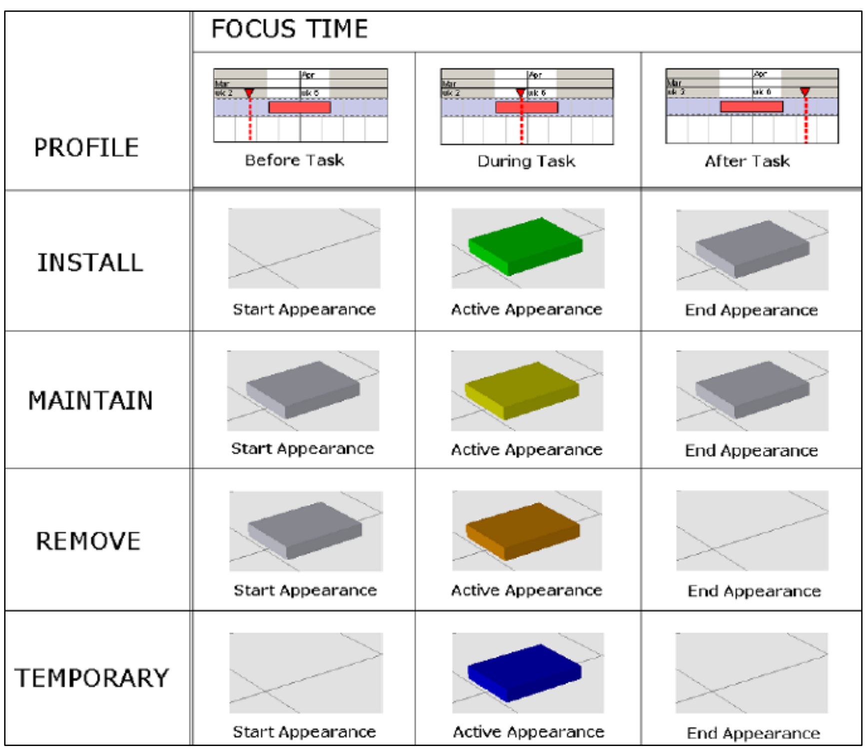


FIGURE 5.2: Default Resource Appearance Profiles (Synchro 2015a)

5.1.1 Visual Status Representation

Once construction begins, Synchro also allows the user to designate a schedule as a baseline and update that baseline as needed. This gives Synchro data necessary to make comparisons regarding planned status and actual status. Within the program, comparisons can be made through the Gantt chart or by using multiple 3D windows to view the baseline model and the update model simultaneously. While this comparison capability exists, variations present between the baseline and the update must be noted manually within the 3D environment. 3D objects do not appear, nor do they possess the ability to appear, with an altered appearance if discrepancies occur.

For example, Status Mode in the proposed deliverable centers around the ability to alter 3D object appearance if the task associated with that object deviates from the baseline schedule. As described in Section 4.3.1.1, visual indicators inform the user if the task started late, early, or on time and if the task is projected to finish early, late, or on time. Current capabilities within Synchro limit 3D object appearance based on previously assigned Resource Appearance Profiles, which only have the capacity to show three visual scenarios, before, during, and after an activity. There are currently no mechanisms in place that allow 3D appearances to be automatically altered through the comparison of baseline schedule data and update schedule data.

In addition to discrepancies within baseline and update schedules, there are no visual display options to represent the schedule metrics of SPI and CPI. Cost Status Mode, described in Section 4.3.1.2, uses color and color hue to communicate information pertaining to SPI and CPI through 3D objects. While these metrics are available to view in numerical format, 3D object display cannot be manipulated to represent this data in a visual manner. Again, Synchro only has the ability to show 3D objects in a before, during, and after state. While this is useful when viewing animations prior to the start of construction to understand when activities are occurring, the updating process requires the ability to alter appearance through information generated in the updating process.

5.1.2 Grouping of 3D Objects

In order to achieve the capabilities within the proposed deliverable, Synchro also needs the ability to convey status by applying visual attributes to individual 3D objects or groups of 3D objects. This directly relates to Section 4.3.2 of the proposed format, which discusses how geometries are grouped in order to display status of several activities at once. Currently, Synchro uses the traditional method of viewing project status, which considers the entire project at once. Concern is placed on an overall sense of “ahead of schedule” or “over budget” for all work completed to date, without being able to view status of the aggregate activities that make up the whole. However, the proposed format provides the ability to view status of individual activities that have been impacted in the selected update period. Furthermore, activities within the selected update period can communicate status collectivity, by WBS, by activity code, or by individual activity.

