

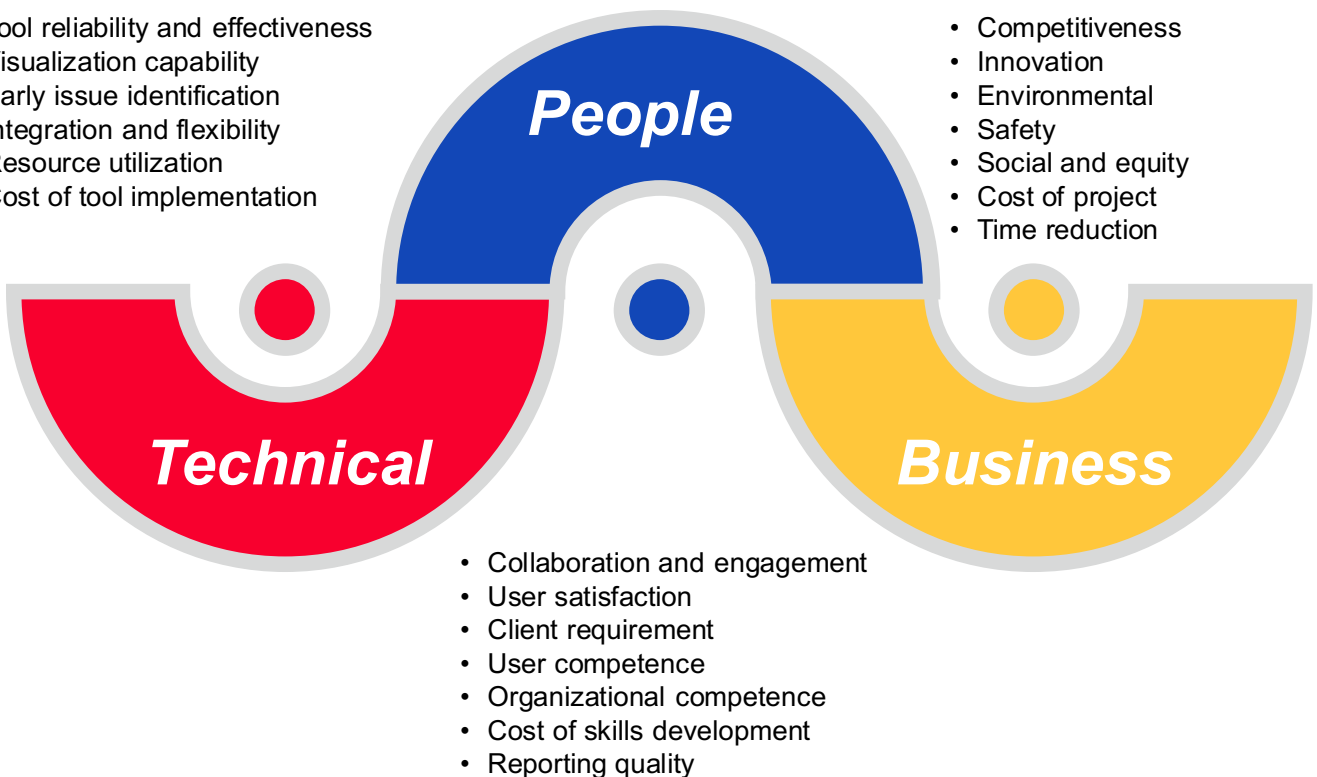
Linear Scheduling Evaluation and Best Practices Development – Final Report

WA-RD 898.2

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September 2021

- Tool reliability and effectiveness
- Visualization capability
- Early issue identification
- Integration and flexibility
- Resource utilization
- Cost of tool implementation



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**LINEAR SCHEDULING EVALUATION
AND BEST PRACTICES DEVELOPMENT
FINAL REPORT**

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EXECUTIVE SUMMARY

The purpose of this research effort was to evaluate the importance and promote the use of the linear scheduling method (LSM) in planning and constructing linear projects. Recently, the LSM has received increased research attention, and the theoretical background has been solidified and expanded in various aspects, including critical path detection, computerization, schedule optimization, and resource leveling. In practice, several recent projects that used the LSM have received positive feedback from the Washington State Department of Transportation (WSDOT) engineers. The LSM can be an effective tool for completing constructability reviews earlier in design and identifying coordination opportunities. It can also enhance processes related to project cost risk assessment, value engineering, and stakeholder engagement. To demonstrate the capabilities of the LSM, this multiphase research included surveys and interviews of relevant industry personnel as well as pilot use of the LSM with off-the-shelf software programs in a selected project.

In Phase I of the research, the authors conducted a literature review and synthesized the potential application of LSM in transportation projects. The strategies for effective use of the LSM, knowledge gaps, and lessons learned were identified. Five case studies sponsored by the departments of transportation (DOTs) of various states in the United States that evaluated the use of the LSM in roadway constructions were reviewed. These studies found that, for linear projects, the LSM improved schedule overview, facilitated better communication, ensured work continuity, and enhanced project control. However, none of the case studies were recent, which shows the necessity of this research to assess how the LSM is currently implemented in practice. The Phase I research also revealed the need for a benefit-cost analysis (BCA) in Phase II of the research to demonstrate the cost-effectiveness of using the LSM and how the LSM can be best utilized by WSDOT.

During Phase II, linear scheduling user questionnaires were distributed and expert interviews were conducted to gain insights into the benefits, challenges, and implementation processes of the LSM in different organizations (i.e., owners, contractors, and consultants). A project performance measurement framework was developed to

facilitate the BCA. An additional questionnaire was created to gather input from subject matter experts and identify performance indicators that can be used in the measurement framework.

Several off-the-shelf linear scheduling software programs were categorized and compared in Phase I. Two of the software programs—GraphicSchedule and TILOS—were examined further in Phase II. GraphicSchedule is a lightweight Excel add-in that enables users to create a one-page linear schedule visualization from an existing critical path method (CPM) schedule. On the other hand, TILOS is a stand-alone scheduling program that is capable of building from scratch a linear schedule with many features, such as calendars, work breakdown structure (WBS), work rate calculation, logic links, clash detection, and progress tracking. A linear project in the early planning stage was provided by WSDOT as a case study to assess the usefulness of the software programs as well as the measurement framework. Both GraphicSchedule and TILOS demonstrated the potential to support the implementation of the LSM in WSDOT. Live and recorded training sessions for both software programs were organized by the authors to introduce the LSM to the wider WSDOT community.

Chapter 1 of this report provides an overview of the research objectives and overall methodologies. Chapter 2 gives a summary of the current development of the LSM in both research and practice and of the existing project performance measurement framework based on extensive literature review. Chapter 3 contains a detailed description of the methodologies adopted at various stages in this research, including surveys, interviews, and case studies. Important findings are presented in Chapter 4. Chapter 5 provides recommendations on the implementation of the LSM within WSDOT based on currently available tools and resources in the market. Conclusions from the entire research are presented in Chapter 6.

CHAPTER 1

INTRODUCTION

The ever-increasing need to fully understand and communicate project information to diverse audiences and communities continues to be a challenge. In addition, WSDOT's design teams, working with multiple and varied partners and internal specialists, need to be able to quickly grasp the nature of a project, its context, and the work activities that will occur, including where and when they will take place.

Traditional project scheduling methods provide an overwhelming amount of data for large projects that can be cumbersome and confusing to interpret. Project meetings with various stakeholders therefore become less effective and unproductive because stakeholders do not have a shared understanding of the project progress and schedule.

The most common questions asked regarding projects are cost, duration, and appropriate justification. The LSM has the potential to be an extremely effective tool that can help answer those questions and can further enhance WSDOT's current processes related to project cost risk assessment and value engineering analyses.

BACKGROUND

In recent years, using the LSM to manage and communicate the progress of projects has received positive feedback from WSDOT engineers. Engineers have noted that linear scheduling has the potential to be an effective tool to enhance WSDOT's current processes related to project cost risk assessment and value engineering. However, little research has focused on examining the quantifiable benefits of employing the LSM on a project. A lack of empirical data demonstrating the benefits of LSM with real project examples exists, so WSDOT has been unable to determine how the method can best be adopted. This research is the first step in informing WSDOT and other transportation project stakeholders of the potential benefits and impacts of using the LSM with projects. Phase I of this study involved completing a rigorous literature review. Phase II included conducting surveys, interviews, and case studies. Surveys distributed to a broad population informed interview questions. Interviews were then conducted with multiple stakeholders representing WSDOT, as well as with contractors and vendors co-selected and sampled by the research

team with guidance from WSDOT. Selective case studies reflected projects of different sizes and complexity.

GOAL AND OBJECTIVES

The overarching goal of the research (including both Phase I and Phase II) was to investigate the costs and benefits of utilizing the LSM in WSDOT linear projects to assess the method's feasibility and added value. The objectives of this research were as follows:

1. Produce a synthesis (i.e., literature review) that summarizes the use of the LSM and associated best practices for infrastructure projects.
2. Develop applicable project performance metrics to quantify the benefits of using the LSM for transportation projects.
3. Produce a vendor selection guideline by discussing available tools and software that are currently available from the market.

KEY DEFINITIONS

The following definitions provide an understanding of the key terms used in this synthesis report. The terms marked with an * were previously defined in the Phase I Report (WA-RD 898.1). Definitions of some of these terms have been updated in this final report:

- *Analytic hierarchy process (AHP)*: A structured technique for organizing and analyzing complex decisions based on mathematics and psychology (Forman and Gass 2001).
- *Building information modeling (BIM)**: The holistic process of creating and managing information for a built asset. Based on an intelligent model and enabled by a cloud platform, BIM integrates structured, multidisciplinary data to produce a digital representation of an asset across its lifecycle, from planning and design to construction and operations (Autodesk Inc. 2021).
- *Likert scale*: A Likert scale is commonly used to measure attitudes, knowledge, perceptions, values, and behavioral changes. A Likert scale involves a series of statements that respondents may choose from in order to rate their responses to evaluative questions (Vagias 2006). The 7-point and 5-point Likert scales are the most commonly used in surveys. Examples of Likert scales for level of agreement are given in Table 1.1.

Table 1.1. Examples of Likert scales level of agreement

7-point	5-point
1—Strongly disagree	1—Strongly disagree
2—Disagree	2—Disagree
3—Somewhat disagree	3—Neither agree nor disagree
4—Neither agree nor disagree	4—Agree
5—Somewhat agree	5—Strongly agree
6—Agree	
7—Strongly agree	

- *Linear scheduling method (LSM)**: A two-dimensional (2D) time-location scheduling method designed for construction projects of linear, repetitive, and location-based nature.
- *Performance category*: The variable that measures the overall performance of a linear scheduling tool.
- *Performance indicator**: The variable under performance category that provides a way to measure a particular performance category of a linear scheduling tool.
- *Performance metric**: The variable under performance indicator that provides a way to measure a particular performance indicator of a linear scheduling tool.

OVERALL METHODOLOGY

To achieve the objective of this research project, several tasks were defined and carried out in sequence. Each task utilizes one or more methods, including user surveys, interviews, and case studies, to collect robust information from different sources. The overall research framework is illustrated in Figure 1.1, and the details of the tasks are given below.

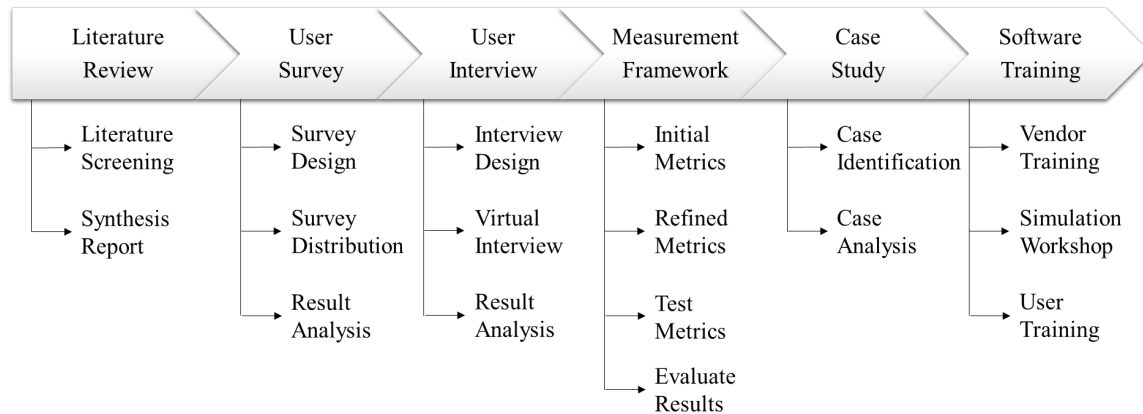


Figure 1.1. Research methodology overview.

Task 1. Conduct Literature Review

The goal of Task 1 was to collect the most current information on linear scheduling practices, related processes, and available tools. The research team identified academic, practical/application-based, as well as DOT-specific resources, to conduct the preliminary screening of literatures. After reviewing the selected literatures, a synthesis report was prepared to document the findings (i.e., Kim et al. 2019).

Task 2. Distribute User Surveys

The objective of Task 2 was to capture through online surveys the knowledge of design and construction professionals with experience using the LSM in transportation projects. The survey questions were designed by the research team in consultation with WSDOT staff, and the surveys were distributed via multiple channels to reach the target audience.

Task 3. Conduct Interviews

The objective of Task 3 was to conduct interviews with selected LSM frequent users. The interview questions were built on the user survey created in Task 2 but with some modifications. The one-on-one interviews allowed the interviewees to provide more insight into the implementation of the LSM in their organizations, as well as into the benefits and challenges of using the LSM in practice.

Task 4. Develop Measurement Framework

The purpose of developing a measurement framework was to provide a method for the stakeholders to assess the usefulness of the LSM and make informed decisions on the

adoption of the LSM. Task 4 aimed to develop such a framework for linear scheduling through the identification of categories, indicators, and metrics considered by experts when adopting or maintaining the use of linear scheduling tools in their projects.

Task 5. Conduct Case Study

To showcase the use of the LSM in projects that are relevant to WSDOT, the research team selected a WSDOT-owned project in early design and developed linear schedules for the project team to review. Feedback from the project team was also used to validate the measurement framework established in Task 4.

Task 6. Develop Software Training Programs

The objective of Task 6 was to pilot the use of off-the-shelf linear scheduling software programs within WSDOT. Live training sessions and recorded training videos were offered to interested users from WSDOT who could potentially serve as early adopters and promoters of the LSM in the organization.

Task 7. Finalize Guidelines and Prepare Research Report

The last task was to compile a final report from the findings of the previous tasks and provide practical guidelines for LSM implementation within WSDOT.

CHAPTER 2

LITERATURE REVIEW AND CURRENT PRACTICE

It is widely accepted in the construction industry that bar charts or network-based scheduling methods such as the CPM are typically not the optimal tools for projects that include activities of a linear or repetitive nature at different locations (either horizontally or vertically)—for example, highway construction or multi-unit housing development projects. Although both methods are still used extensively by planners and schedulers for these projects, especially in the United States, the bar charts and network-based scheduling methods are limited in three aspects, as discussed in Lucko et al. (2014):

- Both methods focus solely on time and have only one dimension. The productivity of all the activities cannot be shown.
- The time resolution in workdays limits the capability to provide an accurate schedule.
- The rectangular areas used in both methods are not efficient in a graphical representation.

Instead, alternative techniques have been developed in parallel to bar charts and network-based methods for linear and repetitive projects that contain the added dimension of location. Currently, the most widely used names are repetitive scheduling method (Harris and Ioannou 1998; Ioannou and Yang 2016), location-based scheduling method (Andersson and Christensen 2007; Kenley and Seppanen 2009; Seppanen 2016; Sharma and Bansal 2018), and LSM (Johnston 1981; Lucko 2008; Lucko 2009; Lucko et al. 2014; Lucko and Gattei 2016; Mattila and Abraham 1998). LSM is used in this report to refer to the scheduling technique for projects that are linear, repetitive, and location based.

