Linear Scheduling Evaluation and Best Practices Development: Phase I Report

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LINEAR SCHEDULING EVALUATION AND BEST PRACTICES DEVELOPMENT PHASE I REPORT

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16. Abstract

Relevant literature review was conducted of best practices related to the use of linear scheduling method (LSM) for heavy civil construction projects. The comprehensive literature review revealed an additional need to understand how LSM could be best utilized for WSDOT, which includes conducting an investigation into off-the-shelf software programs that could be integrated with existing platforms that WSDOT is currently using.

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EXECUTIVE SUMMARY

The purpose of this research effort is to ultimately promote the importance of linear scheduling for assisting designers/engineers when thinking through a project and visualizing how it will actually be built. Linear scheduling is promoted primarily because recent projects that used the linear scheduling method (LSM) received positive feedback from Washington State Department of Transportation (WSDOT) engineers. The objective of this (Phase I) study was to conduct a relevant (and in its broadest sense) literature review of best practices related to the use of LSM for heavy civil construction projects.

Deliverables for Phase I include this synthesis report that summarizes the use of linear scheduling and associated best practices from existing studies. The synthesis:

- Discusses the use of LSM by state transportation agencies and other owners as documented by existing studies.
- Presents the pilot efforts using LSM and lessons learned to date.
- Identifies challenges and barriers to implementation of LSM. One of the study hypotheses was the need for a thorough benefit-cost analysis (BCA), which warrants developing an LSM project performance measurement framework. Therefore, while the development of the performance measurement framework was not part of this deliverable, a chapter that discusses this point is included.
- Examines the tools and software available to implement LSM.
- Discusses the knowledge gaps and future research opportunities, part of which will guide the development of the Phase II work.

The entire study includes Phase I and Phase II. Findings from Phase I will inform Phase II development. Phase II study objectives will involve the following objectives:

- Identify the metrics and framework to evaluate the benefits of LSM.
- Quantify the benefits of projects using LSM.
- Develop best-practice guidelines pertaining to the use of LSM.

The main preliminary finding from the Phase I efforts involves the need for a BCA to demonstrate the cost-effectiveness of a project. The proposed BCA should be applicable to a range of major project types, including bridges, roadways, and tunnels, with different project sizes and complexity. To make this possible, more case examples need to be discussed as part of the Phase II work. To create an appropriate BCA, the research team proposes working with stakeholders to better articulate and measure the intangible benefits such as the quality of a project and communication among stakeholders. The comprehensive literature review revealed an additional need to understand how LSM could be best utilized for WSDOT, which includes conducting an investigation into off-the-shelf software programs that could be integrated with existing platforms that WSDOT is currently using.

1. INTRODUCTION

1.1. Background

In recent years, the application of the linear scheduling method (LSM) to manage and communicate the progress of projects has received positive feedback from Washington State Department of Transportation (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 LSM with a project. There is a lack of empirical data demonstrating the benefits of LSM with real project examples, so WSDOT has been unable to determine how the method can best be adopted. This synthesis study is the first step in informing WSDOT and other transportation project stakeholders of the potential benefits and impacts of using LSM with projects. Phase I of this study involved completing a rigorous literature review. Phase II will include conducting surveys, interviews, and case studies. Surveys distributed to a broad population will inform interview questions. Interviews will then be conducted with multiple stakeholders representing WSDOT, as well as contractors and vendors co-selected and sampled by the research team with guidance from WSDOT. Selective case studies will reflect projects of different sizes and complexity.

1.2. Synthesis Goals and Objectives

The overarching goal of the research (including both Phase I and Phase II) is to investigate the costs and benefits of utilizing LSM in WSDOT linear projects to assess the method’s feasibility and added value. This report addresses four key objectives completed as Phase I of this study:

- Investigate the benefits and challenges of LSM by reviewing its application in various linear projects as well as exploring other scheduling best practices (Chapter 2).
- Investigate the current technological advancements of LSM by examining the various functions in the commercial software available on the market (Chapter 3).
- Develop a conceptual performance measurement framework to quantify the benefits of LSM adoption by reviewing performance measures of construction firms, linear projects, and building information modeling (BIM) tools (Chapter 4).
- Develop initial research tools for Phase II of the study in the form of the proposed survey and interview questions (Chapter 5 and Chapter 6).

1.3. Key Definitions

The following definitions provide an understanding of the key terms used in this synthesis report.

- *Linear scheduling method:* A two-dimensional (2D) time-location scheduling method designed for construction projects of linear, repetitive, and location-based nature.
- *Building information modeling:* An intelligent three-dimensional (3D) model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure(Autodesk Inc., 2019).

- *Performance criteria:* The first level of hierarchy in the performance measurement framework. The criteria are grouped based on similar performance indicators.
- *Performance indicator:* The second level of hierarchy in the performance measurement framework that consists of qualitative or quantitative factors that can be measured to represent the performance of criteria.
- *Performance metric:* The third level of hierarchy in the performance measurement framework where the indicators could be measured using different metrics.

1.4. Synthesis Methodology

This study used a literature review as the main research method to develop an initial understanding of the current scheduling best practices as well as the LSM concept, benefits, and challenges. Additionally, a literature review of performance measurement frameworks related to construction firms, linear construction projects, LSM, and BIM tools was used to synthesize the performance measurement framework of LSM. The researchers explored various sources of references, including academic literature (e.g., the American Society of Civil Engineers' *Journal of Management in Engineering* and *Journal of Construction Engineering and Management*, the Transportation Research Board's *Transportation Research Record*, and so forth), industry publications, state department of transportation (DOT) websites, and government reports (e.g., American Association of State Highway and Transportation Officials [AASHTO], Federal Highway Administration [FHA]).

In addition to an academic and industry-based literature review, the researchers conducted a review of the existing LSM software to further identify the benefits, challenges, and feasibility of adopting LSM tools. The software review included holding meetings with different LSM software vendors and undertaking demonstrations and testing of selected software.

During the literature review phase, the research team also solicited feedback from various subject matter expert groups through webinars and presentations. The research team presented the early findings of this study at a WSDOT Webinar Wednesdays session in March 2019 and at the Cost Risk Estimating Management Community of Practice meeting in June 2019. The webinar and meeting were used as platforms for researchers to present some preliminary findings at an early stage, gather input, and attract potential interviewees and participants for future stages. The feedback was systematically analyzed to improve the relevance of the study to the application (real-world) context.

Figure 1.1 shows the type of questions and concerns that were brought up during the webinar. A list of the questions and comments is given in Appendix I. The feedback provided insights that helped the researchers identify five categories to focus on: investigating the existing research related to LSM (research specific), aligning the study with WSDOT's current policies and practices (WSDOT specific), refining the LSM performance metrics (performance metrics), identifying lessons learned from previous projects using LSM (example projects), and investigating various commercial software packages available on the market (software).