5.1.3 Object Visibility

Within Synchro, there are many options that allow the user to filter activities and visible 3D objects based on standard attributes or user defined attributes. Examples include dates, type of work, assigned resources, activity codes, etc. However, the drawback for many of these filtering options is that they must be set up manually by the user. Section 4.3.3 of the proposed deliverable format describes the ability to utilize a Status Range Slider to control the visibility of 3D objects. 3D objects corresponding to activities falling within the specified range will automatically be shown in the 3D windows. There is no need to manually create 3D object filters and continuously toggle various 3D sets. The Status Range Slider can also determine objects to be displayed as context within the 3D window. This cannot be achieved automatically within Synchro and requires manual object grouping in order to display the desired information.

5.2 Output Discrepancies

With the missing links determined within the inner workings of Synchro software, the next step consisted of analyzing the current output methods and formats. This step is equally as important because desired information must be communicated in a way that conveys current project status in a clear and concise manner. Exporting data from Synchro can be done in a variety of ways, but each method currently acts as a standalone option in the form of a still image, an animation, or a 3D PDF view.

Still images are essentially screen captures of the various windows within Synchro, exported as JPEG images or PDF files. The Gantt chart is the item most commonly exported as an image so that it can be printed and distributed to those who require a copy of the schedule. Objects in the 3D window can also be captured at a singular moment in time, in accordance with any focus time selected by the user. While static depictions can be useful in certain situations, this particular output typology lacks the ability to communicate progress over time.

Animations are the most common form of exportation from Synchro. Animations are created within the software and allow for the visualization of the entire construction sequence. Emphasis can be placed on particular areas of interest by slowing down the animation and maneuvering the camera closer to the work. The animation is exported in the form of an AVI file, and can contain not only the main animation window, but also a time indicator, a resource appearance legend, and additional 3D viewpoints. Items to be included in the AVI file are configured by the schedule creator prior to export. End users can then view the animation through a digital video player, stopping and starting as necessary. A standard layout of an animation produced with Synchro can be seen in Figure 5.3.