LINEAR SCHEDULING METHOD

Although the origins of the method are not clear, in the construction scheduling-related literature (Harris and Ioannou 1998; Hassanein and Moselhi 2004; Lucko and Gattei 2016; Mattila and Abraham 1998), the introduction of the term *linear scheduling method* has been attributed to Johnston (1981) in his work on highway construction. The diagram

used in the LSM has close ties with the *line-of-balance* (LOB) diagram, as shown in Figure 2.1. The LOB was originally developed by the U.S. Navy to convey the actual status of the elements of a production program to planned progress (Naval Material Command 1962). Lumsden’s work in the 1960s (Lumsden 1968; National Building Agency 1968) is considered an example of the early adoption of LOB in construction. Studies by other researchers followed, such as Arditi et al. (2002), Seppanen and Aalto (2005), Nageeb and Johnson (2009), Damci et al. (2013), Lucko and Gattei (2016), and Su and Lucko (2016), and the LOB diagram took its current form.

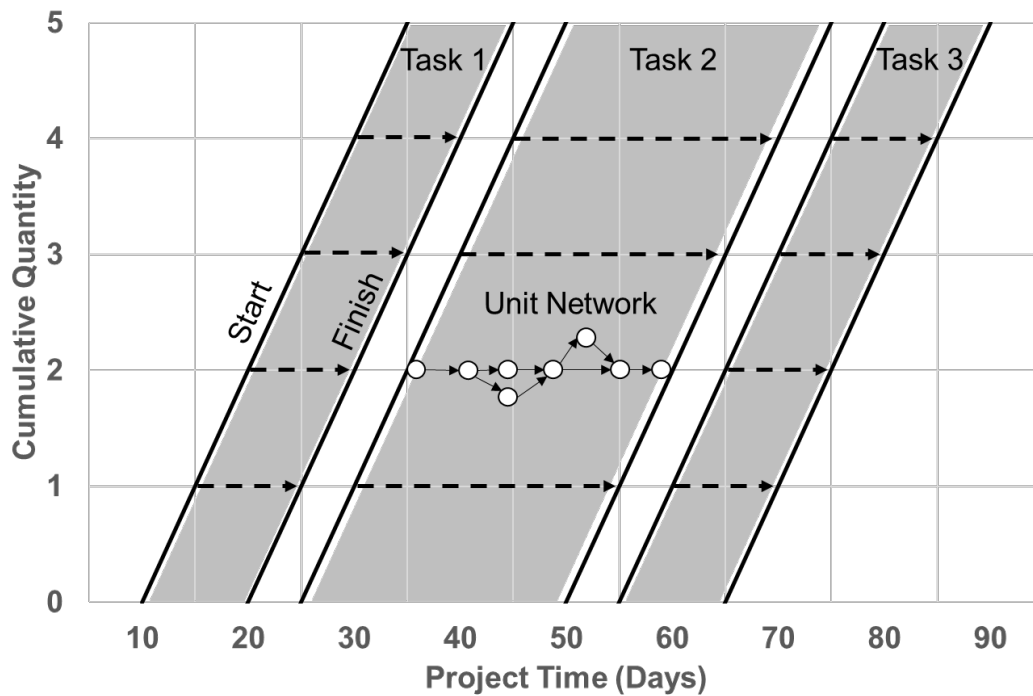


Figure 2.1. Example of a modern LOB diagram based on Kenley and Seppanen (2010).

Although the LOB diagram appears to consist of continuous lines, the vertical axis—cumulative quantity—suggests that the progress of the tasks can only be tracked discretely. For projects where the equipment and crew move continuously along the length of the project, such as highway and tunnel construction, it is necessary to develop a method to reflect the movement of resources in a continuous manner. Based on this factor, the *flowline method* was introduced, which is similar to the LOB but with critical differences.

An example of a flowline diagram is shown in Figure 2.2. Although not mentioned by Johnston (1981) when the LSM was introduced, the flowline method is still considered the foundation of the current LSM because it bears the same characteristics that give the LSM diagram its current form (Lucko and Gattei 2016). Compared to the LOB diagram, the flowline diagram is especially advantageous when the number of tasks increases and the dual-line LOB diagram may potentially become cluttered.

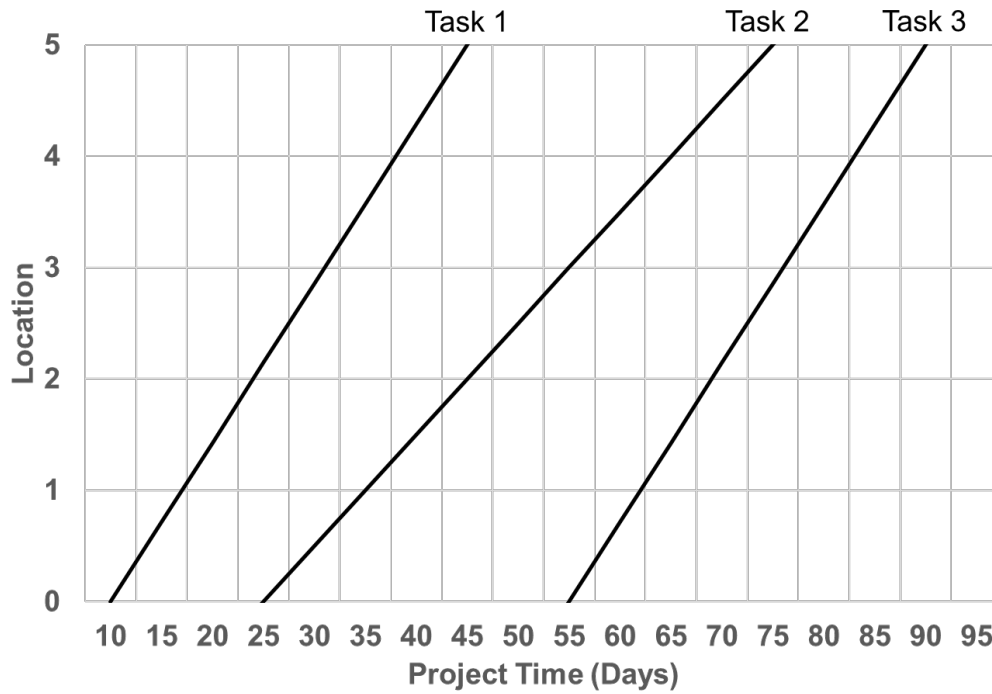


Figure 2.2. Example of flowline diagram.

An increasing amount of research has been conducted on the LSM to enhance its capability and improve its user experience. A simple LSM diagram is given in Figure 2.3 for a bridge project. The location along the bridge is drawn horizontally, while the time is drawn vertically from bottom to top. A drawing of the bridge is placed along the location axis to facilitate a better understanding of the project scope. More sophisticated drawings, such as CAD sketches or satellite images, may also be used.

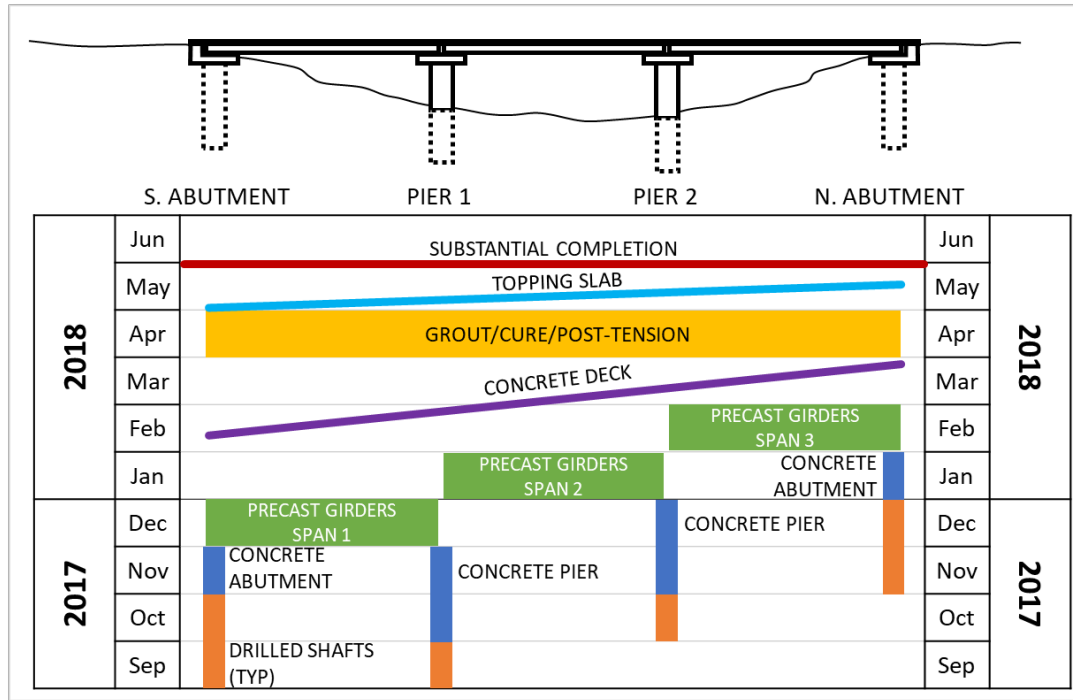


Figure 2.3. Example of modern LSM diagram (Wonneberg 2021).

Over the years, new research efforts have strengthened the LSM and expanded its functionality; however, the underlying principles of LSM remain unchanged. As summarized by Lucko and Gattei (2016), these principles are as follows:

1. The LSM diagram is a 2D chart with continuous time and location axes.
2. The resolution of both axes is determined by the user based on available data.
3. The location axis can be drawn either horizontally or vertically, depending on the nature of the project.
4. Tasks are represented by lines between the start and finish time-location coordinates. Other shapes are also used to illustrate stationary activities, environmental restrictions, or milestones.
5. The project is assumed to proceed along one direction of the time axis. The slope of the task lines is proportional to the production rate.
6. Work conflicts and interruptions are shown by intersecting and broken lines.

As discussed in the Phase I report (Kim et al. 2019), after a thorough literature review, the LSM was found to improve schedule overview, work continuity, and project control in most cases. The detailed benefits and challenges of the LSM found in case studies

are provided in Appendix I and II. Nevertheless, the LSM remains an unfamiliar tool for many DOTs and contractors. Significant cultural change is needed for the successful adoption of the LSM, and support from management teams is also essential.

LINEAR SCHEDULING SOFTWARE

The collection of software with LSM capability or designed specifically for linear projects has expanded greatly throughout the years. In comparison to five software programs identified and reviewed by Duffy (2009), 10 programs have been identified in the current market, as listed in Table 2.1. Based on its LSM scheduling capability, each program is placed into one of three categories: visualization tool, expanded functionality, or integrated system.

The LSM programs in the visualization category can generate a time-location diagram based on a network-based schedule. The programs are usually compact with limited functions. Programs in the expanded functionality category are capable of conducting work rate calculation and resource allocation in addition to providing visualizations. The integrated system category contains programs with full scheduling capabilities comparable to network-based scheduling tools.

Developers of GraphicSchedule, MAGNET Project, TILOS, and Vico Suite are based in the United States. GraphicSchedule is an Excel add-in and a good representative of a compact LSM tool. MAGNET Project was excluded due to its lack of support for exchanging data with other CPM scheduling tools. Although TILOS and Vico Office Suite are both stand-alone LSM scheduling tools, Vico Office Suite is geared toward BIM projects, while TILOS is more suited to the construction projects that are relevant to WSDOT. Additional information related to the implementation of these software programs in practice was collected through user surveys and interviews. Findings from the surveys and interviews were instrumental in the selection of appropriate LSM software programs to be implemented within WSDOT.

Table 2.1. Summary of software with LSM functionality.

Category	Tool Name	Company
Visualization Tool	GraphicSchedule	GraphicSchedule Inc. (Arroyo Grande, CA, USA)
	Turbo-Chart	Linear Project Software (Sydney, Australia)
	Time Location Plus	Naylor Computing (UK)
	Powerproject	Elecosoft UK Ltd. (Buckinghamshire, UK)
	Spider Project	Spider Project Team (Moscow, Russia)
Expanded Functionality	ChainLink	Steven Wood Software (Northampton, UK)
	Time Chainage	Peter Milton Planning (London, UK)
Integrated System	MAGNET Project	Topcon Positioning Systems Inc. (Livermore, CA, USA)
	Vico Office Suite	Trimble Inc. (Sunnyvale, CA, USA)
	TILOS	

PROJECT PERFORMANCE MEASUREMENT FRAMEWORK

From the studies related to business performance in construction, as well as adoption of a BIM tool and other software in digital technology and construction industry, several themes emerged as main performance indicators proposed for measuring the value of adopting the LSM tool. The following sections describe the performance indicators related to technical, people, and business performance categories. These three categories represent wider groups in which a performance indicator belongs, and its functional role resides in the initial indicator pool formation. Figure 2.4 illustrates the initial performance categories and indicators identified from the literature review.

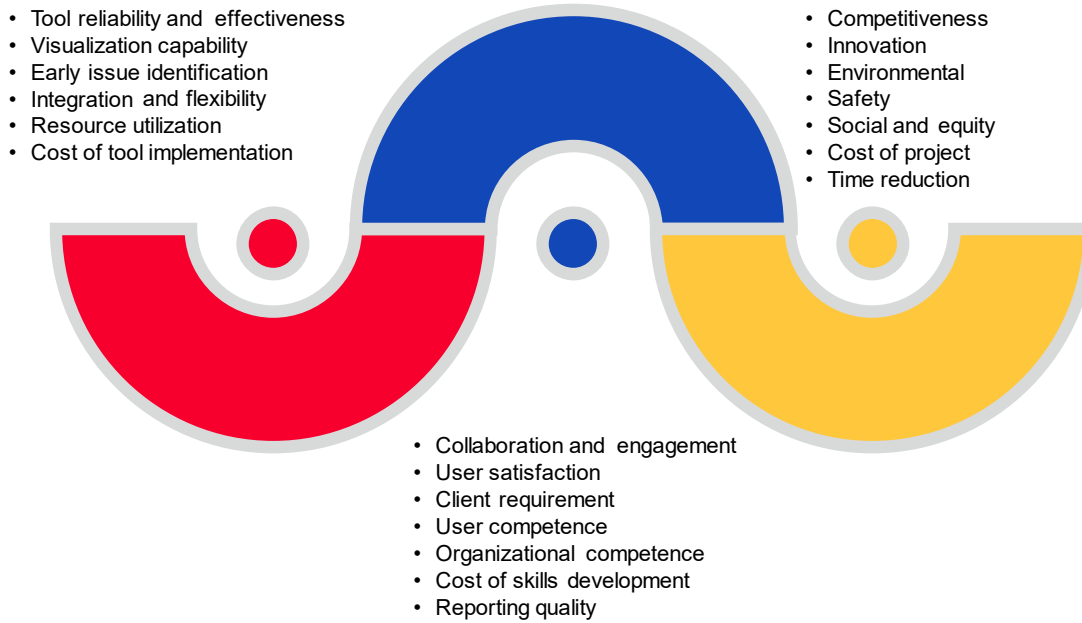


Figure 2.4. Initial performance categories and indicators of LSM tools.

Technical Performance

The technical performance category can be described through six indicators, as summarized in Table 2.2.

Table 2.2. Technical performance indicators and definitions.

No	Technical Indicator	Definition
1	Tool reliability and effectiveness	The extent to which LSM tool produces effective, credible, and consistent results.
2	Visualization capability	The ability of the LSM tool to provide a graphical representation of information to understand patterns in data.
3	Early issue identification	The LSM tool's ability to identify issues from the early stage of a project.
4	Integration and flexibility	The ease and reliability of the LSM tool to maintain the flow of information with other systems and the ease and reliability to which it can be adjusted to meet the user's specific needs.
5	Resource utilization	The extent to which the LSM tool's different features are being used effectively to make the most of the LSM tool's available features.
6	Cost of tool implementation	The financial factor related to the LSM tool implementation, which may include system purchase price, consultant cost expenses, system maintenance cost, and infrastructure cost of the LSM tool.