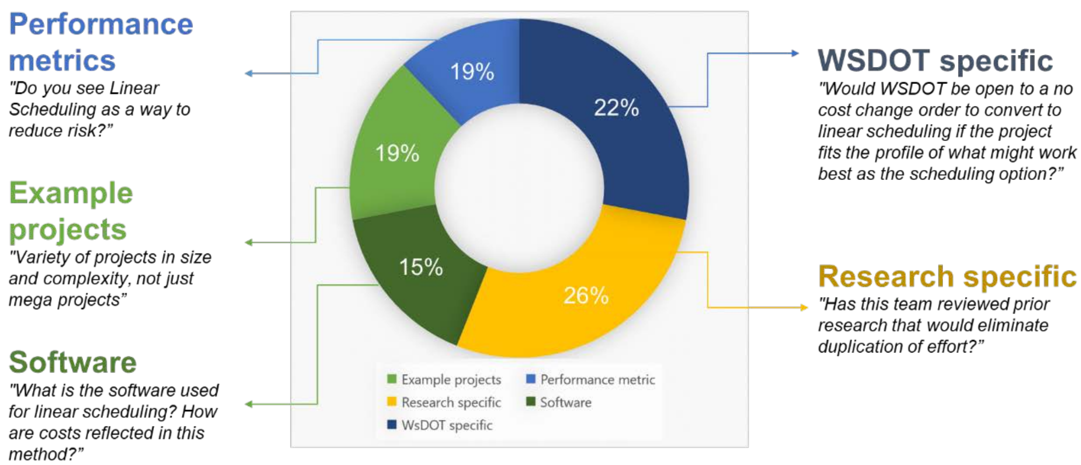

Figure 1.1. Categories of Initial Feedback for the Study Based on WSDOT Webinar on March 13, 2019

1.5. Synthesis Organization

This report consists of seven chapters. The first chapter introduces the study scope, objectives, and methodology. Chapter 2 provides an overview of the LSM concepts, current practices, and benefits and challenges. Chapter 3 presents the existing commercial LSM software. Chapter 4 discusses the initial development of performance measurements for quantifying the benefits of LSM. Chapter 5 and 6 describe the development of the survey questionnaire and interview questions, respectively, that will be used for the next phase of the study. Finally, Chapter 7 summarizes the information presented in the report and offers conclusions and a plan for future research on the assessment of LSM performance.

2. LITERATURE REVIEW OF LINEAR SCHEDULING METHOD

2.1. Background

It is widely accepted in the construction industry that bar charts or network-based scheduling methods such as the critical path method (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 their 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. Kenley and Seppanen (2009) identified various names that have been used in the literature for these alternative techniques, including the following:

- Harmonograms.
- Repetitive scheduling method.

- Vertical production method.
- Time-location matrix model.
- Time-space scheduling method.
- Disturbance scheduling.
- Horizontal and vertical logic scheduling for multistory projects.
- Horizontal and vertical scheduling.
- Multiple repetitive construction process.
- Representing construction.
- Time versus distance diagrams.
- Linear balance charts.
- Velocity diagrams.

Currently, the most widely used names are repetitive scheduling method (Harris & Ioannou, 1998; Ioannou & Yang, 2016), location-based scheduling method (Andersson & Christensen, 2007; Kenley & Seppanen, 2009; Seppanen, 2016; Sharma & Bansal, 2018), and linear scheduling method (Johnston, 1981; Lucko, 2008, 2009; Lucko et al., 2014; Lucko & Gattei, 2016; Mattila & Abraham, 1998a). LSM is used in this report to refer to the scheduling technique for projects that are linear, repetitive, and location-based.

2.2. History of LSM

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

(1981) coined the term in an attempt to integrate some methods presented by other authors for transportation-related construction projects that basically incorporated the premises of LSM (Gorman, 1972; Harris & Evans, 1977).

The diagram used in LSM has close ties with the objective chart used in the line-of-balance method (LOB). An example of the LOB diagram is shown in Figure 2.1.

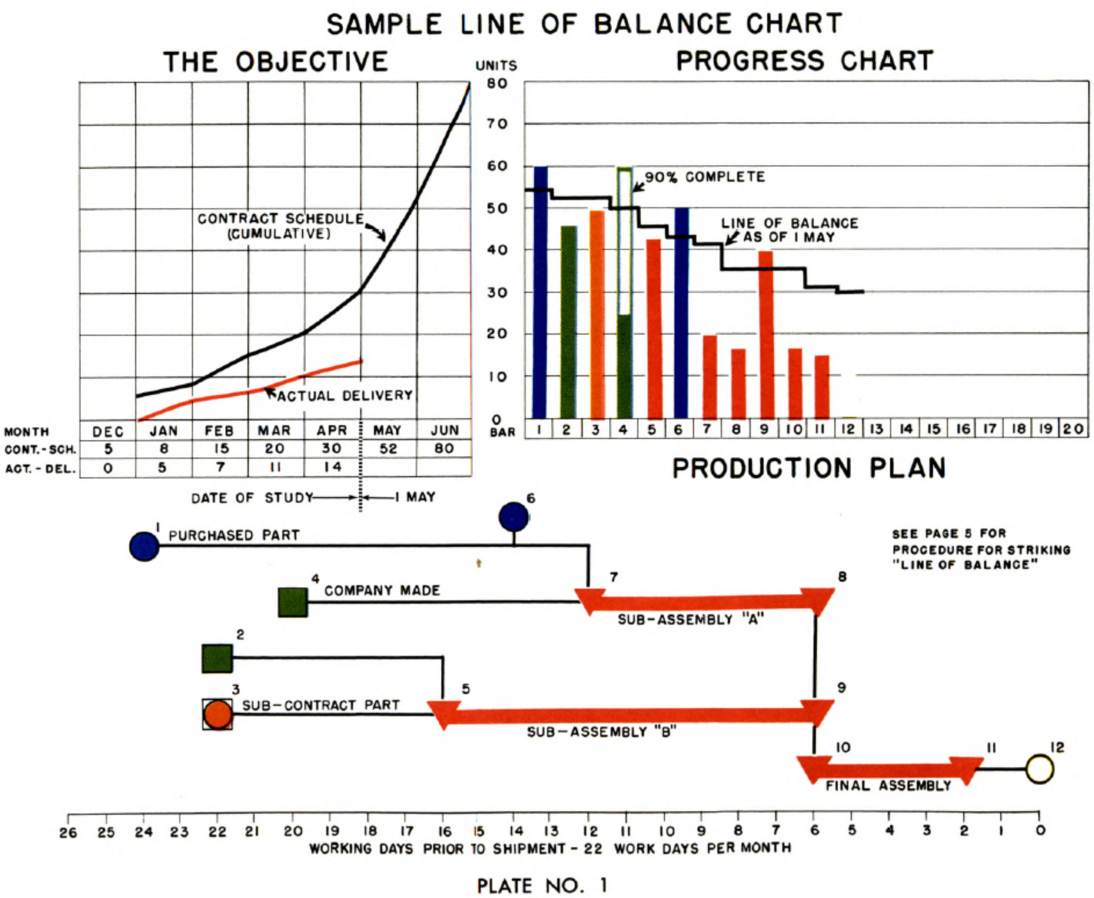

Figure 2.1. Example of the Original Line-of-Balance Diagram (Naval Material Command, 1962)