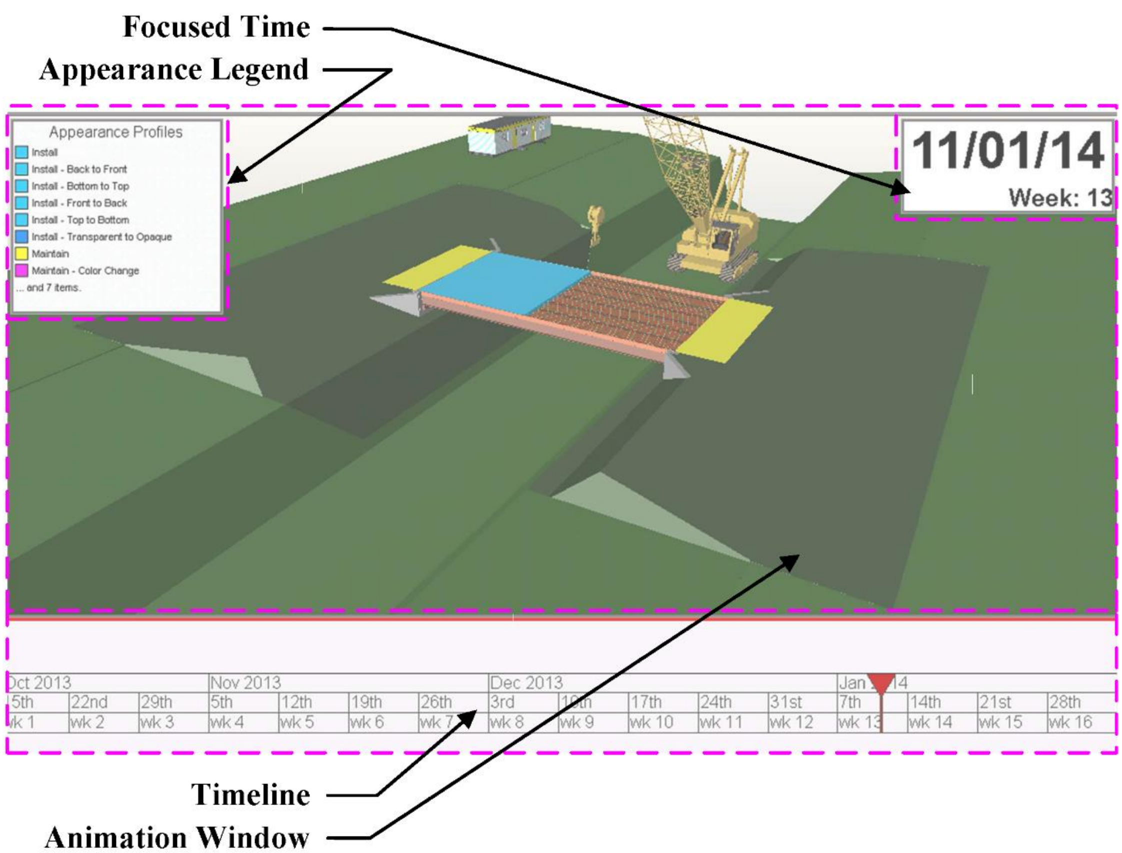


FIGURE 5.3: Basic Synchro animation layout

The downfall with animations, however, is the inability to manipulate the 3D view in a manner desired by the user. Viewers are restricted to the specific content shown within the animation and cannot alter the views within the AVI. Synchro does provide the ability to produce a 3D PDF containing objects seen within the 3D window, but display options are not maintained upon export. It would be expected that 3D elements seen within the 3D window would export exactly as shown, including visual attributes set in place by Resources Appearance Profiles. However, after many trials and various setting used, this was not experienced. An example can be seen in Figure 5.4, which compares a still image of the 3D window within Synchro and the corresponding file that was exported in the form of a 3D PDF.