Tool Reliability and Effectiveness

Tool reliability refers to the extent to which a tool produces effective, credible, and consistent results. Nine studies mentioned the reliability of a tool as a critical indicator for measuring the success of adoption of the tool. For example, the sequence of activities in pipeline construction projects is usually not the concern; instead, the issue is to accurately assess and achieve the optimum production rates for timely completion. Thus, a linear scheduling model with varying production rates was developed to allow the development of schedule durations with minimal project information (Duffy et al. 2011).

In the context of BIM, Li et al. (2014) mentioned the importance of the ability to conduct quantity take-off accuracy as part of their study on quantifying the benefits of a BIM tool. In addition, BIM metrics should also include how accurate and reliable the model data—such as project information, geometry, fabrication model, and the like—are for end users during operation and maintenance (Liu et al. 2016; Pärn et al. 2017).

When developing a key performance indicator (KPI) assessment methodology for decision-making support, Mourtzis et al. (2018) proposed an evaluation of a product-service-system business model using KPIs, which was applied in a real industrial case of the mold-making area to evaluate the results. Two KPIs cited under the manufacturing category include (a) the number of deviations between the targeted values of the KPIs and the monitored data, and (b) the overall equipment effectiveness, which refers to how effectively a manufacturing operation is utilized. Another study mentioned the importance of evaluating the exchangeability and fault tolerance of a hardware as important criteria when evaluating whether to adopt a new technology (Furukawa 2017).

Visualization Capability

Visualization capability refers to the ability of a tool to provide graphical representation of information to understand patterns in data. Five studies mentioned the visualization capability as an indicator when considering tool adoption. This quality is especially the goal in a study by Duffy et al. (2011), which was to expand the linear scheduling capabilities to account for variance in production rates when and where the variance occurs and to enhance the visual capabilities of linear scheduling. The model created in this study was in a graphical format that allows the construction team to visualize

the obstacles in the project when and where they occur by using a new feature called the activity performance index.

In a review of the state-of-the-art knowledge-based decision tools in facilities management (FM), Pärn et al. (2017) identified three of the functionalities to be related to visualization, which include 3D visual approach for maintenance management, visualizer (a graphical decision support tool for service life prediction for asset managers), and FM visual analytics system for failure detection. Though these functions indicate the importance of visualization capability, the study suggested limitations, such as the need for a substantial amount of manual data input, and limits in showing how learning can occur for an organization and in showing knowledge capture as a method, respectively.

In the area of digital technology, Jetter et al. (2018) identified spatial representation of contextual information (such as to measure how the tool reduces errors in identifying the correct position of components) as one of the KPIs that is able to benchmark the impact of using ready-for-market augmented reality for several industrial applications in design, education, and training.

Early Issue Identification

Early issue identification refers to the tool's ability to identify issues from the early stage of a project. One of the key features of BIM is the clash detection, which identifies if the locations of an element are in conflict with others. Aziz et al. (2016) provided a direction to promote BIM in the organization and revealed that a capability to update information and clash detection is one of the benefits of using BIM to improve the working environment. Similarly, Coates et al. (2010) measures the performance of the BIM implementation using "a better product" indicator since the use of BIM is expected to produce a better product through mitigations such as clash detection as well as a reduction of mistakes, buildability issues, and insurance costs.

In another field of study, Jetter et al. (2018) developed KPIs to benchmark the impact of using ready-for-market augmented reality tools on automotive maintenance performance and found that the reduction of time and errors was the most important external variable in the technology acceptance model positively impacting the perceived usefulness of the system.

Integration and Flexibility

Integration and flexibility refer to the ease and reliability of maintaining the flow of information with other systems as well as the ease and reliability for which it is possible to adjust a tool to meet the specific needs of the user. One of the issues in LSM adoption is that the LSM and LOB can both analyze repetitive work possess virtues but lack a unified theory so that they can complement each other. Su and Lucko (2016) provided a 3D-integrated perspective view of the time, work, and resource performance. Their study united LSM and LOB so that crews can be optimized seamlessly. Dirza et al. (2019) proposed a new formulation for an integrated scheduling and control problem using Max-Plus-Linear representation, which results in setting the optimal (integrated) scheduling policy.

In an enterprise resource planning (ERP) study about the system selection and operational performance evaluation, Niu et al. (2017) suggested the need of an ERP system to better integrate the cross-regional and cross-department system. The ERP system should have excellent system flexibility to provide the ease of in-house development and integration.

Resource Utilization

Resource utilization refers to how effective and productive the features of the tool are. It also refers to making the most of the available resources/features of a tool. Su and Lucko (2016) compared the virtues of the LSM and LOB and found that the LSM has a resource utilization component. In the LSM, changing values in the model using singularity functions will modify the entire resource profile, while the LOB is not integrated with scheduling but currently requires separate analysis. Various studies have attempted to increase the capability of LSM tools so that they can be utilized more, such as by expanding the capabilities of the LSM to account for variance in production rates when and where the variance occurs (Duffy et al. 2011). Measuring resource utilization may also consider the usability aspects of the tool (Jetter et al. 2018).

Cost of Tool Implementation

Cost of tool implementation is a financial factor that a company must take into consideration. This cost may include the system purchase price, consultant cost expenses, system maintenance cost, and infrastructure cost. An ERP system implementation study

revealed that more than 54 percent of a project will exceed the budget due to unexpected technical or organizational issues (Panorama 2014). Although the long-time implementation of the ERP system may be more significant, the implementation time is also a critical attribute to be considered when measuring the cost of system adoption for the LSM.

People Performance

The people performance category consists of seven indicators, as summarized in Table 2.3.

Table 2.3. People performance indicators and definitions.

No	People Indicator	Definition
1	Collaboration and engagement	The extent to which the LSM tool helps different stakeholders work together to achieve a mutual goal while keeping its users involved in the adoption initiatives.
2	User satisfaction	The satisfaction of everyone who uses the LSM tool.
3	Client requirement	The criteria established by the user's working partners, such as clients, designers, or contractors, that includes a vision, mission, and objectives that the project must achieve.
4	User competence	The ability of the user to utilize the LSM tool.
5	Organizational competence	The databases, technology, routines, and culture in the organization that impact project performance.
6	Cost of skills development	The cost of improving individual capabilities and leadership qualities of both employees and project leaders, such as through training and through trials of the LSM tool.
7	Reporting quality	The quality level of analytical reporting of a project using the LSM tool.

Collaboration and Engagement

Collaboration and engagement in construction is an important aspect that affects the project performance and fosters long-term relationships. It is considered an external competence by Mladenovic et al. (2013) that includes partners' strengths and skills as well as relationships between partners. Meng (2012) identified the following relationship indicators: mutual objectives, gain and pain sharing, trust, no-blame culture, joint working, communication, problem-solving, risk allocation, performance measurement, and continuous improvement. Meng's study showed that adopting a working collaboration can

significantly avoid time delays and improve quality performance, while open communication can significantly avoid cost overruns and defects.

User Satisfaction

User satisfaction refers to the satisfaction of everyone who uses the constructed facilities. It was cited in 14 articles reviewed for this study and found in construction performance, BIM, and digital technology adoption studies. It can be measured by employing a survey that measures user satisfaction performance during the operation and maintenance period. It can also be measured by repeat orders received from a client (Kim and Arditi 2010; Yu et al. 2007). This satisfaction may also refer to the satisfaction of one's own organization and includes employees who work on specific projects. Indicators under internal satisfaction can be measured by the degree of employee satisfaction (Kim and Arditi 2010) or the employee turnover rate (Yu et al. 2007).

Client Requirement

Client requirement refers to the criteria set by the working partners of the users, such as clients, designers, or contractors. These criteria usually include a vision, mission, and objectives the client wishes the project to achieve. Ensuring that a project meets client requirements will result in client satisfaction and retention, which were measured by Coates et al. (2010) as one of the KPIs to evaluate the performance of BIM adoption.

User Competence

User competence is the ability of the user to utilize the linear scheduling tool. A study of Indian construction projects identified the importance of the project manager's competence, including technical and monitoring capabilities, as key to a project's success (Iyer and Jha 2006).

Organizational Competence

Organizational competence refers to databases, technology, routines, and culture in the organization that impact project performance. It has a positive relationship with individual competence, which is the KPI of an organization's competency (Yu et al. 2007). A good organization should also have an efficient structure of communication within the organization (Iyer and Jha 2006).

Cost of Skills Development

Cost of skills development refers to the cost of improving individual capabilities and leadership qualities of both employees and project leaders. The most common way to quantify employee competencies is based on the number of training sessions and formal education (Nybø 2004) of employees or the percentage of employees with professional licenses/certifications (Kim and Arditi 2010). However, Omar and Fayek (2014) proposed that construction project competencies should focus on not only technical but also behavioral competencies, such as personal skills, to communicate with different stakeholders, as well as leadership and decision-making skills. Finally, Iyer and Jha (2006) found that the project manager's competence is the most significant success factor in the schedule performance of construction projects.

Reporting Quality

Reporting quality refers to the quality level of analytical reporting on a project using an LSM tool. High-quality reporting can affect the investor or analyst's confidence and may result in better investments or project decisions.

Business Performance

There are seven indicators related to the business performance category, as summarized in Table 2.4.

Table 2.4. Business performance indicators and definitions.

No	Business Indicator	Definition
1	Competitiveness	The quality of a project being comparably better than others because of the use of the LSM tool.
2	Innovation	The extent to which the LSM tool helps enable and support the growth of the business through innovation.
3	Environmental	Aspects of the LSM tool that may help mitigate any environment-related issues.
4	Safety	The extent to which the LSM tool helps project completion without major accidents or injuries.
5	Social and equity	The extent to which the LSM tool helps address commitment to fairness, justice, and equality in the project.
6	Cost of project	The financial effectiveness and efficiency of a project due to the LSM tool adoption.
7	Time reduction	The extent to which the LSM tool helps reduce the time needed to complete any of the processes that comprise the project life cycle.

Competitiveness

Competitiveness refers to the quality of a project being comparably better than others because of the use of the LS tool. Adopting a new technology in a project or organization is motivated by attempts to attain competitiveness advantages for the product or project delivery in the market (Aziz et al. 2016; Coates et al. 2010).

Innovation

Innovation and technology transfer are important performance objective categories identified in both the public and private sector of public-private partnership (PPP) transport projects (Mladenovic et al. 2013). Technological innovation, such as novel management methods or equipment models, can be measured by the number of information and technology (IT) applications in a company (Kim and Arditi 2010).

Environmental

Environmental indicator refers to any aspect in the tool that may help mitigate any environment-related issues. Construction projects impact the environment across their life cycle (Shen and Tam 2002). Factors under this performance may include land use/site selection, water quality, air quality, noise quality, ecology and biodiversity, visual impact, waste management, energy and carbon emissions, pollution control, erosion and sediment control, and flora and fauna (Amiril et al. 2014).

Safety

Safety refers to completing the project without major accidents or injuries (Bubshait and Almohawis 1994). Safety performance can be measured by calculating the accident rate of a specific project, which is expressed as the ratio of the total number of construction site accidents to the total number of workers employed on a specific project (Construction Industry Review Committee 2001). Furthermore, (Lim 2009) considered not only safety of the road worker but also of the road user as part of the critical sustainability factors for road infrastructure projects.

Social and Equity

Social and equity are two important performance indicators. One transportation goal is to improve the quality of life through connectivity, such as by reducing roadway congestion, improving access to public transit, and allowing a more efficient mix of land uses (Shelton and Medina 2010). Jeon and Amekudzi (2005) found that social well-being

is one of the important indicators for sustainable transportation systems and can be measured in many ways, such as by examining the quality of transit for people with impaired mobility, the affordability of public transit service for lower-income residents, and the accessibility of individuals without a car.

Cost of Project

Cost of project refers to the financial effectiveness and efficiency of a project due to the LSM tool adoption. This factor becomes one of the key factors being considered when implementing various new technologies. For example, integrating BIM into facility management has benefit for the effective operational cost (Aziz et al. 2016).

Time Reduction

Time reduction refers to the extent to which the LS tool helps reduce the time needed to complete any of the processes that comprise the project life cycle. The ability to increase the time efficiency in completing a task can be associated with cost efficiency. For example, an empirical study confirmed that an augmented reality application in industrial applications was perceived to significantly contribute to a reduction in time and errors when completing a maintenance task (Jetter et al. 2018).

CHAPTER 3

RESEARCH METHODOLOGY

As depicted in Figure 1.1, this research was carried out in multiple stages involving different tasks. The completion of each task required one of various methods, including surveys, interviews, and case studies. The following sections describe in detail the design and procedures related to surveys, interviews, and the case study.

HUMAN SUBJECTS RESEARCH APPROVAL

To protect the safety, rights, and welfare of research participants and to ensure institutional compliance with federal and state regulations and university policies, any research involving human subjects is required to seek approval from the appropriate Institutional Review Board (IRB). This research project was considered to be University of Washington (UW) research involving human subjects for surveys and interviews. An application package was prepared detailing the survey and interview design and procedures, descriptions of the responsibility of each team member, survey and interview questions, and data protection measures. The package was submitted to the UW Human Subjects Division for IRB review on October 18, 2019 (IRB ID: STUDY00008637). The UW IRB completed the review on November 6, 2019. The proposed survey and interview activities were determined to be exempt from federal human subjects' regulations, including the requirement for IRB approval and continuing review. The official letter of determination is included in Appendix III.

SURVEYS

Throughout this research project, multiple surveys were designed and distributed to collect relevant information in order to complete the tasks. To avoid confusion, a list of the surveys is provided below. Each survey is also given a short name that is used in texts, figures, and tables in subsequent sections:

1. Linear Scheduling User Experience and Tool Assessment Survey (Survey I).
2. Third Party Linear Scheduling Training Course Survey (Survey II).
3. Indicators of Linear Scheduling Performance Pilot Survey (AHP Pilot).

4. Indicators of Linear Scheduling Performance Survey (AHP Full-Scale).
5. Perceptions of Linear Scheduling Performance Survey (Survey III).

As illustrated in Figure 3.1, findings from the five surveys were used in three aspects of the research. Surveys I and II focused on LSM user experience. The AHP Pilot and AHP Full-Scale surveys supported the building of the performance measurement framework. Survey III collected feedback regarding the case study and also validated the AHP Full-Scale survey. The periods of the survey distribution are shown in Figure 3.2.

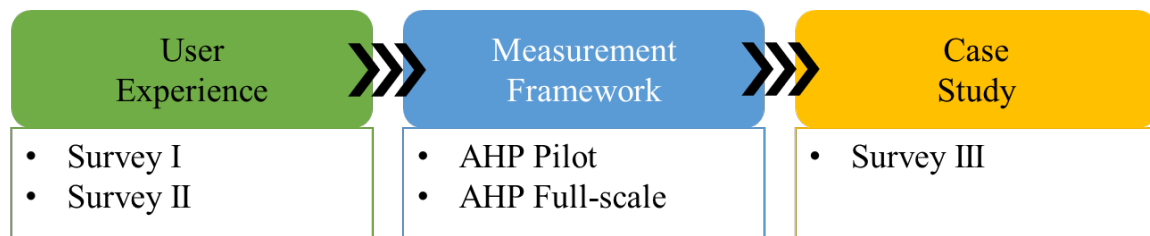


Figure 3.1. Relationship and purposes of the surveys.

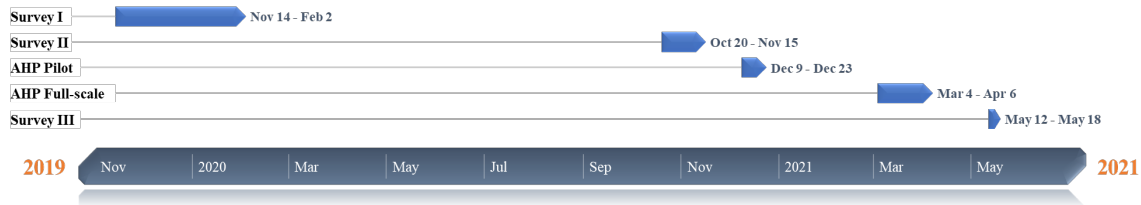


Figure 3.2. Timeline of the survey distributions.