The LOB diagram consists of the objective chart, the progress chart, and the production plan illustration. 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). The combination of the three charts provides a status check at certain control points during the manufacturing process and reflects how well the various phases of manufacturing are synchronized to meet the required delivery schedule (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, and that work shifted the focus of LOB to the objective charts and omitted creating or analyzing the line of balance itself in the progress chart (Lucko & Gattei, 2016). 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, as shown in Figure 2.2. In the figure, the tasks are denoted by the shaded area with a start line and a finish line showing the duration of each task. Since LOB is widely used in housing construction, the vertical axis usually represents the cumulative quantity of completed housing units, which could also be adapted into completed stations for linear projects such as tunnels and highways. The activities of each task can be modeled into a unit network using CPM, which determines the duration of each task for each construction unit. For repetitive projects, it can be assumed that the task duration remains the same for all the units; therefore, the start and finish lines of each task stay parallel. The slope of the lines indicates the production rate of each task. An efficient LOB schedule aims to balance the production rates for different tasks so that the tasks do not overlap for the same unit, ensuring that resources, including labor and equipment, flow from one unit to the next without delay or interruption.

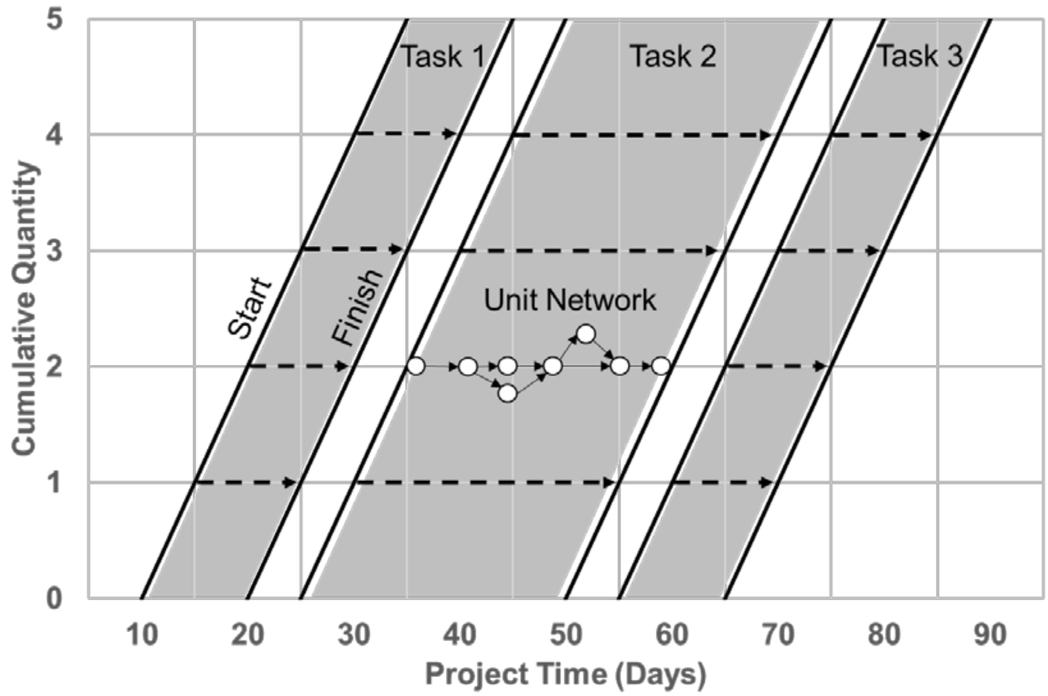

Figure 2.2. Example of Current LOB Diagram (based on Kenley & Seppanen, 2010)

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. In this representation, the activities are carried out along the horizontal lines corresponding to each integer number on the vertical axis, as shown in Figure 2.2, by the dashed arrows. Tracking activities in discrete units may be desired for certain repetitive construction projects, such as multi-unit housing developments and high-rise commercial building construction where each housing unit or each building floor could be treated as a discrete entity. However, 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.

The flowline method is a scheduling technique similar to LOB but with critical differences. Although not mentioned in Johnston (1981) when 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 its current form (Lucko & Gattei, 2016).

Kenley and Seppanen (2010) attributed the introduction of the flowline method to Peer (1974) and Selinger (1980). An example of the flowline diagram is shown in Figure 2.3. Unlike in the LOB diagram, each task is represented by a single line. The vertical axis shows the location along the length of the project—that is, the distance to the starting location in miles for a highway construction project. Each point on the task line represents the planned location of resources at a specific time. It is apparent by comparing Figure 2.2 to Figure 2.3 that the flowline diagram gives a much cleaner look for the same schedule. This diagram is especially advantageous when the number of tasks increases rapidly for large-scale projects, where the dual-line LOB diagram could be crowded and difficult to understand. As Lucko and Gattei (2016) pointed out, a LOB diagram could be enhanced by embedding the detailed network illustration between the start and finish lines, and it is easy to show multiple crews working on different units at the same time, which does not seem to be possible in a flowline diagram due to its single-task line structure. However, a detailed network may not always be necessary for a high-level schedule presentation, and the number of crews or other resources can be depicted by adding a resource chart to the flowline diagram that shares the same time axis.