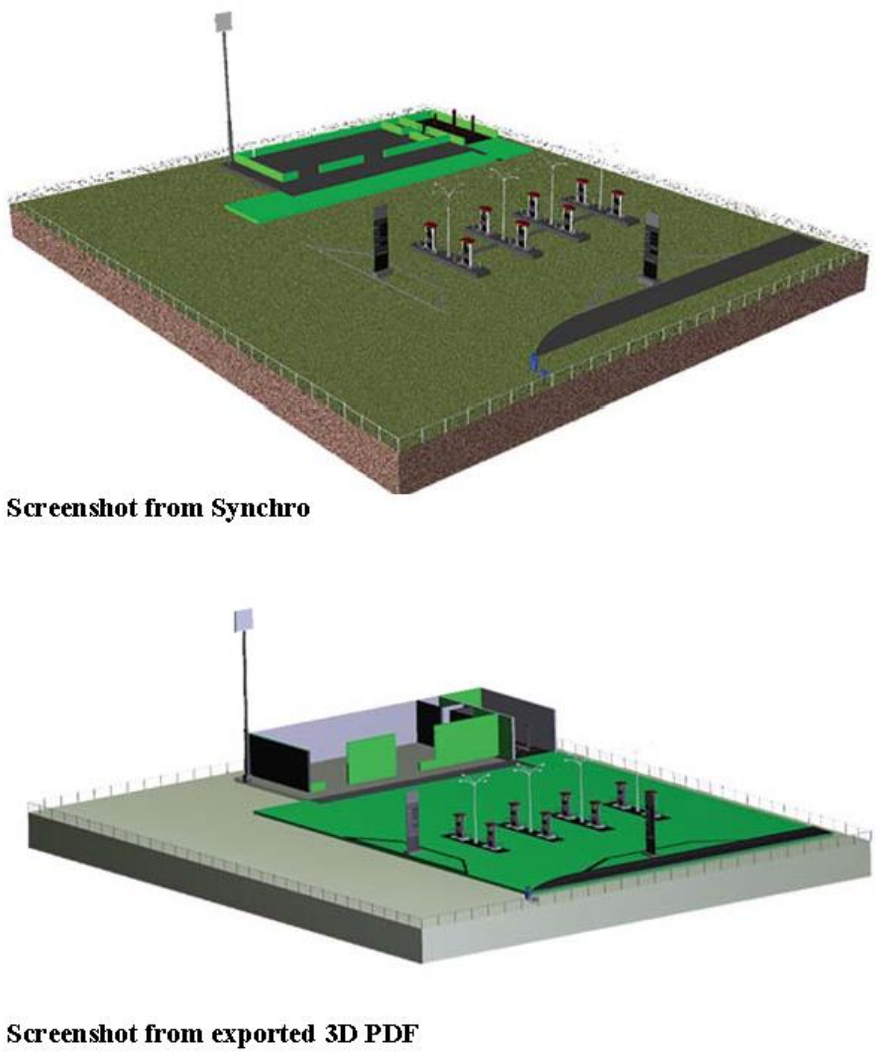


FIGURE 5.4: Export display discrepancies

The exported 3D PDF does possess basic navigation abilities and can be viewed in any PDF reader. Users can alter the visibility of individual geometries within the PDF, allowing for the customization of the displayed objects. While the basic capability of an interactive 3D PDF can be achieved, Synchro does not allow for the implementation of additional information into the exported file, such as time indicators or activity information. Currently, the only way to truly interact with the schedule update is through the Synchro program. However, providing users with the original Synchro file could lead to unintended changes. The lack of options for configuring the information for exportation limits the ability for producing a useable deliverable in a "view only" mode, which is the suggested format for the proposed deliverable.

In addition to Synchro Pro Software, the company also produces the program Open Viewer, which allows users to interact with the actual Synchro file in a view only scenario. While this additional software provides a viable option for viewing schedule information from the Synchro, there is no structure present that directs users to specific update information. Users would need a previous knowledge of complex scheduling and project management software to even begin to analyze project status.

Viewing status within the original program itself also eliminates the actual deliverable. In addition to communicating project status to all parties involved, performing a schedule update also produces records for archiving purposes, in both physical and digital forms. Archived documents are sometimes called upon for clarification between the owner and the contractor, or in worst case scenarios, to settle legal disputes. Utilizing a software such as Open Viewer eliminates the record produced showcasing the occurrence of a schedule update.

5.3 Summary

Synchro software is powerful in its current capacity as a project management tool. Construction sequencing can be tested prior to the start of construction, allowing issues to be mitigated well before hand. However, once construction begins, the tools present within the software are not specifically designed for producing documents that communicate schedule update information.

While Synchro contains the data necessary to achieve the visual output described in the previous chapter, the software does not currently contain the functions necessary to achieve the desired output. Additional options for filtering and comparing baseline data and update data would allow for the necessary comparisons to be made, which could automatically generate predefined groups of activities and 3D objects. These specialized groups then require the ability to take on particular visual displays based on the previously compared data. Synchro currently limits the variation in 3D object representation, as well as the automatic generation of 3D object groups.

Even if the visualization desired is achieved, issues are still present in the methods used to export required information. The technology required to produce interactive 3D PDF files exists, but the format and content of the proposed deliverable cannot yet be achieved through Synchro Software. Information in the form of 3D models is not combinable with standard written and numerical data, which is crucial for the success of the proposed deliverable for 4D schedule updates.

CHAPTER 6: SUMMARY AND CONCLUSIONS

This research consisted of the proposal of viable deliverable for schedule updates utilizing 4D technology, followed by a gap analysis that identified discrepancies between current capabilities and proposed capabilities. 4D technology has brought value into the construction industry by allowing users the ability to visualize the planned construction sequence prior to stepping out onto the job site. A background in construction scheduling and project management is no longer required in order to grasp the plan of action proposed by the contractor. Utilizing 4D visualization allows construction professionals to cater to a larger audience and communicate their intended plan more effectively.

While there are benefits associated with 4D technology, the application of such technology is typically used prior to the start of construction. Once the projects starts, the benefits provided through 4D visualization tend to be pushed into the background. This research worked to provide an applicable method for bringing the benefits experienced through 4D visualization throughout the project via the schedule update. As the most frequent scheduling process, the update provides the most suitable avenue for implementing 4D visualization. This allows for actual project progress to be digitally represented through 3D geometries that correspond with physical completion on site, eliminating the need to attempt to understand progress conveyed through traditional schedule metrics.

From the research conducted, several conclusions were drawn regarding the proposed 4D update deliverable. These involve the immediate future and what is necessary to implement such a deliverable, followed by the impacts that could be experienced on the scale of the project. Additionally, implementation and use of this 4D deliverable will impact the construction industry as a whole and bring benefits that cannot be realized through alternate means.