Linear Scheduling User Experience and Tool Assessment Survey (Survey I)

Using the information gained from the literature review, Survey I was developed to assess current practices in the adoption of the LSM and its associated benefits and challenges. The survey was designed to capture the expertise and knowledge of design and construction professionals with various levels of experience using the LSM in transportation projects. In developing the survey, the research team aimed to identify the following:

- General steps in the adoption of the LSM and their relationship with the rest of the project planning and control activities.

- Resources (information, personnel, tools) required for completing each step and the outcome of each step.
- Benefits and challenges in the adoption of the LSM with respect to the proposed LSM performance framework.
- Appropriate contacts for targeted interviews.

The list of survey questions is provided in Table 3.1. The first section of the survey covers background information about survey respondents, including job title, affiliations, project experience, and level of familiarity with the LSM. The subsequent sections of the survey cover technical aspects of the LSM and include the following subsections:

- LSM processes and procedures, including major activities and their timeframe.
- Benefits and challenges of using the LSM, broken down by project phases and project goals (time, cost, quality, communications, competitiveness).
- Tools and resources needed for supporting the LSM, including software packages, personnel involved, and interaction between parties involved in the project (owner, consultant or design firm, contractor, etc.).

The research team discussed each question in detail with the WSDOT staff to clear up any possible confusion that might arise from the wording of the questions and the given options. Questions that might appear to be sensitive to some subjects were removed if the information could be obtained through alternative means.

Both Qualtrics (2021) and SurveyMonkey (2021) were considered as the potential platform for distributing the survey. After comparing the functionality and cost of the two platforms, SurveyMonkey was selected. The finalized survey questions were entered into SurveyMonkey and tested multiple times from November 7 through November 13, 2019, by three team members to uncover any errors or confusion in the workflow. The format of some questions were modified, and introductory paragraphs were added to facilitate better understanding of the survey. The tested survey was open to collect responses on November 14, 2019. In addition to the WSDOT prequalified consultant list, user networks of software vendors such as GraphicSchedule and TILOS were utilized to solicit responses from LSM users in North America. The survey link was distributed through multiple online channels including direct emails, email newsletters, and LinkedIn posts.

Table 3.1. List of questions for Survey I.

Theme	Question	Format
Background Information	What is the name of your organization?	Open-ended text
	What is the contractual role of your organization in construction projects?	Multiple choice
	What is your job title?	Open-ended text
	How many years of experience do you have in your current role?	Multiple choice
	How familiar are you with the linear scheduling method (LSM)?	5-point Likert scale
Linear Scheduling Processes and Procedures	Does your organization use the LSM?	Multiple choice
	If no, did your organization ever consider using the LSM?	Multiple choice
	If your organization did consider using the LSM, why was it not adopted?	Open-ended text
	If yes, when did your organization first use the LSM?	Multiple choice
	If your organization uses the LSM, which group or individual (job title) is in charge of planning and implementing the LSM?	Open-ended text
	If your organization uses the LSM, do you have established guidance or procedures for using it?	Multiple choice
	Can you share your LSM processes?	File upload
	In which type of projects does your organization use the LSM (e.g., tunnel, highway, bridge)?	Multiple choice
	At which phase of the project does using the LSM start?	Multiple choice
	At which phase of the project does using the LSM end?	Multiple choice
Benefits and Challenges	What are the benefits of using the LSM (i.e., cost, time, quality, safety, communication)?	Ranking
	Please list any other benefits related to the use of the LSM that were not included in the previous question.	Open-ended text
	Can you share examples and include project documents?	File upload
	What are the challenges of using the LSM (i.e., cost, time, quality, safety, communication)?	Ranking
	Please list any other challenges related to the use of the LSM, that were not included in the previous question.	Open-ended text
	Can you share examples and include project documents?	File upload
	Do you agree that the benefits of using the LSM offset its challenges?	7-point Likert scale
Tools and Resources	Which software program do you use for the LSM?	Multiple choice
	Who (job titles) within your organization is involved in developing and implementing linear scheduling plans?	Open-ended text
	Who (job titles) outside of your organization (other parties in the project) is involved in developing and implementing linear scheduling plans?	Open-ended text
	How often do you update your linear scheduling plans during the course of the project?	Multiple choice
General	Generally speaking, in the construction industry, do you agree that the LSM is going to fade away?	7-point Likert scale
	Please explain in two to three sentences your answer to the previous question.	Open-ended text

Third Party Linear Scheduling Training Course Survey (Survey II)

During an interview on November 30, 2020, with the CEO of Linear Project Software Pty Ltd., it was learned that the company had recently distributed a linear scheduling mini-course survey in October to its customers. The purpose of the survey was to gage the interest among their customers in learning the linear scheduling software developed by the company, called Turbo-Chart. The company is based in Australia and expected to have customers from different countries. Unlike Survey I, in which the responses were expected to be mostly from North America, the results of this third-party survey provided additional insight into the current status of linear scheduling usage in the industry in other parts of the world.

Indicators of Linear Scheduling Performance Survey

The Indicators of Linear Scheduling Performance Surveys were designed using the AHP. An AHP survey was structured as a hierarchy model, as shown in Figure 3.3, to let the experts provide relative comparisons between pairs of indicators using the AHP scale. The performance indicators categorized under technical, people, and business performance were used to develop the AHP survey in Qualtrics (2021).

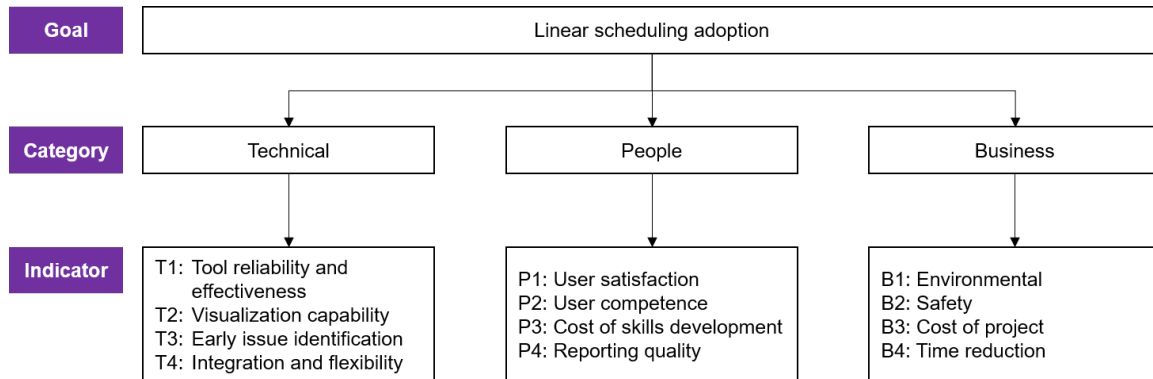


Figure 3.3. AHP hierarchy of linear scheduling adoption.

The first section of the survey contained general demographic questions, including the organization name, contractual role, job title, experience, and familiarity with the LSM. The second section of the survey was to let the experts comment on the relevancy of the proposed indicators, along with the descriptions. This section also asked if other indicators

should be considered that were not mentioned. The third section of the survey was the pairwise comparison of each performance category and then the pairwise comparison of each indicator in the same category. The categories and indicators at the same level were compared using Saaty's 1–9 scale. The interpretation of each number is given in Table 3.2. As an example, if a respondent felt very strongly that “visualization capability” was more important than “early issue identification,” the response would be to select the 7 closer to visualization capability. If a respondent strongly felt that “early issue identification” was more important than “visualization capability,” the response would be to select the 5 closer to early issue identification. This section also included open-ended questions that allowed respondents the opportunity to further elaborate on the answers for category and indicator comparisons. After calculating the weights of the factors, the authors checked the consistency ratio (CR) of the matrix to check judgment inconsistencies. If the CR is less than a threshold value of 0.1, then the matrix can be considered as having an acceptable consistency, and the derived priorities from the comparison matrix are meaningful (Saaty 1990). The local priorities were then calculated using Saaty's principal eigenvector of pairwise comparison matrices. These priorities are local because they are the priorities of elements in the same level of the hierarchy. Next, the local priorities were multiplied by the respective group priority to determine the global priority for each factor.

Table 3.2. AHP fundamental scale.

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extreme importance
9	Extreme importance

AHP Pilot

A pilot survey study was performed to evaluate the AHP survey design. Three experts from WSDOT participated in the pilot study. The participants helped to validate the questionnaire design and reduce the indicators to manageable numbers based on whether they were relevant, practical, measurable, and important.

Participant 1 was a design support manager, with 15 to 20 years of experience in the current role and perceived to be moderately familiar with the LSM. Participant 2 was a research manager/engineer, with one to three years of experience in the current role and perceived to be slightly familiar with the LSM. Participant 3 was a Project Management and Reporting System support engineer/transportation engineer 3, with five to 10 years of experience in the current role and perceived to be slightly familiar with the LSM.

AHP Full-Scale

A survey questionnaire was performed to assess the priorities of performance criteria and indicators using the AHP method. A web-based questionnaire was developed using Qualtrics (2021) that could effectively represent the AHP pairwise questions. The survey was distributed over three weeks beginning March 2021. The target participants included WSDOT team experts who previously participated in the interview part of this study and others recruited through snowball sampling by letting participants share the survey with their connections. Distribution involved sending the survey through emails, handing it out during meetings, and publishing it in participants' organization newsletter and on a professional networking platform. Three reminders were also sent out via these conduits.

Perceptions of Linear Scheduling Performance Survey (Survey III)

This survey aimed to identify the prospective users' perceptions toward the LSM tool performance. It was conducted as a follow-up to the AHP study prioritizing the performance indicators and the case study comparing the LSM and non-LSM design. Based on AHP analysis, six of the most important indicators included (1) tool reliability and effectiveness, (2) visualization capability, (3) early issue identification, (4) integration and flexibility, (5) safety, and (6) cost of project. These indicators were used to design the statement questions, as shown in Table 3.3. The survey used a 7-point Likert scale ranging from strongly disagree to strongly agree.

Table 3.3. List of questions for Survey III.

No.	Performance Indicator	Survey Question: In comparing the LSM with the non-LSM schedule, please rate the following: “The LSM tool...”
1	Visualization capability	Has improved visualization capability to understand patterns in data.
2	Early issue identification	Allows me to identify issues in the early stage of a project better.
3	Tool reliability and effectiveness	Is more reliable to produce effective, credible, and consistent results.
4	Integration and flexibility	Can be integrated with existing systems and adjusted to meet the user’s specific needs.
5	Safety	Improves safety by monitoring project completion without major accidents.
6	Cost of project	Improves the efficiency of project cost by optimizing work.

The survey was distributed to a targeted group of WSDOT representatives who have been participating in the case study part of this research. They included team members of I-90 and SR 28 projects. The survey was distributed via email on May 12 and May 14, 2021, and was open for one week. In total, six survey responses were received from May 12 to May 18, 2021.

EXPERT INTERVIEWS

The interviews with selected linear scheduling users were planned for after the completion of Survey I. The goal of the interviews was to confirm the survey results and obtain additional information beyond what was gained from the survey, including information on linear scheduling processes and specific tools that were used in different organizations.

The planned questions for each interview are shown in Table 3.4. The interview questions were developed based on the Survey I questions (see Table 3.1) with the same themes. Some questions were reworded or added to allow the interviewee to elaborate and expand on their responses.

Candidates for interviews were identified within the GraphicSchedule and TILOS user network. The users who were familiar with linear scheduling and used linear schedules regularly were contacted. In total, 10 of the users agreed to be interviewed. The interviewees were instructed to allocate 40–50 minutes for the session and were sent the

list of questions at least two days prior to the interview. Due to COVID-19 restrictions, all of the interviews were conducted virtually via either Zoom or Microsoft Teams depending on each interviewee's preference.

Table 3.4. List of interview questions.

Theme	Questions
Background Information	What is your job title?
	How many years of experience do you have in your role?
	How familiar are you with the LSM (on a scale of 1 to 10)?
	What motivated you to start using the LSM?
LSM Processes and Procedures	Which group or individual (job title) is in charge of planning and implementing the LSM?
	Which phase of the project does your scheduling work involve (e.g., pre-construction, during construction)?
	In your experience, does the requirement of the LSM often come from the owner or is it something you advertise?
	In what types of projects do you usually use the LSM, e.g., highway, rail?
	What are the major steps in developing the LSM in a project?
	How often do you update the schedule?
Benefits and Challenges	What are the benefits of using the LSM? If possible, please break down the benefits by project phases and/or project outcome affected (cost, time, quality, safety, communication).
	Can you share examples and include project documents?
	What are the challenges of using the LSM? If possible, please break down the challenges by project phases and/or project outcome affected (cost, time, quality, safety, communication).
	How does your organization overcome these challenges?
	Can you share examples and include project documents?
	Do the benefits of using the LSM offset its challenges? Please explain.
Tools and Resources	What software do you mainly use for the LSM?
	Does the software work well with the traditional scheduling tools, such as Primavera P6?
	Do you think the software poses any challenges for people who want to learn?
	Who (job title) within your organization is involved in developing and implementing the LSM?
	What is the role of each individual (in terms of information input and expertise) in developing and implementing the LSM?
	Who (job title) outside of your organization (other parties in the project) is involved in developing and implementing the LSM?
	What is the role of each individual (in terms of information input and expertise) in developing and implementing the LSM?
	Can you share examples and include project documents?
General	Generally speaking (in the construction industry), do you think the LSM is going to thrive or fade away? Why?

CASE STUDY

To showcase the value of the LSM, the research team conducted a case study within WSDOT. After discussion with the WSDOT technical monitor, it was agreed that a project early in design would be suitable for this purpose. The network-based schedule of the project was obtained and used to build a linear schedule. Subsequently, the project team could review the linear schedule and assess its value in improving the performance of the project. The State Route 28 (SR 28) East Wenatchee corridor improvements project team expressed interest in participating as the potential case study.

The SR 28 East Wenatchee project addresses the long-standing problems on the Sunset Highway Corridor between the Odabashian Bridge and Downtown East Wenatchee (WSDOT 2020). Nearly 15,000 vehicles travel on this stretch of road every day, and as the area continues to grow, conflicts between north-south traffic traveling on SR 28 and traffic crossing or turning off and on the highway are increasing. Currently, the corridor is not ideal for multimodal options such as bicycling or transit. This project aims to enhance safety and mobility on SR 28 in East Wenatchee from 9th Street N.E. to Hadley Street with intersection improvements and widening the existing roadway to accommodate four lanes with a restrictive median.

The research team met with the SR 28 project team on March 17, 2021, to establish communication between the two teams. The SR 28 team were asked to provide the following items to facilitate the creation of a linear schedule:

- A list of construction activities to be displayed on the linear schedule.
- The start and end time and location for each activity.
- The type of each activity—line activity, block activity, environmental restriction, and so on.
- An aerial image or engineering drawing that could be displayed alongside the linear schedule.
- Logic links and time lags associated with each activity.
- Type of work calendar used in the construction.
- Planned work rate for each activity.
- Resource allocation and cost estimate if available.

Based on the information received from the SR 28 team, the research team drafted linear schedules using both GraphicSchedule and TILOS. Both versions of the schedule were provided to the SR 28 team for comparison and assessment.

CHAPTER 4

DATA ANALYSIS

Empirical data collected through surveys, interviews, and the case study were analyzed, and important findings are presented in this chapter.

SURVEYS

Survey I

Survey I was open from November 14, 2019, through February 2, 2020. A total of 74 responses were collected.