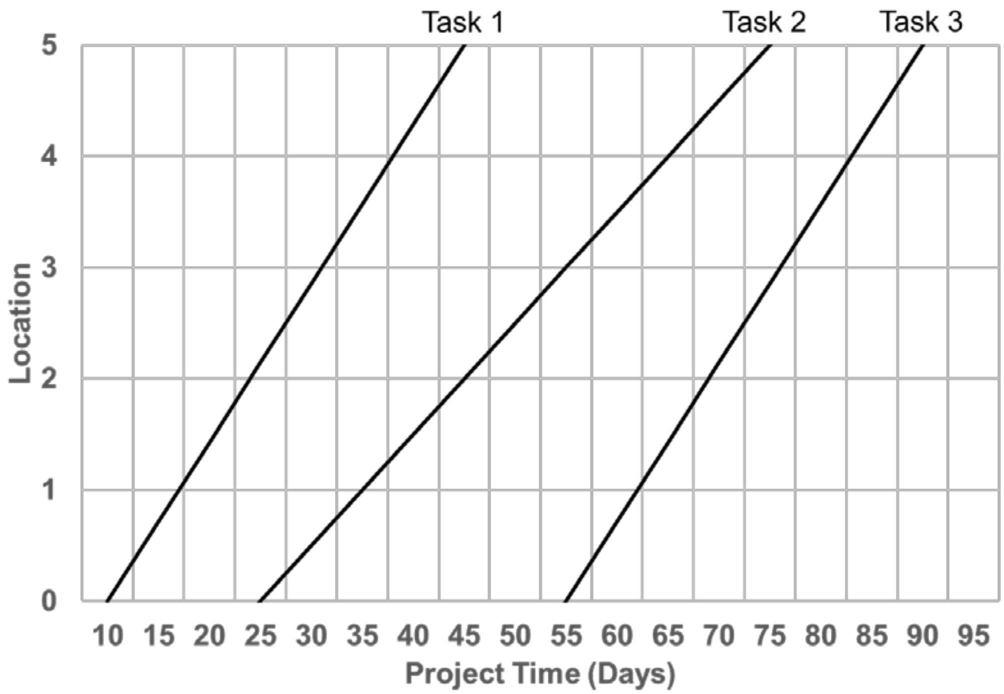

Figure 2.3. Example of a Flowline Diagram

Another scheduling method worth mentioning is the Graphical Planning Method® (GPM). With a patent approved in 2013 (Ponce de Leon, 2013), GPM is a variation of CPM designed to be an engaging and interactive tool which could result in a hands-on, planning-dominated experience for stakeholders (Ponce de Leon, 2009). Therefore, GPM is essentially a network-based scheduling technique. The redesigned interactive graphs and network diagrams on a time-scaled calendar could facilitate better communication and collaboration among different project stakeholders. An example GPM diagram is given in Figure 2.4. It is important not to confuse GPM with LSM as GPM do not include location as a dimension during scheduling.

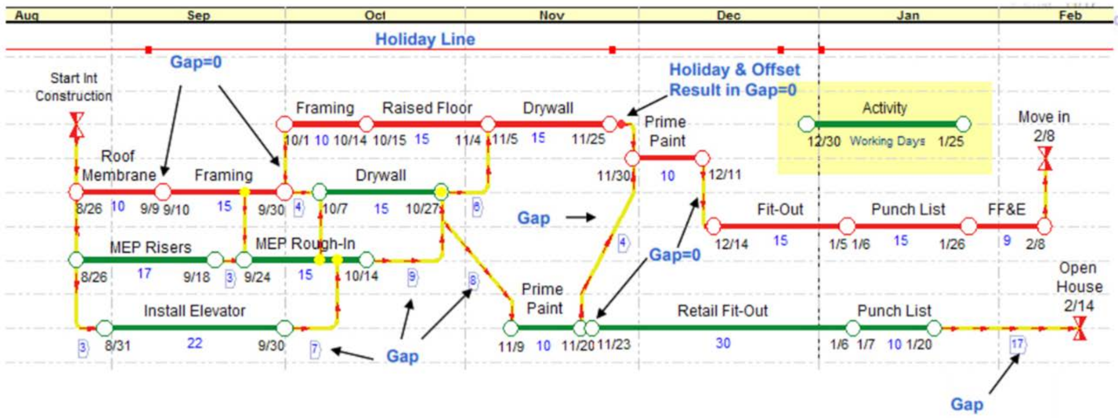

Figure 2.4. Example of a GPM Diagram (PMA Technologies, 2019)

2.3. Advancement of LSM

An increasing amount of research has been conducted on LSM to enhance its capability and improve its user experience. Nevertheless, the underlying principles of LSM remain the same as when it was introduced by Johnston (1981). Lucko and Gattei (2016) summarized these principles, as follows:

- The LSM diagram is a 2D chart with continuous time and location axes.
- The resolution of both axes is determined by the user based on available data.
- The location axis can be drawn either horizontally or vertically, depending on the nature of the project.
- 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.
- 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.
- Work conflicts and interruptions are shown by intersecting and broken lines.

A simple LSM in its current format is given in Figure 2.5. The location along the tunnel is drawn vertically from the bottom to top while the project time is drawn horizontally from left to right. A drawing of the tunnel is placed along the location axis to facilitate a clearer presentation. More sophisticated drawings, such as CAD sketches or satellite images may also be used.

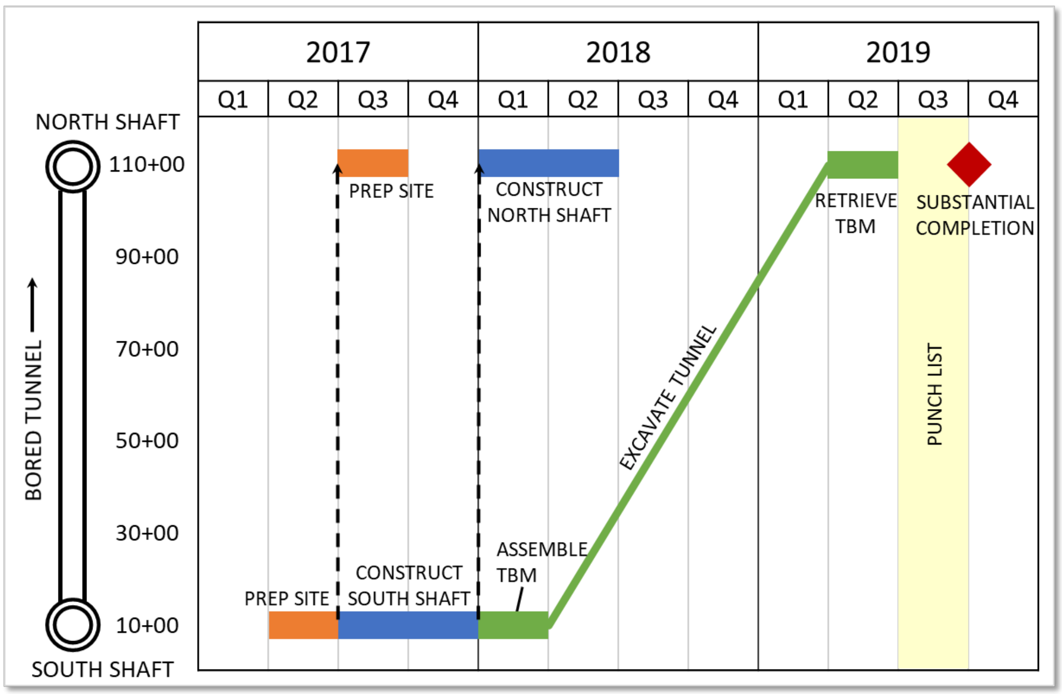

Figure 2.5. Example of LSM Diagram for a Tunnel Project (Wonneberg, 2019)

Even though the graphical elements of LSM appear to have changed very little compared to the earlier time-location or time-distance diagrams, such as in Gorman (1972) and Rowings and Rahbar (1992), the theoretical foundation of LSM has been strengthened and the functionality expanded by various studies. Research efforts in four aspects of

LSM—critical path detection, computerization, schedule optimization, and resource leveling—can be summarized as follows.