6.1 Achieving the Desired Goal

The second portion of this research focused on identifying current 4D capabilities in comparison with capabilities proposed in the 4D update deliverable. Through a gap analysis, various discrepancies were noted using Synchro Software. The primary differences centered upon the representation of 3D geometries within Synchro. While graphical attributes can be applied to 3D objects, the range of representation is limited and only has the ability to show 3D geometries in terms of before, during, and after their respective activities. These Resource Appearance Profiles must be set by the schedule update creator and cannot be modified once a deliverable is produced. The proposed deliverable aims to utilize information generated from the schedule update to dictate graphical display of 3D objects. This methodology truly allows project progress to be represented visually through 3D geometries.

From the gap analysis, it can be noted that the limitation in creating the proposed deliverable is not the availability of schedule update information, but rather the visual application of that information. Actual start and finish dates and remaining durations are all contained within the 4D model, which allows for the computation of schedule metrics that indicate progress. It was concluded that achievement of the proposed deliverable is not farfetched due to the availability of update information present within Synchro. The application of update information to 3D objects is the capability needed to create the proposed deliverable.

6.2 Local Scale Impacts

Following the implementation of the proposed 4D update deliverable, there are immediate benefits that can be experienced through the use of 4D technology in the updating process. First and foremost, the ability to visualize progress with respect to the baseline schedule can be done within a 3D environment. Additionally, activities impacted within the established Status Range will possess visual attributes that inform the viewer of status. The visual representation is supplemented through the use of typical update information, such as a Gantt chart and numerical schedule metrics, which allows the user to consider many different aspects and the effect on progress. By utilizing 3D objects as the primary method of conveying status information, users can be cued in to conclusions that are not readily apparent through tabular data alone.

The proposed format also gives the user the ability to quickly filter and view progress within the 3D environment. While Synchro provides the ability to filter activities, it must be set up manually and then applied to the 3D display. The Status Range Slider can easily filter 3D objects and allow the user to focus on a particular area of concern. Within the selected Status Range, the user can view status by individual activities, or as a whole. Viewing the status of a specific group of activities can inform the user of developing trends, which can aid in the strategic approach for project completion. Furthermore, these trends can be quickly identified through status visualization in a 3D environment.

Visual inspection of project status is enabled through the implementation of 4D technology. While the concept of visual inspection is not new, the method of representation utilized in the proposed 4D update deliverable provides users access to vast amounts of visual information regarding status.

6.3 Industry Scale Impacts

Implementing the proposed 4D update deliverable would also have a considerable impact on the construction industry as a whole. Implementation of a 4D update deliverable would not only bring positive outcomes to individual projects, but to the entire construction community. 4D technology allows for all parties involved in the construction process to participate and be active decision makers. Prerequisite knowledge of construction scheduling is not a necessity when visualization tools are used as the primary means of communication.

Specifically regarding the schedule updating process, the use of 4D visualization allows for a clear and concise explanation of current progress. Rather than pointing to activities on a schedule and using schedule metrics as an explanation, contractors can utilize the 3D display environment to communicate which 3D objects are in question and how they have impacted progress.

Communicating in a universally understood language allows for more parties to participate in the discussions about maintaining progress. Users who consult the 4D update deliverable gain the ability to speak in an informed manner regarding project status. Fresh ideas can now be proposed by those who would typically not concern themselves with the schedule update because their knowledge of the process was limited. 4D technology allows for increased collaboration in problem solving efforts through the ability to communicate visually.

Utilizing 4D technology also shifts the focus from nuts and bolts of schedule updating to a discussion that centers on actual project progress. That is, instead of bombarding users with numerous metrics and graphs to indicate that the project is behind schedule, tools such as 4D visualization can be used to translate that information into an understandable deliverable. Discussions regarding progress can then focus on what has occurred, why it occurred the way it did, and what modifications should be made in order to maintain the current status or remediate the current status. While schedule metrics and numerical data are valuable, using them exclusively hinders the complete understanding of overall sequencing of the project. Delivering necessary information in conjunction with 4D visualization capabilities provides the construction industry an opportunity to shift from traditional thinking towards progressive project delivery.

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