Subject Background

Respondents from consulting firms represented the largest group (39.2 percent), followed by general contractors (27 percent) and owners (13.5 percent). Only 2.7 percent of the respondents were subcontractors, and the remaining respondents were from other organizations. The respondents worked in various roles in their organizations, including scheduling, project control, and project planning. Over 90 percent of the respondents had at least three years' working experience in their current role, while 39 percent of the respondents had over 20 years of working experience. The respondents also appeared to have a high level of familiarity with the LSM. The majority of the respondents (86.4 percent) were at least moderately familiar with the LSM, with 56.7 percent of the respondents reporting that they were either very familiar or extremely familiar with the LSM. This result was expected considering that individuals who were not familiar with the LSM were less likely to participate in the survey.

Process and Procedures

Forty out of the 74 respondents (54.1 percent) reported that their organizations did use the LSM as a scheduling tool. Within the 40 respondents, 18 used the LSM for the first time less than five years ago, while another 18 used the LSM for the first time over five years ago. These responses verify that, although the LSM has been implemented in many organizations, it is still a relatively new method in the industry. Of the 23 respondents (31.1 percent) who reported that their organizations did not use the LSM, eight reported that the LSM had been considered but not adopted, while five stated that their organizations never

considered using this method. Reasons for not adopting the LSM included incompatible project types, software cost, and widespread use of the CPM by partner organizations.

Many organizations already using the LSM do not have established guidance of procedures for users to follow. Within the 40 respondents whose organizations did use the LSM, about 43 percent stated that their organizations did not establish guidance or procedures. The successful implementation of the LSM in these organizations often depend on the users to take initiative.

Not surprisingly, highways were the most cited projects (60 percent) on which the LSM has been used by survey respondents, followed by tunnels (52.5 percent) and bridges (50 percent). The other types of projects mentioned by some respondents include pipelines, railways, and power transmission lines. The majority of the LSM users (55 percent) started the process at the planning or preliminary design phase, while 20 percent did not start until the construction began. Most of the respondents (82.5 percent) indicated that the end of the process was at the completion of construction or post-construction. These responses reveal that the usage of the LSM does cover the major project phases, from planning to construction, in most cases.

Benefits and Challenges

To understand the benefits and challenges of using the LSM, the survey participants were asked to rank five factors—communication, time, cost, quality, and safety—in terms of how they were positively or negatively affected by LSM implementation. Communication and time were two factors ranked highest as being positively affected by using the LSM. The visual capability of linear schedules facilitates better understanding of the project space, constraints, and production rates, which in turn improves communication efficiency within the project team. Interestingly, time was also ranked as the highest negative factor affected by using the LSM. The respondents' comments revealed that the learning curve of the LSM and the difficulty in the initial setup of a linear schedule often posed challenges for users and organizations.

Overall, most respondents (54 percent) did agree that the benefits of using the LSM offset its challenges; only 5.5 percent of respondents disagreed with that position.

Tools and Resources

The majority of the LSM users (62.5 percent) reported using TILOS, followed by Turbo-Chart (30 percent) and GraphicSchedule (25 percent). Time Location Plus and ChainLink were also used by a small number of respondents. Other programs used by the respondents included Excel and AutoCAD. A majority of the respondents (55 percent) updated their linear schedule at least monthly. Some respondents indicated that the update frequency varied across project phases (more often during planning) and also depended on the type of projects (daily for pipelines and weekly for roadways) as well as client needs.

In general, more respondents (47.3 percent) believed that the LSM would remain a viable tool in the construction industry; only 4.1 percent of respondents believed that the LSM would fade away. Respondents listed the following contributing factors as being important in sustaining the use of the LSM in the industry:

1. Support from owners in using the LSM (e.g., require the use of the LSM in contracts).
2. Better integration with CPM tools.
3. Identification of specific reasons for using the LSM (e.g., claim analysis, resource optimization, clash detection).

Survey II

This third-party survey conducted by Linear Project Software Pty Ltd. was posted on the company's LinkedIn page from October 20, 2020, through November 15, 2020. A total of 76 responses were collected.

The green highlighted areas in Figure 4.1 show the locations of the Survey II respondents. As opposed to Survey I respondents, who were mostly from North America, Survey II had a larger international coverage.



Figure 4.1. Survey II respondents' locations (highlighted in green).

Most of the respondents (90 percent) were contractors and consultants, and the respondents largely reported unfamiliarity with linear scheduling, which is not surprising considering that Survey II was designed for users who were interested in taking the Turbo-Chart training course. Therefore, participants were not expected to have extensive experience in using the LSM.

To Survey II respondents, lack of basic knowledge remained the biggest challenge to using the LSM. The respondents expected the training course to offer some basic and intermediate elements related to the LSM, as shown in Figure 4.2. Most respondents agreed that using case studies and actual examples to illustrate the LSM would facilitate a better understanding. Respondents with relatively little knowledge of the LSM were interested in basic training elements, including cost and benefit of the LSM, time-location chart creation, compatibility of LSM software and CPM software, as well as applications in different construction industries. Respondents who had some basic knowledge wanted to learn advanced techniques such as time-location chart editing and data analytics.

Contrary to Survey I, whose purpose was to find the current best practices of the LSM in the field, findings from Survey II offer some guidance in designing future LSM training courses for WSDOT employees.

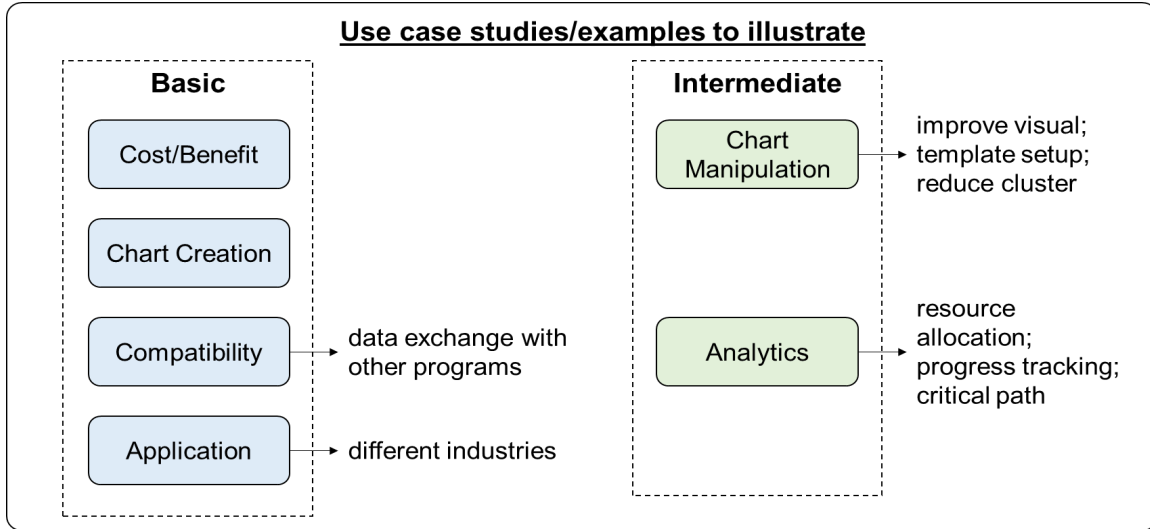


Figure 4.2. Expected training elements from Survey II respondents.

AHP Survey

AHP Pilot

Two participants agreed that people performance is the most important category for linear scheduling adoption. Participant 1 weighted the importance as high as 60 percent, significantly higher than Participant 2, who assigned a weight of 44.4 percent. Participant 3 weighted technical performance, 60.8 percent, as the most important category. All three participants ranked and weighed the 20 performance indicators differently. The consistency ratios were all above 10 percent, which made the conclusion less reliable. However, in practice, consistency ratio above 10 percent has to be accepted in some cases. Since this was a pilot survey, the researchers did not further analyze the results for recommendations to the study. However, one of the comments suggested significant revision by shortening the survey length. Although some questions in the pilot version were not asked in the final survey, the number of performance indicators were reduced to shorten the study further. The researchers analyzed the AHP survey to reduce the survey's length by excluding some performance indicators that had a low importance level.

Table 4.1. Summary analysis of AHP pilot survey.

Name	Pilot Participant 1					Pilot Participant 2					Pilot Participant 3				
	R	M	W	Rank	CR	R	M	W	Rank	CR	R	M	W	Rank	CR
Technical performance	—	—	21%	2	45%	—	—	11%	3	0%	—	—	61%	1	9%
People performance	—	—	60%	1	—	—	—	44%	1	—	—	—	27%	2	—
Business performance	—	—	19%	3	—	—	—	44%	1	—	—	—	12%	3	—
Tool reliability and effectiveness	Y	Y	18%	4	29%	Y	Y	10%	5	11%	Y	Y	30%	1	18%
Visualization capability	Y	Y	19%	3	—	Y	Y	33%	1	—	Y	Y	24%	2	—
Early issue identification	Y	Y	30%	1	—	Y	Y	30%	2	—	Y	Y	21%	3	—
Integration and flexibility	Y	Y	4%	6	—	Y	Y	13%	3	—	Y	Y	16%	4	—
Resource utilization	Y	Y	10%	5	—	Y	Y	10%	4	—	Y	Y	3%	6	—
Cost of tool implementation	Y	Y	21%	2	—	Y	Y	4%	6	—	Y	Y	5%	5	—
Collaboration and engagement	Y	Y	6%	5	10%	Y	Y	12%	5	15%	Y	Y	11%	4	12%
User satisfaction	Y	Y	16%	3	—	Y	Y	21%	1	—	Y	Y	28%	2	—
Client requirement	N	N	3%	7	—	Y	Y	12%	4	—	Y	Y	9%	5	—
User competence	Y	Y	6%	4	—	Y	Y	19%	2	—	Y	Y	14%	3	—
Organizational competence	N	N	4%	6	—	Y	Y	10%	6	—	N	N	3%	7	—
Cost of skills development	Y	Y	43%	1	—	Y	Y	9%	7	—	Y	Y	6%	6	—
Reporting quality	Y	Y	23%	2	—	Y	Y	17%	3	—	Y	Y	28%	1	—
Competitiveness	Y	Y	10%	5	27%	Y	Y	7%	5	12%	Y	N	6%	6	15%
Innovation	Y	Y	22%	2	—	Y	Y	4%	7	—	Y	Y	10%	4	—
Environmental	Y	Y	5%	7	—	Y	Y	6%	6	—	Y	Y	26%	1	—
Safety	Y	Y	12%	4	—	Y	Y	36%	1	—	Y	Y	22%	3	—
Social and equity	Y	N	8%	6	—	Y	Y	18%	2	—	Y	N	26%	2	—
Cost of project	Y	Y	29%	1	—	Y	Y	13%	4	—	Y	Y	4%	7	—
Time reduction	Y	Y	15%	3	—	Y	Y	15%	3	—	Y	Y	7%	5	—

Note: R: Relevant; M: Measurable; W: Weight; Y: Yes; N: No. “—”: Not applicable

Table 4.1 summarizes the AHP analysis based on three participants who completed the pilot survey between December 9, 2020, and December 23, 2020. The table shows the researchers' recommendations on the indicators to include in the full-scale survey based on pilot study analysis. Next, the results were discussed in a follow-up meeting with a pilot participant on February 11, 2021, to finalize the list of recommended indicators to include in the AHP Full-Scale survey. The full-scale survey was used to measure the performance of a project adopting the LSM.

Importance of technical performance

Participant 1 ranked early issue identification as the most important indicator, Participant 2 ranked visualization capability first, and Participant 3 ranked tool reliability and effectiveness first. The least important indicators rated by each of the three participants were integration and flexibility, cost of tool implementation, and resource utilization.

Integration and flexibility were within the top three priorities of Participant 2 (ranked third). The cost of tool implementation was also within the top three priorities of Participant 1 (ranked second). Thus, the researchers recommended keeping these indicators for the final survey. Resource utilization was ranked fifth, fourth, and sixth by Participants 1, 2, and 3, respectively; this indicator was excluded from the final survey.

Importance of people performance

Participant 1 ranked the cost of skills development as the top priority, Participant 2, ranked user satisfaction as the most important indicator, and Participant 3 ranked reporting quality as the most important indicator. The least important indicators rated by each of the three participants were client requirement, cost of skills development, and organizational competence.

Client requirement was ranked seventh, fourth, and fifth by Participants 1, 2, and 3, respectively. Cost of skills development was the most important indicator for Participant 1, although it was ranked seventh and sixth by Participant 2 and 3, respectively. Organizational competence was not considered a priority by any of the three participants (ranked sixth and seventh). Based on this evaluation, client requirements and organizational competence were excluded from the final survey.

Importance of business performance

The most important indicator for Participant 1 was the cost of the project, while Participant 2 put safety as the primary performance indicator. Participant 3 ranked environmental as the most important indicator. However, the least important indicators overall (when considered by all participants) were environmental, innovation, and cost of project.

Since the cost of the project and environmental were indicators each marked most important by a participant, these indicators were included in the final survey. Innovation was the second priority rated by Participant 1, so the researchers kept this indicator in the final survey. Among other business performance indicators, competitiveness was the only indicator consistently ranked low by all three participants (ranked fifth and sixth). Furthermore, participants were unsure about how competitiveness could be effectively quantified or and felt it more challenging to obtain the data on the subject. Based on this evaluation, the researchers proposed that competitiveness to be excluded from the final survey.

Summary

The pilot study aimed to improve the quality of the survey draft before it was officially distributed. One of the significant comments the researchers received was to reduce the length of the survey to increase the participation rate. The researchers reserved the three most important indicators of technical, people, and business performance by each participant based on the AHP analysis results. Finally, the researchers proposed some indicators that ranked significantly low, were considered irrelevant, or were challenging to be practically measured be removed from the future study. A follow-up with a pilot participant was conducted to achieve a consensus of the indicators to exclude from the research and to resolve the risk of inconsistent personal judgment for the final survey. Based on the evaluation of the pilot study results and a follow-up with a pilot participant, the indicators shown in Table 4.2 were included in the final survey.

Table 4.2. Final list of performance indicators.

Technical	People	Business
Tool reliability and effectiveness	Cost of skills development	Cost of the project
Visualization capability	User satisfaction	Safety
Early issue identification	User competence	Environmental
Integration and flexibility	Reporting quality	Time reduction

Based on the pilot study, the researchers were able to decrease the number of indicators from 20 initial indicators to 12 indicators, which manifested in a reduction from 57 to 18 pairwise questions.

AHP Full-Scale

Respondent characteristics

A total of 15 surveys were collected, of which 14 AHP surveys were completed and usable for further analysis. Participants included three WSDOT representatives, and the remaining respondents were contractors and consultants. Almost 80 percent of the respondents had over 10 years of experience in their current role. In terms of familiarity with the LSM tool, over 70 percent of respondents considered themselves very familiar to extremely familiar with it, which helped to justify the reliability of their personal judgment. The respondent characteristics are summarized in Table 4.3.

Table 4.3. Respondent profiles.

No.	Organization	Role	Title	Experience (Year)	Perceived Familiarity
1	Kiewit	General contractor	Sr. Scheduling Manager	15 to 20	Extremely familiar
2	Linear Project Software	Software Developer	Co-Founder/CEO	Over 20	Very familiar
3	Tarr Whitman Group (TWG) LLC	Consultant	Principal	5 to 10	Very familiar
4	HNTB	Consultant	Construction Manager	10 to 15	Extremely familiar
5	Petroglyph Project Analytics and Consulting Inc.	Consultant	CEO	15 to 20	Extremely familiar
6	WSDOT Olympic Region	Owner	Project Development Engineer	1 to 3	Slightly familiar
7	WSDOT	Owner	WSDOT Assistant State Construction Engineer	1 to 3	Moderately familiar

No.	Organization	Role	Title	Experience (Year)	Perceived Familiarity
8	Sound Transit	Owner	Principal Construction Manager	Over 20	Extremely familiar
9	WSDOT—Ferries Division	Owner	Sr. Marine Engineer	10 to 15	Slightly familiar
10	Deutsche Bahn	General contractor	Planning Engineer	10 to 15	Very familiar
11	Parsons	Consultant	Senior Project Controls Engineer	15 to 20	Extremely familiar
12	Heavy Constructors, Inc.	General contractor	Manager	10 to 15	Moderately familiar
13	Piemme Group	Owner	Executive Partner	15 to 20	Very familiar
14	Ministry of Transport and Communications	Consultant	Cost Estimator	10 to 15	Very familiar

Relative importance of performance indicators

Table 4.4 summarizes the analysis results of 14 individual responses. The most important category is technical performance, followed by business and people performance. The results show high inconsistency; however, the results were presented in the progress meeting and received no further disagreement, implying that the meeting attendees agreed with the aggregate results.