- **Critical Path Detection.** Harmelink and Rowings (1998) introduced a method to determine the critical path (called the controlling activity path) in a linear schedule. The controlling activity path can further enable the determination of activity float and allow the linear schedule to be updated. A similar concept of controlling sequence was proposed by Harris and Ioannou (1998) for the determination of the project duration. However, the controlling sequence can include both critical and noncritical activities. A comparison of these two approaches was given by Mattila and Park (2003).
- **Computerization.** Lack of sophisticated and readily available software has been widely recognized as a weakness of LSM. A number of researchers have attempted to develop new software or modify existing software to aid the use of LSM in practice. Hegazy et al. (1993) introduced a prototype PC-based program for scheduling and control of linear projects comprising uniform repetitive activities. Jongeling and Olofsson (2007) showcased the combined use of LSM and 4D CAD as a way to reduce waiting, rework, and disruptions. Sharma and Bansal (2018) demonstrated the use of a geographic information system (GIS) as a platform to apply LSM to a highway construction project in hilly terrain. Duffy et al. (2011) and Duffy et al. (2012) developed an automated alignment-based LSM program for applying temporal and spatial changes in production rates. The program was validated in a natural gas pipeline project and proved beneficial for

helping the project team better understand how changes in the project plan and schedule would impact the production rates.

- **Schedule Optimization.** The optimization of the schedule of a linear, repetitive, and location-based project includes many different elements, such as project cost, project duration, production rates, and cash flow. Moselhi and El-Rayes (1993) incorporated cost as the decision variable of a dynamic programming model capable of generating optimized schedules with a minimum overall cost for repetitive projects. Altuwaim and El-Rayes (2018a, 2018b) presented a novel optimization model for the scheduling of repetitive construction projects that simultaneously minimizes project duration, crew work interruptions, and interruption costs. Tamosaitis (2017) proposed an optimization method to find the shortest duration of a complex workflow. This method enables the user with no specialized tools to select the preferred sequence for a complex workflow to achieve an optimized duration as near to the shortest possible duration as possible. Roofigari-Esfahan and Razavi (2017), on the other hand, developed an uncertainty-aware optimization framework to optimize the duration of linear projects while minimizing potential congestion. Hsie et al. (2009) formulated a model that considered limited availability of resources to identify the optimal set of production rates in different periods for each crew. The proposed model addressed work continuity while maintaining lead time and lead distance between operations. Lucko (2007, 2008) introduced a novel analytical method for LSM that used singularity functions resulting from several advantageous mathematical properties to describe all activities and their relationships. The use of the singularity functions was later expanded to resource and cash flow optimization (Lucko, 2011a, 2011b).

- **Resource Leveling.** Mattila and Abraham (1998b) used an integer linear programming formulation in a highway construction project to demonstrate its capability in leveling resources. Georgy (2008) presented a genetic algorithm-based system for performing the necessary task of resource scheduling under the LSM scheme. The day-to-day fluctuation in resource usage was minimized through the resource leveling process, which further encompassed optimizing the rate of progress and buffer for each activity. Lucko (2010) developed a resource leveling model based on singularity function. This new model was implemented in a computer application and was especially suited for linear scheduling.

2.4. Benefits and Challenges of LSM

The benefits and challenges of LSM have been extensively discussed in the literature. A comparison is often made between LSM and CPM using actual or simulated construction projects (e.g., Kallantzis et al., 2007; Yamin & Harmelink, 2001). Although the application of LSM in the U.S. construction industry has been limited, a search in the literature still produced several case studies sponsored by various state DOTs. The findings of these case studies are summarized in Table 2.1. All of these studies were conducted using actual highway construction projects. However, no studies more recent than 2009 and sponsored by state DOTs in the United States were found, which shows the necessity of the current study supported by WSDOT. Additional case studies have also been found in other countries that applied LSM in different types of construction projects. The findings of these case studies are summarized in Table 2.2. A recent study by Sharma and Bansal (2018) compared the strengths and weaknesses of different scheduling techniques, including bar charts, network-based methods, and LSM. The details of their findings are summarized in Table 2.3.

Although the project types and locations varied, some common features can be observed from the case studies. Some agreed-upon benefits of LSM are as follows:

- **Improved schedule overview**. The added dimension allows the LSM diagram to show location information using limited space. The line representation of repetitive tasks reduces the clutter and provides a clear view of the entire schedule. The improved overview, in turn, facilitates better communication among the management team, contractors, and workers.
- **Improved work continuity**. The visualization of resource movement on the LSM diagram enables the scheduler to identify work conflicts and interruptions easily. It shifts the scheduler's focus to the continuous flow of resources, such as construction crews and heavy equipment.
- **Improved project control**. The location feature of LSM allows the progress of construction activities to be tracked accurately at any given time. It is easy to plot and update the LSM schedule based on completed work. Analysis of different crew sizes, paces, and workflows can be conducted to meet the planned completion date.

Table 2.1. Benefits and Challenges of 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 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

Table 2.2. Benefits and Challenges of 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	• 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 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 P and Gransberg (2016)	Dam Construction	Panama	• LSM can be used in non-traditional ways to provide accurate information for delay claim analysis	

Table 2.3. Comparison of Highway Construction Planning Methods (Sharma & Bansal, 2018)

Method	Strengths	Weaknesses
Bar chart	• Planning and scheduling are done at the same time • Commonly used in practice; easy to prepare and understand	• Limited analytical capabilities • Limited resource planning functions • Interdependencies among activities not depicted
Network-based methods (CPM, PERT, etc.)	• Clearly show the logical sequence and interdependencies among activities • Highly developed analytical capabilities and computational algorithms • Economical and powerful software is readily available	• The network becomes too large and complicated for repetitive projects • No standard procedure to break down repetitive activities from location to location • No information on work location at a given time • More focused on schedule optimization rather than resource continuity
LSM	• Total number of tasks are reduced • Resource continuity is ensured • Space and time conflicts can be detected • Added location information for better planning and management of tasks • Focused on production efficiency • Work location and crew productivity can be easily visualized	• Relatively unknown in the construction industry • Limited computer implementations • Lack of efficient schedule optimization algorithms • Lack of application in practice • Not as efficient when scheduling many discrete activities at a location

Some challenges to the adoption of LSM in the construction industry in the United States still remain. As Harmelink and Yamin (2000) reported, a survey regarding LSM usage for different state DOTs showed that 65 percent were not familiar with the method. This number is surely smaller today given the development of LSM during the past two decades. Nonetheless, LSM remains an unfamiliar tool for many DOTs and contractors. Significant cultural change is needed for the successful adoption of LSM, and support from management teams is also essential. Meanwhile, software development specific to LSM has resulted in a large collection of tools with different levels of functionalities that can be used by schedulers. An overview of the available software on the market is given in Chapter 3.

2.5. Conclusion

This chapter discussed the history of the development of LSM. Different terms used by various researchers were summarized and reviewed before introducing LSM as the term used in this report. The LOB and flowline methods, which are closely related to LSM, were reviewed in detail, and it was shown that the modern LSM took its form from the flowline method. A thorough literature review was conducted on theoretical research designed to advance and expand LSM in critical path detection, computerization, schedule optimization, and resource leveling. The benefits and challenges of LSM were discussed by examining case studies in the United States as well as in other countries. Although its use in the construction industry remains relatively low, LSM has been found to improve schedule overview, work continuity, and project control in most cases.

3. EXISTING COMMERCIAL SOFTWARE FOR LINEAR SCHEDULING

The collection of software with LSM capability or designed specifically for linear projects has expanded greatly throughout the years. In comparison to five software tools identified and reviewed by Duffy in 2009 (Duffy, 2009), researchers in this study identified ten available tools. Table 3.1 summarizes the software tools and presents their different levels of functionality. Based on its LSM scheduling capability, each tool is placed into one of three categories: visualization tool, expanded functionality, and integrated system.

Table 3.1. Summary of Software with LSM Functionality

Category	Tool Name	Company
Visualization Tool	GraphicSchedule	GraphicSchedule Inc. (Arroyo Grande, CA, USA)
	Turbo-Chart	Linear Project Software PTY Ltd. (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)
	LinearPlus	PCF Limited (Hertfordshire, UK)
Integrated System	MAGNET Project	Topcon Positioning Systems Inc. (Livermore, CA, USA)
	TILOS and Vico Office for Time	Trimble Inc. (Sunnyvale, CA, USA)

3.1. Visualization Tools

As shown in Figure 3.1, the main function of visualization tools is to generate a time-location diagram using a network-based schedule. Among them, Turbo-Chart and Time Location Plus are compact stand-alone programs that work with other scheduling tools such as Microsoft Project and Primavera P6. Network-based schedules generated in MS Project or P6 with added location information can be imported, and a time-location diagram will be generated accordingly. GraphicSchedule is an Excel add-in that also works with MS Project and P6. The compact nature of Turbo-Chart, Time Location Plus, and GraphicSchedule means that they have limited functionality, are easy to learn, and are cost-effective. They can be used along with MS Project, P6, or other scheduling software if other features of LSM are not required.

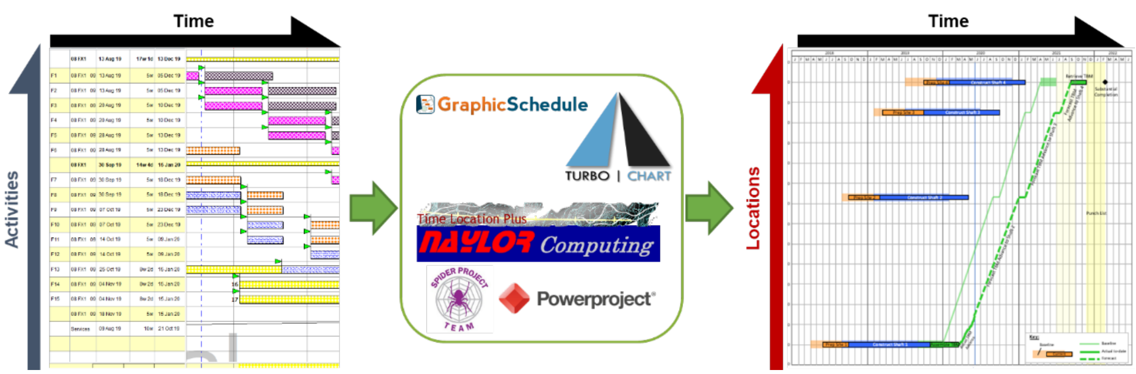

Figure 3.1. LSM Visualization Tools That Convert a Network-Based Schedule into a Time-Location Schedule

Powerproject and Spider Project are both stand-alone programs with network-based scheduling capability. Users are able to create an entire CPM schedule using both programs, including resource definitions and assignments. The time-location diagram is a built-in function of both programs. Although Powerproject and Spider Project provide many more functions than GraphicSchedule, Turbo-Chart, and Time Location Plus, in term of LSM-related functions, they are limited to providing a visual representation.

3.2. Expanded Functionality

ChainLink, Time Chainage, and LinearPlus are three stand-alone programs with expanded functionality designed specifically for LSM as shown in Figure 3.2. In contrast to the visualization tools, these programs are capable of conducting work rate calculation and defining and assigning resources. The work breakdown structure and activity code are supported. What-if scenarios can be created to showcase the impact on the schedule. ChainLink allows the user to operate on a two-screen display with time-location and Gantt charts on the same page. TimeChainage allows the identification of the critical path and available float. Both TimeChainage and LinearPlus are capable of tracking the project process.