Table 4.4. Summary of AHP results.

Category	Category rank	Category priority (%)	Consistency ratio (%)	Indicator	Local indicator priority (%)	Local rank	Global indicator priority (%)	Global rank
Technical	1	7.9–72.8	2–166	Tool reliability and effectiveness	3.8–63.9	3	2.8–46.5	3
		—	—	Visualization capability	8.5–61.8	1	6.2–44.9	1
		—	—	Early issue identification	5.3–51.5	2	3.9–37.4	2
		—	—	Integration and flexibility	4.5–53.9	4	3.3–39.2	4
People	3	5.2–70.1	0–106	User satisfaction	3.8–51.4	3	0.2–2.7	11
		—	—	User competence	11.8–50.9	1	0.6–2.7	9

Category	Category rank	Category priority (%)	Consistency ratio (%)	Indicator	Local indicator priority (%)	Local rank	Global indicator priority (%)	Global rank
Business	2	6.5–69.4	0–72	Cost of skills development	4.0–59.5	4	0.2–3.1	12
				Reporting quality	7.1–60.8	2	0.4–3.2	10
				Environmental	3.2–48.3	4	0.7–10.7	8
				Safety	6.1–64.0	1	1.4–14.1	5
				Cost of project	7.3–52.3	2	1.6–11.6	6
				Time reduction	3.8–57.9	3	0.8–12.8	7
Note: “—”: Not applicable								

EXPERT INTERVIEWS

Ten interviews were conducted with selected LSM experts from July through December in 2020. The schedule of the interviews is given in Table 4.5. All of the interviews were conducted virtually and recorded with permission from each interviewee. The recordings were later reviewed, transcribed, and summarized by the research team to produce generalized findings.

Table 4.5. Interview schedule.

Subjects	Invitation Date	Interview Date
1	June 22, 2020	July 7, 2020
2	June 22, 2020	July 30, 2020
3	June 22, 2020	August 28, 2020
4	August 21, 2020	August 27, 2020
5	August 21, 2020	September 1, 2020
6	August 21, 2020	September 1, 2020
7	August 31, 2020	September 3, 2020
8	September 21, 2020	December 7, 2020
9	November 17, 2020	November 23, 2020
10	November 17, 2020	November 30, 2020

Expert Background

As shown in Table 4.6, the 10 interview subjects were evenly spread among different types of organizations (i.e., owners, contractors, and consultants). All of the subjects were familiar with the LSM and used it frequently in their work. Eight out of the 10 subjects had over 10 years of working experience with the LSM at the time of the interviews. Most of the subjects have worked in both the pre-construction and construction phase of a project. As discussed with the subjects, the creation and management of linear schedules were usually assigned to the project controls group. However, other work groups may also be tasked with linear-scheduling-related work, including estimating, scheduling, construction management, and communication.

Table 4.6. Interview subjects' background information.

Subjects	Job Title	Organization Type	Construction Phase Involved
1	Lead Scheduler	Owner	Pre- and during construction
2	Lead Scheduler	Contractor	Pre-construction
3	Senior Planning Advisor	Owner	Pre-construction
4	Project Superintendent	Contractor	Pre- and during construction
5	Program Interface Management Manager	Owner	Pre- and during construction
6	Senior Scheduling Manager	Contractor	Pre- and during construction
7	Principal/Operations Manager	Consultant	
8	Principal Construction Manager	Owner	Pre- and during construction
9	CEO/Director	Consultant	Pre- and during construction
10	Communication Manager	Consultant	Pre- and during construction

Linear Schedule Development Process

The interviewees elaborated on their respective processes for developing a linear schedule. Although the detailed procedures varied for each interviewee given their different organizations and job roles, some major steps were essential for every process when developing a linear schedule.

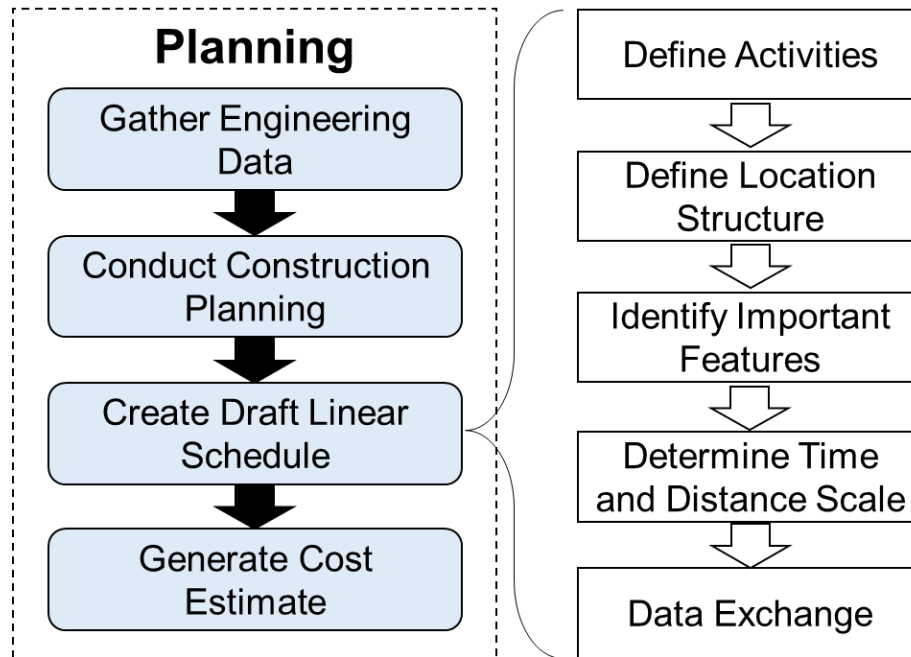


Figure 4.3. Standard process for creating a linear schedule in the project planning phase.

As illustrated in Figure 4.3, when a linear schedule is created during the project planning phase, the schedulers usually begin by gathering engineering data (e.g., route, geotechnical information, crossings). The next step is to conduct construction planning (e.g., define spread breaks, work crews, planned production rates, etc.). The third step is to create a draft linear schedule based on the collected engineering data and construction planning. The development of the draft linear schedule can also be described using a separate workflow. Before setting up the linear schedule, schedulers must define the essential visual elements, including the work activities, stationing points, and important features (e.g., river crossings, intersections, environmental restrictions). The time and distance scale of the linear schedule should be configured so that all of the visual elements can be displayed properly on the one-page diagram. It is common to have a data exchange between the CPM scheduling program, such as Primavera P6, and linear scheduling program, such as TILOS, so that existing data in the CPM schedule can be used without recreation in the linear scheduling program. This process for creating a draft linear schedule can be repeated with updated engineering data and construction planning to generate refined linear schedules. By taking into consideration all relevant context information, the linear schedule can lead to a comprehensive capital cost estimate. Naturally, any change to

the linear schedule later results in a corresponding change in the cost estimate. When construction begins, the linear schedule developed during the planning phase can be set as the baseline schedule and progress of the activities can be tracked throughout the construction phase by updating the linear schedule periodically.

Linear Scheduling and Project Control

Almost all of the interviewees have experience in creating linear schedules early in the planning phase, which ensures that the schedules have accurate background information and the intended level of detail. However, the value of continually using the schedules throughout the construction phase cannot be ignored. Several experts referred to the linear schedule as an effective tool in project control, especially for resolving construction delay claims. As noted by Kenley and Seppanen (2010), linear schedules enhance the owners' project control capability by offering more embedded information in the planning and scheduling system. For typical linear projects with repetitive activities, strong correlations exist between activities conducted at different locations using the same resources. The traditional CPM has no mechanism to manage the correlation between the duration of activities in different locations, and the level of detail in the information available is often insufficient to pinpoint the cause of delay (Kenley and Seppanen 2010).

In addition to the WBS commonly used in the CPM, location information contained in a linear schedule conforms to a location breakdown structure (LBS). The LBS allows the repeated activities at different locations to be represented by a single task instead of creating copies of the same activities at each location with duplicated chains of logics. Thus, a task is defined as the combination of activities in a sequence of locations that can be done by a single crew or split among multiple crews (Kenley and Seppanen 2010). The internal logics among activities at each location and the external logics among tasks spanning multiple locations provide the schedulers a much improved mechanism for project monitoring and control. At the planning phase, the baseline schedule can establish finish dates at each location. When construction commences and the schedule is updated, it is easy to identify delays from activities across different locations, and it forces the contractor or subcontractor to initiate control actions immediately to minimize the impact. This helps the owner and the contractor to see the upcoming claims. By tracking the progress and production rate of activities across different locations, schedulers can also

forecast future progress more realistically, which in turn provides management with better information for future control action decisions. As Kenley and Seppanen (2010) pointed out, management should concentrate on preventing upcoming production problems instead of focusing on shortening the duration of the critical path.

Benefits of Linear Scheduling

The interviewees agreed that the biggest advantage of a linear schedule over a CPM schedule lies in its capability to visually convey essential project information in a clear and efficient manner. The use of linear schedules in team meetings often improves communication and helps identify and proactively mitigate project risks. Once the team members are familiar with linear schedules, they can better participate in the schedule development process, which in turn results in a more effective plan and a greater buy-in from stakeholders.

Because of the added location information, the LSM is a more effective method than the CPM for identifying issues related to the geographical spread of the project in early stages so that actions can be taken to resolve them before any delays occur. Examples include land acquisition to route the projects, eminent domain, terrain, and cultural sites. In addition, a linear schedule helps project teams in different disciplines have advanced knowledge of the operations happening in their work area led by other teams. Any crew conflict on the work site can be identified early and resolved without causing any delay.

The LSM also enables the visualization of production rates. At the planning phase, it helps facilitate offsetting resources and finding crew balance by shifting resources from activities of higher production rates to other activities with lower rates. During construction, when an activity's actual progress is plotted against the baseline, it is easy to recognize any activities that cause delays so that claims and disputes can be resolved quickly.

Challenges of Linear Scheduling

Despite the many benefits of using the LSM, certain challenges may prevent its implementation for many organizations. The LSM has a rather steep learning curve for beginners. Even for schedulers who are familiar with CPM schedules, it takes a lot of effort to establish a basic understanding of the purpose of linear scheduling and how it can be helpful to a project. Software programs for linear scheduling are not easy to use either

compared to other CPM scheduling tools. With a limited user market and limited funding support, these software programs usually cannot advance at a rapid pace.

Developing linear schedules requires additional resources. Although some owners have started requiring linear schedules in contracts, they are not substitutes to CPM schedules, and building the linear schedule is often an extra step the project team has to take. While the LSM is a great visualization tool, when the density of activities at a single location is high, practical limitations exist in printing and displaying them on a one-page diagram. In such instances, some workarounds are needed to make the diagram legible. During construction, updating each activity's progress on a linear schedule is also more complicated. In addition to knowing how much work has been completed, the scheduler also needs to know the current location of all the crews.

The gap in the knowledge and understanding of the LSM often leads to resistance in adoption. Since using the LSM requires additional effort, when the organization is skeptical about its benefit, it is difficult to implement such techniques.

CASE STUDY

Linear Schedule Development

After the initial meeting with the SR 28 project team in March, the research team received the required items from the project engineer on April 1, including the activity data (type, location, duration, etc.), pre-activities and metadata, and important map features. These items were critical for the research team to build a linear schedule. The research team completed the first draft of the linear schedule using TILOS on April 12. Both the WSDOT technical monitor and the SR 28 project engineer reviewed the draft. The SR 28 project engineer agreed that the linear schedule was useful in the planning stage to facilitate early consideration for constructability. It was also suggested that cost information could be added to the schedule to show the weekly burn rate for the construction. The project engineer shared the cost data on April 15, and a revised linear schedule with a weekly cost histogram was completed on April 16, as shown in Figure 4.4. A similar schedule was also developed using GraphicSchedule (see Figure 4.5). Both versions of the schedule were shared with the SR 28 team. The project engineer agreed that they both provided similar output, although TILOS had more capabilities. However, for a simple schedule at the early design stage of the project, either output would be valuable for the team.

Benefits and Challenges

The linear schedules developed in TILOS and GraphicSchedule were based on simple schedule data stored in Excel spreadsheets. From the linear schedules, it is easy to notice some intersections of activities—for example, Sidewalk Part 1 and Paving Part 1, and Drainage Part 2 and 15th Roundabout (RAB) Part 2. The intersection of two activities indicates that two work crews will be at the same location at the same time. Project teams can then further review these activities and make modifications if necessary to ensure that no conflicts are present at the work site. For the SR 28 project, the Culvert Part 3 activity had to be carried out within the in-water-work window. From the linear schedules, it appeared that the current schedule did not allow this activity to meet the window. Therefore, the schedule had to be adjusted to assign the Culvert Part 3 activity an earlier start date. Otherwise, the project would have continued into the subsequent year to complete the remaining tasks.

Some challenges exist in developing the linear schedule with only preliminary data for a project in early design. With only the duration for each activity and logic links, the start and end date for each activity need to be calculated. This process is not problematic in TILOS since it supports work calendars and logic definitions. However, it is challenging for GraphicSchedule since it relies on Excel functions for any calculation. Functions in Excel involving workday calculations are often not sufficient for scheduling purposes because of the lack of a flexible built-in work calendar.

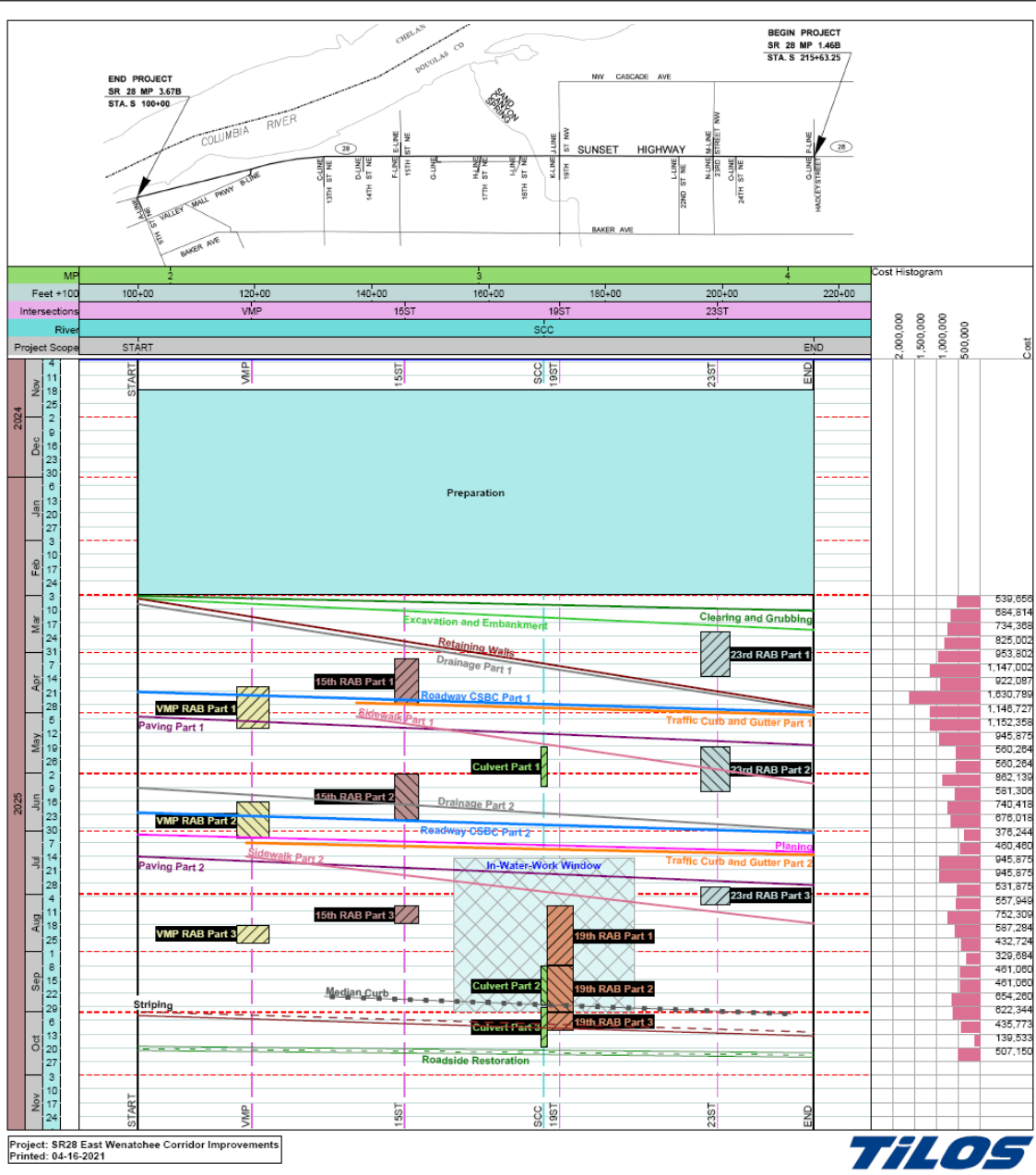


Figure 4.4. SR 28 project linear schedule built in TILOS.