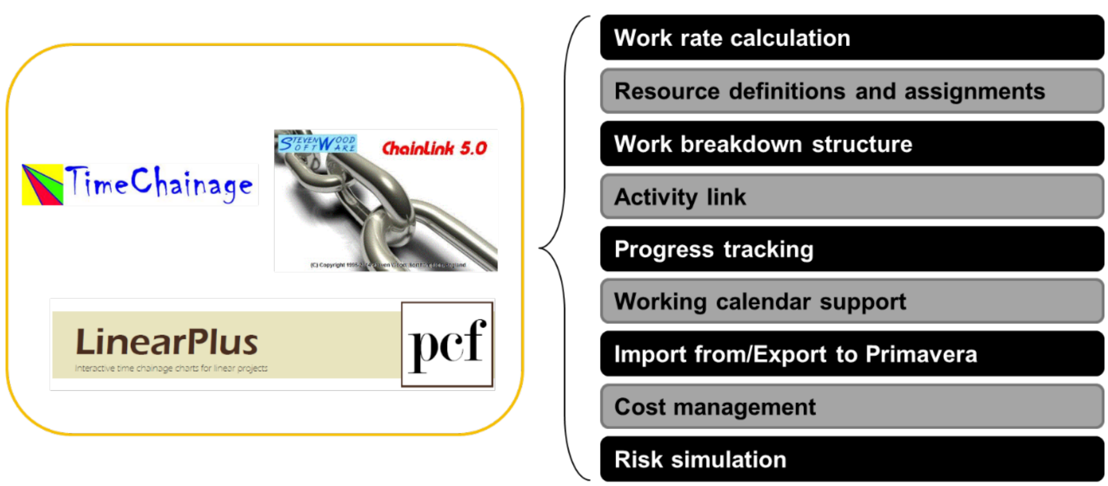

Figure 3.2. LSM Tools with Expanded Functionality

3.3. Integrated Systems

MAGNET Project, TILOS, and Vico Office for Time are all stand-alone programs with full scheduling capabilities. Each one is also part of a larger software family (see Figure 3.3), which suggests that they can often be used together with other programs in the family that may augment functionality beyond scheduling.

The MAGNET software family was evolved from DynaRoad (2005–2013) and was originally designed for mass haul planning. MAGNET Project allows users to calculate project duration based on work rate. Resource definition and assignments are supported. Users can also create what-if scenarios and study alternative schedules. Although the tool can work with other programs within the MAGNET family, data exchange between MAGNET Project and other scheduling software is not supported.

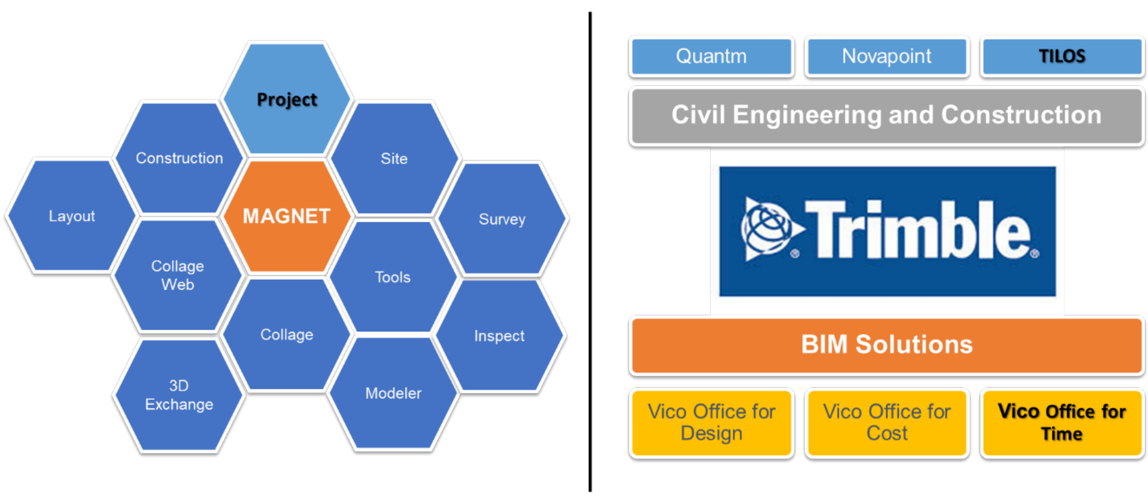

Figure 3.3. LSM Tools as Part of a Software Family

TILOS and Vico Office for Time are both LSM-oriented scheduling tools designed for different types of projects. Vico Office for Time is designed for BIM solutions, while

TILOS is more suited for civil engineering and construction projects. Similar to MAGNET Project, TILOS was also initially designed for mass haul planning. The functions in TILOS are comparable to MAGNET Project, including duration calculation, resource assignment, and what-if scenario analysis. However, TILOS added the automatic clash detection function so that conflicts in a complicated schedule can be easily identified. In addition, TILOS fully supports data exchange with other scheduling tools, such as MS Project, P6, and Powerproject.

3.4. Software Examples

As was shown in Table 3.1, only GraphicSchedule, MAGNET Project, TILOS, and Vico Office for Time are based in the United States. The vendors of GraphicSchedule and TILOS were contacted to obtain further information regarding the use of the programs. GraphicSchedule was selected as representative of the compact LSM tool. MAGNET Project was excluded due to its lack of support for communication with other scheduling software. Although TILOS and Vico Office for Time are both fully functional LSM scheduling tools, Vico Office for Time is geared toward BIM projects, while TILOS is more suited for the construction projects that are of interest to WSDOT, so it was chosen as the representative comprehensive LSM tool. Information sessions for both programs were conducted by the vendors.

3.4.1. Sample Linear Schedule Using 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 3.4. Users have the option to import existing schedules created in other programs (e.g., MS Project and P6) or create the diagram by filling out an activity list. The orientation of the time and location axis can be switched according to the nature of the project. The size and color of the shapes are also customizable to improve task identification and progress tracking. Similar colors with different degrees of brightness are used in Figure 3.4 for the same tasks to compare the planned schedule and actual progress.