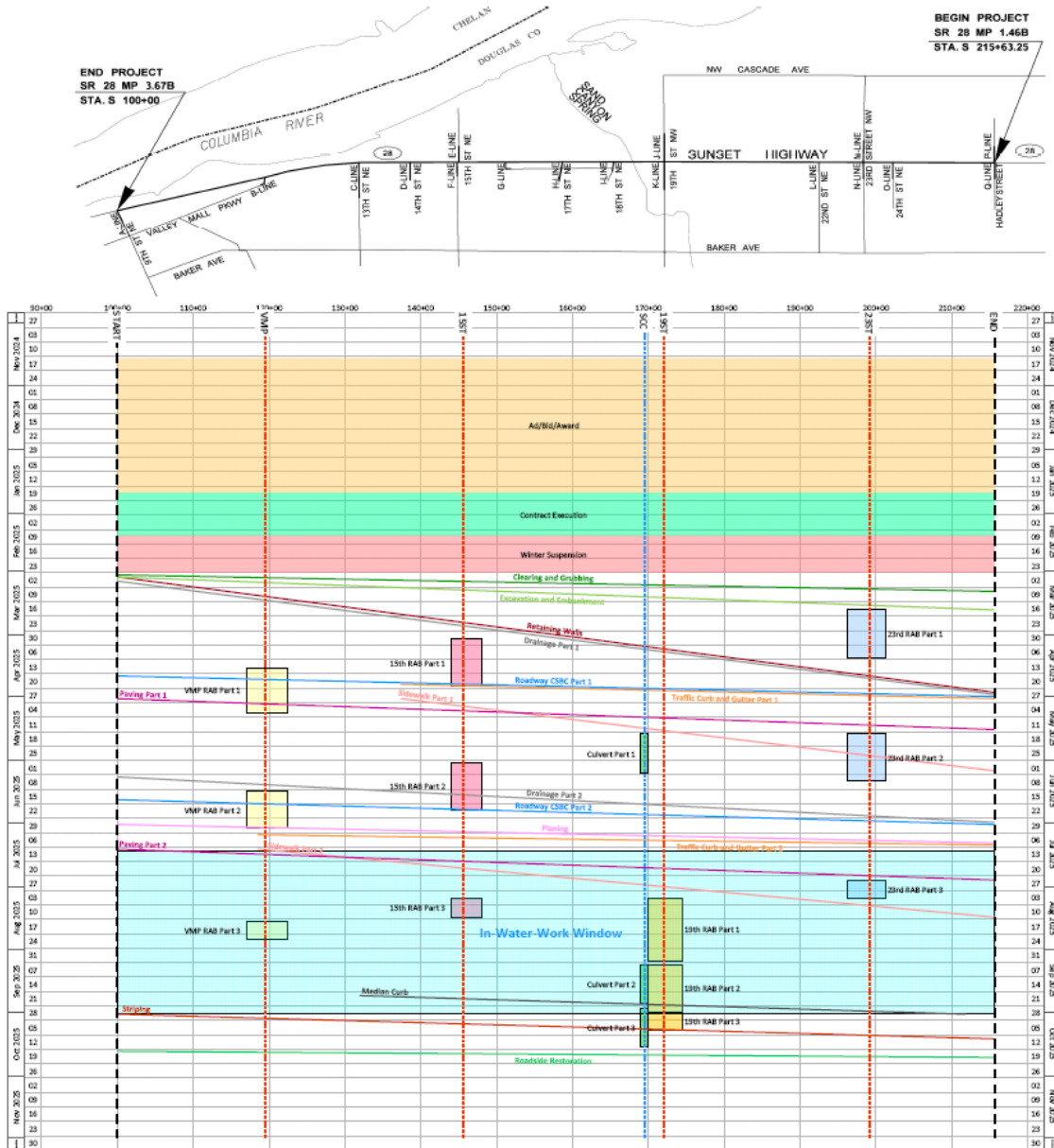


Figure 4.5. SR 28 project linear schedule built in GraphicSchedule.

Survey III

The summary of Survey III responses is shown in Table 4.7. Three questions were fully responded to by all six participants (N = 6), two questions were responded to by five participants (N = 5), and one question was responded to by four participants. The value of responses ranged from 4 (neither agree nor disagree) to 6.33 (agree to strongly agree). The highest agreement level was found for “the LSM tool has improved visualization capability to understand patterns in data” statement. The statement question receiving the second highest agreement level was “the LSM tool allows me to identify issues from the early stage of a project better.” These results are consistent with the prior AHP study that identified visualization capability and early issue identification as the two most important performance indicators. The statement question with the third highest agreement was the “LSM tool can be integrated with existing systems and can be adjusted to meet the user’s specific needs.” This result slightly differs from the AHP result, wherein the tool reliability and effectiveness indicator was more important than integration and flexibility.

It is also worth mentioning that all respondents chose “neither agree nor disagree” to the statement “the LSM tool improves safety by monitoring project completion without major accidents.” According to Sturgis et al. (2014), “neither agree nor disagree” can either be a “hidden don’t know” or it can mean a neutral opinion. The participants who mostly took part in the case study were not able to identify the potential benefits of improving safety, given that the case study only compared the non-LSM with the LSM schedule at the design phase.

Table 4.7. Summary of survey responses.

Participant	Question 1 (N = 6)	Question 2 (N = 6)	Question 3 (N = 6)	Question 4 (N = 5)	Question 5 (N = 4)	Question 6 (N = 5)
1	6	5	4	5	4	4
2	6	6	5	6	4	5
3	6	6	4	4	4	4
4	7	7	6	6	N/A	N/A
5	6	5	4	N/A	N/A	5
6	7	6	5	6	4	5
Average	6.33	5.83	4.67	5.40	4.00	4.60

The agreement level of each LSM performance indicator is shown in Figure 4.6. A 7-point Likert scale was used, as defined in Table 1.1. Interestingly, no respondents selected numbers 1 (strongly disagree), 2 (disagree), or 3 (somewhat disagree) on the Likert scale for any of the six questions.

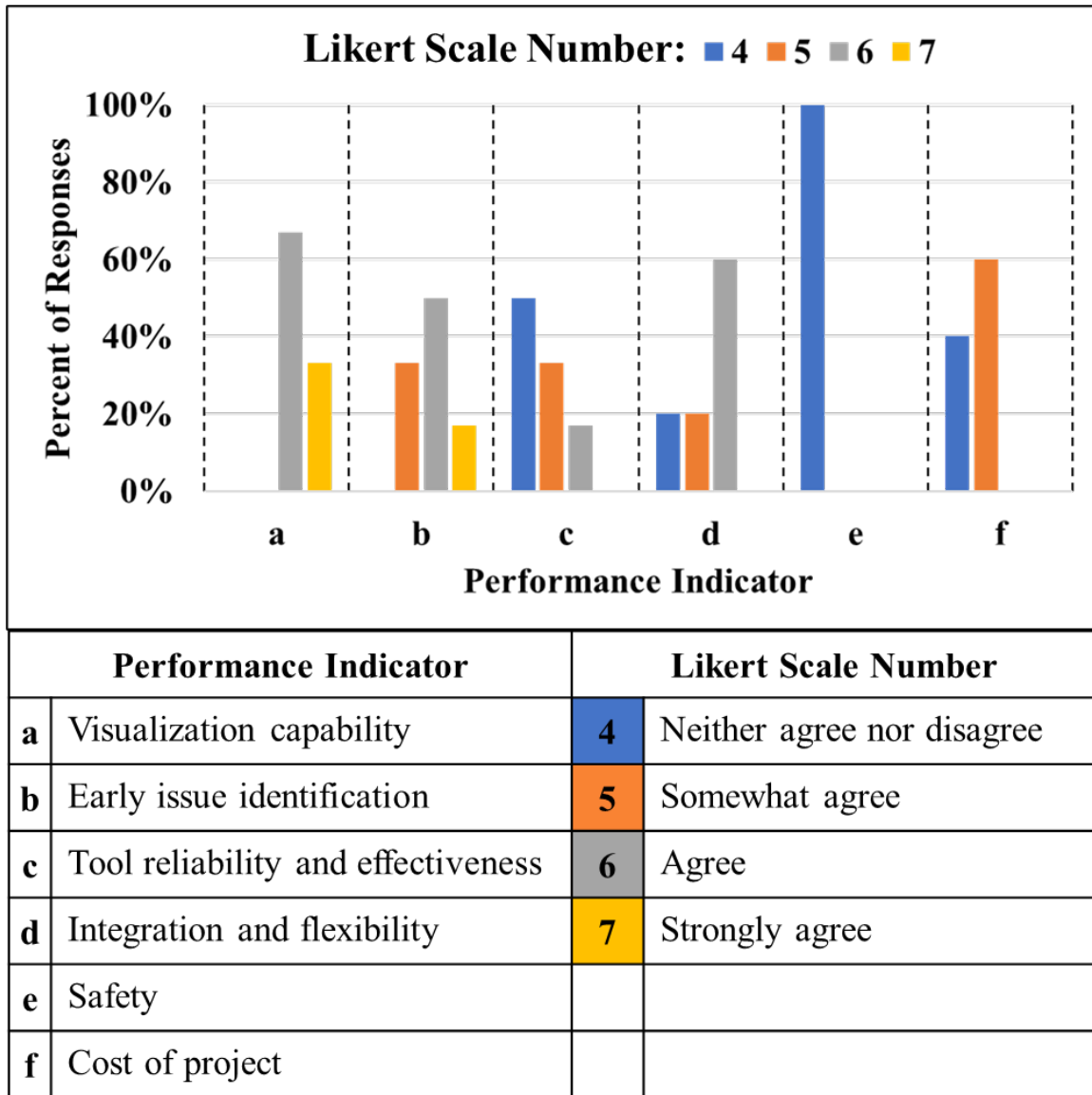


Figure 4.6. Level of agreement on LSM performance indicators.

CHAPTER 5

TOOLS AND RESOURCES TO SUPPORT THE LSM

LINEAR SCHEDULING SOFTWARE

As discussed in Chapter 2, several software programs with varying degrees of linear scheduling capabilities are available in the market. The combined results from Survey I and II suggested that TILOS and Excel were the most commonly used tools to create linear schedules. Similarly, most of the interview subjects also used TILOS, while some used GraphicSchedule and Turbo-Chart. As shown in Figure 5.1, GraphicSchedule and Turbo-Chart are simple visual tools, while TILOS is more complex, with more scheduling functionalities. All three of the programs support data linked to commonly used CPM programs such as P6 and Microsoft Project. Given that GraphicSchedule is an Excel add-in and Excel was a commonly used tool among survey participants, it is logical for WSDOT to consider using GraphicSchedule for groups who only need visual tools and TILOS for groups who require more advanced functions and controls.

Software	Stand-alone/Add-in	Link to P6	Link to MS Project
GraphicSchedule	Add-in	Y	Y
Turbo-Chart	Stand-alone	Y	Y
Time Location Plus	Stand-alone	Y	Y
Spider Project	Stand-alone	Y	Y
Powerproject	Stand-alone	Y	Y
ChainLink	Stand-alone	Y	Y
TimeChainage	Stand-alone	Y	Y
MAGNET Project	Stand-alone	N	N
TILOS	Stand-alone	Y	Y

Figure 5.1. Linear scheduling software program comparison.

TILOS

TILOS is considered the leading LSM scheduling program in the current U.S. market. The interface of TILOS is shown in Figure 5.2. The TILOS interface bears some similarities to Primavera P6, which makes it easier for CPM users to learn the program. In TILOS, users are able to create different views of the same schedule, including a Gantt chart view and time-location view. Additional graphs, such as labor profile, cost histogram, and effort histogram, can be added to the time-location diagram and share the same time axis as the time-location diagram. An example of a cost histogram was shown in the case study (see Figure 4.4).

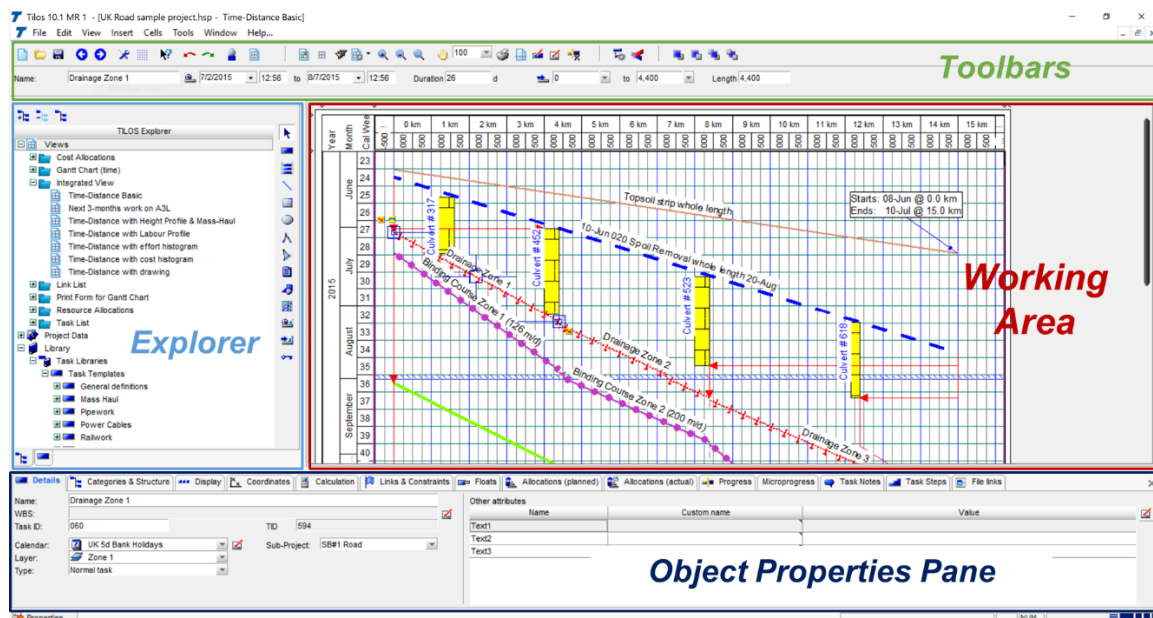


Figure 5.2. TILOS user interface.

Activities in TILOS can be easily tracked during construction. Schedulers can update the progress of an activity in terms of percent completed, distance completed, or quantity completed. When the schedule is updated on the report date, the remaining incomplete portions of all the tasks can be rescheduled. The users can determine for each task if the remaining incomplete portion needs an updated production rate to meet the deadline.

As discussed in Chapter 4 for the case study, potential conflicts are easy to spot on linear schedules as intersections of activities. However, when the number of activities increases, the diagram may become too busy to identify all the conflicts. In that case, TILOS offers a built-in clash detection function that can be useful. When activated, it generates warnings automatically for every detected clash, and the user will be presented a list of all the clashes with the time and location information. Users also have the option to exclude any activities from the clash detection function to avoid unnecessary warnings.

GraphicSchedule

GraphicSchedule is an Excel add-in designed to create the time-location diagram for linear projects. The interface of GraphicSchedule is shown in Figure 5.3. Intended to be lightweight and easy to learn, GraphicSchedule offers limited built-in functions compared to TILOS. The creation of the time-location diagram in GraphicSchedule relies on inputs in the activity list. Users have the option to either manually enter each activity or link the activity to existing schedules created in other CPM programs. Once created, the element of the diagram can be customized like any regular Excel object. Users with experience in Excel should encounter minimal learning difficulties in editing the time-location diagram.

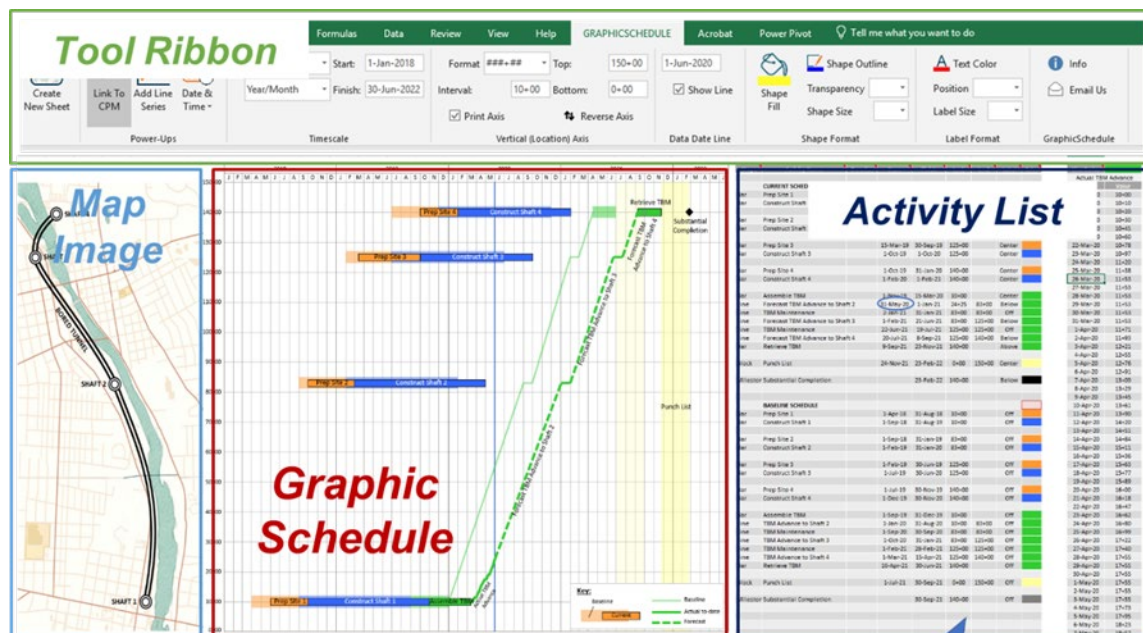


Figure 5.3. GraphicSchedule user interface.

Software Comparisons and Limitations

As a stand-alone program with full scheduling capabilities, TILOS requires more effort in the initial setup. Each linear schedule created in TILOS must be built on an existing template. A TILOS template contains a large amount of predefined information, including work calendars, task templates, project settings, views, data field definitions, resource and cost assignments, and more. Creation of a customized TILOS template for each project requires deep knowledge of TILOS. Usually, schedulers will select one of the built-in templates in TILOS for their projects and only modify certain elements of the template as necessary along the way to avoid creating a new template.

GraphicSchedule, on the other hand, is difficult to use if a CPM schedule is not available. At minimum, the start and end date for each activity should be given so that they can be entered into the activity list. For example, if the available information only includes project start date, duration for each activity, and logic links between activities, it is not reliable to calculate the start and end dates for each activity in GraphicSchedule using Excel functions, especially when the work calendar differs from the standard 5-day week calendar.

EXISTING RESOURCES AND TRAINING MATERIALS

To introduce linear scheduling tools to potential users within WSDOT, virtual live training sessions were organized by the research team with support from the software vendors. The TILOS staff provided overview trainings for TILOS on June 15–16, 2021 (9 AM to 11 AM, PDT), while the research team provided the GraphicSchedule training on June 17, 2021 (9 AM to 11 AM, PDT). The training sessions were offered via Microsoft Teams and recorded. A total of 14 WSDOT employees registered for the training sessions. Training agendas are included in Appendix IV.

In addition to the live training sessions, the research team prepared multiple recorded training video series for WSDOT employees to access at any time. The training videos are meant to introduce interested users to the available software programs and guide them through the creation of a simple linear schedule. The lists of the training videos are given in Table 5.1 and Table 5.2.

Table 5.1. Recorded training videos for TILOS.

Part	Content	Length (min:sec)	Link
1	Overview	05:50	https://youtu.be/ygaAHJ8kSvA
2	User Interface	12:20	https://youtu.be/3IgaIIx_Ek
3	Time and Distance Scale	32:31	https://youtu.be/GDB3is4m5n0
4	Insert Image	09:51	https://youtu.be/fX8sy4umhEU
5	Create Tasks	29:48	https://youtu.be/CdUR7-WmWVg
6	Layers	06:52	https://youtu.be/sng6sNF_YW0
7	Histograms	12:54	https://youtu.be/MczC92fcejM
8	Task Progress	13:06	https://youtu.be/tWB1CoX8Jak
9	Legend	03:43	https://youtu.be/CJTPjT3XbJ0
10	Data Export	08:05	https://youtu.be/0Hbkl59_AJA

Table 5.2. Recorded training videos for GraphicSchedule.

Part	Content	Length (min:sec)	Link
1	Basics	23:55	https://youtu.be/IwVChAjvwk0
2	Progress Tracking	08:48	https://youtu.be/VZLW0dTobvU
3	Link to CPM	08:29	https://youtu.be/1fHPpreky6Q

Live Training Feedbacks

Following the live training sessions, surveys were sent out on June 25, 2021, to gather feedback from the participants in preparation for potential future trainings.

For the TILOS training, five out of six respondents reported that the training met their expectations. The presentation was well received by the students. Given the complexity of the software, respondents would like more future training sessions to gain a more in-depth learning experience. Several respondents suggested a need for additional examples to further explain data import/export between P6 and TILOS. It was also suggested that the pace of the training be adjusted and the training files be better organized so that the participants could reasonably follow the instructor in working through examples.

For the GraphicSchedule training, five out of five respondents reported that the training met their expectations. However, the respondents wished for longer training sessions to cover more details of GraphicSchedule.

CHAPTER 6

CONCLUSION

WSDOT launched the initiative to evaluate, develop, and implement best practices for linear scheduling in transportation projects. Linear scheduling is an effective tool for completing constructability reviews earlier in design and identifying coordination opportunities. It can enhance processes related to project cost risk assessment, value engineering, and stakeholder engagement. This multiphase study included surveys and interviews of key WSDOT project personnel as well as pilot use of linear scheduling with off-the-shelf software in a selected case study.

During Phase I of the project, the research team synthesized the potential application of the LSM for transportation projects and identified the need to investigate commercial software and refine the performance measurement framework. During Phase II of the project, the research team completed user surveys, expert interviews, a case study, and software trainings. The project performance measurement framework was also established to evaluate the use of the LSM in transportation projects.

The findings show that there is value in using the LSM even early in design. If a CPM schedule is available, creating a linear schedule for 20 to 30 high-level activities can be done quickly (within a working day). The linear schedule will aid the project team in identifying issues related to constructability (e.g., environment constraints, activity conflicts) and improve communication among project team members. A linear schedule can prove to be valuable in early risk assessment workshops.

Linear schedules are flexible and can be developed with varying levels of complexity. A summary schedule with a few high-level activities is often sufficient when presenting to management and the public, who may have limited scheduling knowledge. A detailed linear schedule can also be created for just the most important portion of a project instead of covering the entire project scope.

The decision to use the LSM often depends on the nature of the project. The LSM should be used when the project is linear or contains repetitive activities. The duration of the project should be relatively long. Because of the effort required to create the linear

schedule, short-term projects (a few weeks or months) may not last long enough for personnel to invest in a separate linear schedule. However, if constructability may become a potential issue because of geographical or environmental factors near the project site, linear schedules may be of value in identifying the issues early in design to allow actions to be taken promptly. If the LSM is adopted for the project, the project control group is usually responsible for managing the linear schedule. The linear schedule should be maintained and updated whenever changes are made to the CPM schedule, and schedulers should be familiar with data exchange protocols between LSM software (e.g., TILOS, GraphicSchedule) and CPM software (e.g., P6, Microsoft Project).

The LSM is an indispensable tool for linear and repetitive projects. Because of the advancement in computer technologies and better training for schedulers, reason for optimism exists that the LSM will maintain its position in the construction industry. For organizations planning to adopt LSM in the future, significant culture changes should be expected in order to recognize the necessity of using LSM in tandem with CPM, understand the need for additional resources, and highlight the fact that the benefits outweigh costs.

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APPENDIX I

Benefits and Challenges of the LSM Identified in Case Studies Conducted in the United States

Report	Agency	Benefits	Challenges
Chrzanowski Jr. and Johnston (1986)	North Carolina DOT	• LSM diagrams easily convey detailed information • Job progress, resource allocation, and schedule changes can be performed quickly • Facilitates the understanding of workflow by the user	• Restricted to construction projects with repetitive activities • Discrete activities could be included but must be referenced to a network schedule for details • Lack of numerical computerization
Rowings et al. (1993)	Iowa DOT	• Provides a visual link between schedule and actual work • Easy to handle and visualize activities with variable production rates	• Lack of a developed microcomputer-based system for the Iowa DOT and contractors for LSM implementation
Sharma et al. (2009)	North Dakota DOT	• Easy to address traffic regulation issues as well as construction activity using the 2D graph • Helps identify and avoid the conflicts with traffic closure and work progress • Helps reduce unwanted idle time for plants and equipment • Provides an overview of the complete traffic-closing pattern	• Lack of cost- and resource-loading features
Harmelink and Yamin (2000)	Indiana DOT	• LSM schedules are easier to understand, review, and change than CPM schedules	• Lack of conflict detection feature in the software for multiple-lane highway • High learning curve and acquisition costs • DOT inspectors not familiar with the LSM
Yuksel and O'Connor (2000)	Texas DOT	• Easy to communicate • Facilitates the exploration of alternative schedules • Easy to apply schedule compression strategies by visually identifying the activities that drive the project duration	• Lack of clear indication of overlapping activities • Takes considerable time to update due to lack of software support

APPENDIX II

Benefits and Challenges of the LSM Identified in Case Studies Conducted in Other Countries

Reference	Project Type	Project Location	Benefits	Challenges
Andersson and Christensen (2007)	Residential Building	Denmark	- Improved schedule overview - Establishment of workflow - Enhanced project control	- Steep learning curve of a new method - Lack of coherent and standardized information system
Jongeling and Olofsson (2007)	Commercial Building	Sweden	- Reduction of waste in the construction process - Ease of rescheduling and updating	
Kenley and Seppanen (2005)	Residential and Commercial Building	Australia/Finland	The LSM delivered more efficient site work	- Significant cultural change - Management must support the innovation
Lucko et al. (2014)	Residential Building	Brazil	- Facilitated the analysis of different crew sizes, paces, and flows of work to meet the planned completion date - Allowed an intuitive visualization of changes and their impact on cycle times	Impact of the LSM on productivity was difficult to quantify
Rezaei (2015)	Residential Building	Cyprus	- Improved overview and communication - Support for workflow continuity - Support for risk analysis and optimization - Integration with BIM	
Shah (2014)	Road Construction	Portugal	- Support of the selection of required size and sets of heavy construction equipment at the correct locations and when necessary - Assist with the weekly resource planning, progress monitoring, time-space conflict management, earthwork scheduling communication improvement	
Tapia and Gransberg (2016)	Dam Construction	Panama	The LSM can be used in nontraditional ways to provide accurate information for delay claim analysis	

APPENDIX III



UNIVERSITY of WASHINGTON

HUMAN SUBJECTS DIVISION

DETERMINATION OF EXEMPT STATUS

November 6, 2019

Dear Professor Kim:

On 11/6/2019, the University of Washington Human Subjects Division (HSD) reviewed the following application:

Type of Review:	Initial Study
Title of Study:	Linear scheduling evaluation and best practices development
Investigator:	Amy Ahim Kim
IRB ID:	STUDY00008637
Funding:	Name: Washington State Department of Transportation (WSDOT), Grant Office ID: A145060, Funding Source ID: T 1461 Task Order 71 Funding Title(s): "Linear Scheduling, Ph2"

Exempt Status

HSD determined that your proposed activity is human subjects research that qualifies for exempt status (Category 2).

- This determination is valid for the duration of your research.
- This means that your research is exempt from the federal human subjects regulations, including the requirement for IRB approval and continuing review.
- Depending on the nature of your study, you may need to obtain other approvals or permissions to conduct your research. For example, you might need to apply for access to data or specimens (e.g., to obtain UW student data). Or, you might need to obtain permission from facilities managers to approach possible subjects or conduct research procedures in the facilities (e.g., Seattle School District; the Harborview Emergency Department).

If you consider changes to the activities in the future and know that the changes will require IRB review (or you are not certain), you may request a review or new determination by submitting a Modification to this application. For information about what changes require a Modification, refer to the [GUIDANCE: Exempt Research](#).

Thank you for your commitment to ethical and responsible research. We wish you great success!

Sincerely,

Maria C Savage
Associate Director of Operations
Human Subjects Division, University of Washington
Tel: 206-616-7762 /Email: mcsavage@uw.edu

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APPENDIX IV

TILOS Overview Training for WSDOT Petroglyph Projects

June 15, 2021 – 2 Hours

- ♦ Interface overview
- ♦ Navigating the TILOS Library
- ♦ Creating a new project from a template
- ♦ Time scales
- ♦ Distance scales
- ♦ Grid lines
- ♦ Calendars
- ♦ Task templates
- ♦ Adding tasks (activities)
- ♦ Linking tasks (logic/relationships)
- ♦ Text fields
- ♦ Layers
- ♦ Filters

June 16, 2021 – 2 Hours

- Quick review with Q & A
- Distance scale station points and sectors
- Environmental constraints
- Splitting tasks
- Task Templates
- Task groups (fragnet)
- Project Milestones
- Creating a baseline
- Adding Legends and Images
- Importing data from Excel
- Exchanging data with Primavera P6 and/or MS Project - Overview

Items needed for participation in the Webinar training:

- ♦ Laptop/computer with TILOS installed and licensed. NOTE: We will supply 30 day fully functional Tilos licenses in advance of the training. If the WSDOT needs to be advised, or involved, then we will make sure this is complete several days before the training.
- ♦ Second monitor (would be preferred)
- ♦ Wheeled mouse
- ♦ High speed internet connection





GraphicSchedule Training Agenda for WSDOT

June 17, 2021 (9 AM – 11 AM PDT)

- Interface overview
- Creating a new project
- Adding tasks (activities)
- Formatting chart elements
- Use Excel formulas with GraphicSchedule
- Actual vs. Planned progress
- Exchanging data with other scheduling tool

Items needed for the training:

- Laptop/computer with GraphicSchedule installed. A free trial version could be downloaded from this link (<https://graphicschedule.com/wp-content/uploads/2020/10/GraphicSchedule-Setup-v1.14.2.zip>). It will have the full functionality for 30 days. It is recommended to have this done several days in advance before the training.
- A second monitor is recommended.



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