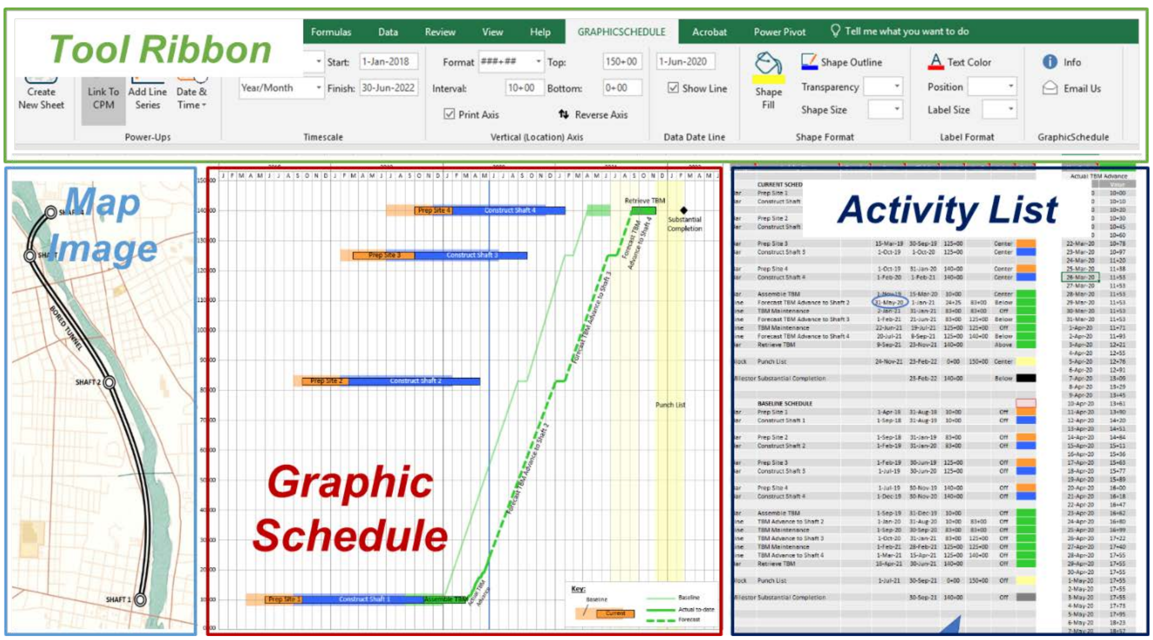

Figure 3.4. GraphicSchedule User Interface

Because GraphicSchedule is built within the Excel environment, it is relatively easy to distribute. Users with experience in Excel should encounter minimal learning difficulties. Although lacking many analytical functions, GraphicSchedule can be used as a companion to MS Project or P6 to create time-location graphs of existing schedules. For schedulers who do not have any knowledge or experience with LSM, it is helpful to start with a simple tool to showcase the benefits of LSM in improving communications among the involved parties in a construction project.

3.4.2. Sample Linear Schedule Using TILOS

TILOS is considered the leading LSM scheduling program on the current U.S. market. The interface of TILOS is shown in Figure 3.5. 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.

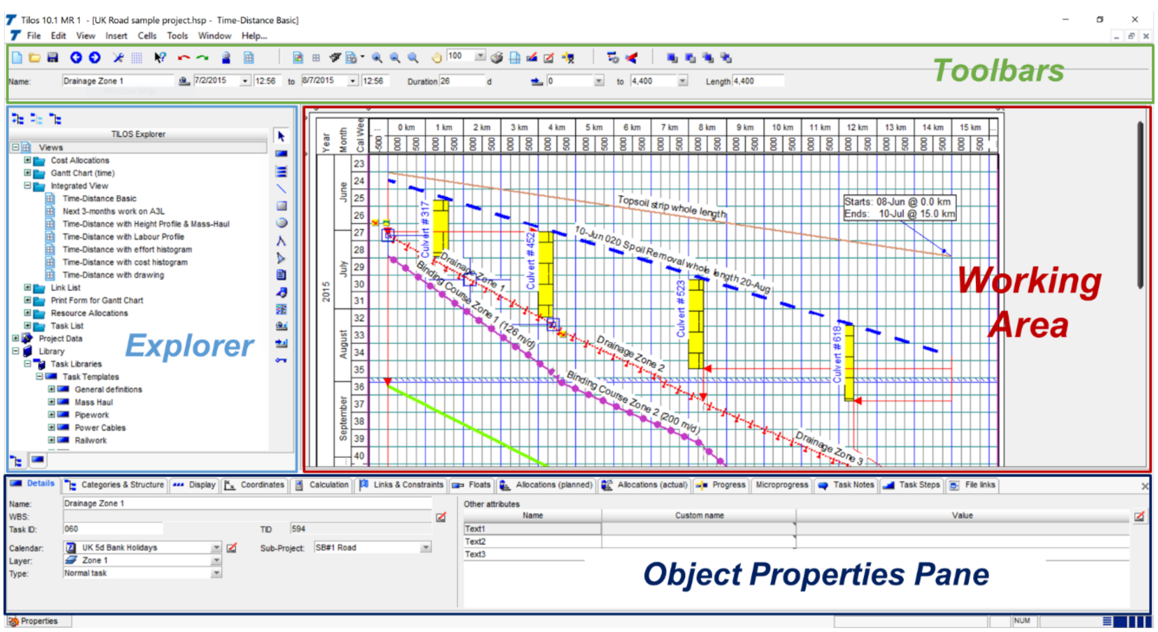

Figure 3.5. TILOS User Interface

A network schedule created in P6 is shown in Figure 3.6. To import this schedule into TILOS, additional columns need to be inserted to define the start and end location of each activity. This may take significant effort from the scheduler if the required location information is not readily available. However, once the locations are defined, TILOS can maintain the integrity of the P6 schedule—such as activity codes, work breakdown structure, activity links, and resource constraints—during the import process.

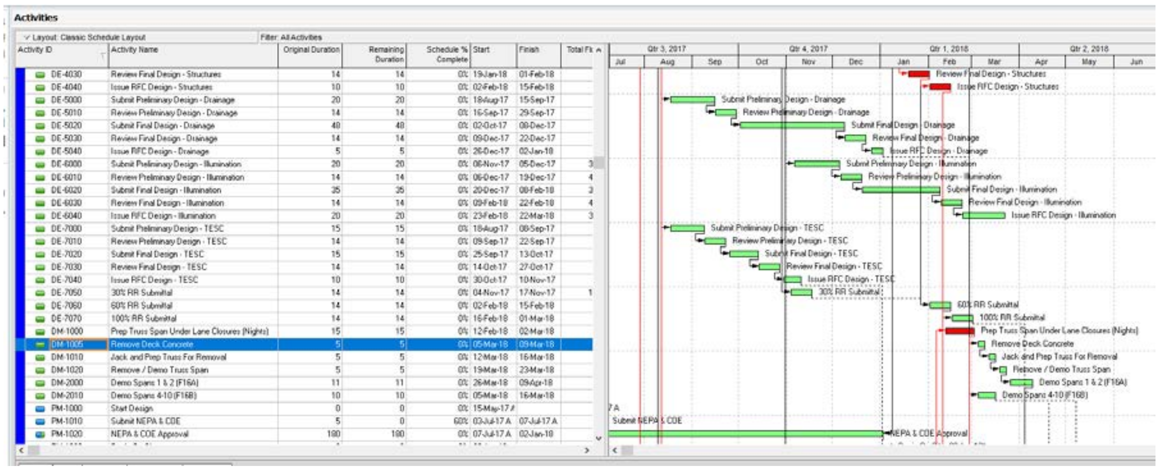

Figure 3.6. Example P6 Schedule

The critical path can be identified in TILOS on both the Gantt chart and time-location diagram. Figure 3.7 shows a comparison of the time-location diagram in normal view and the same diagram when the critical path is highlighted.

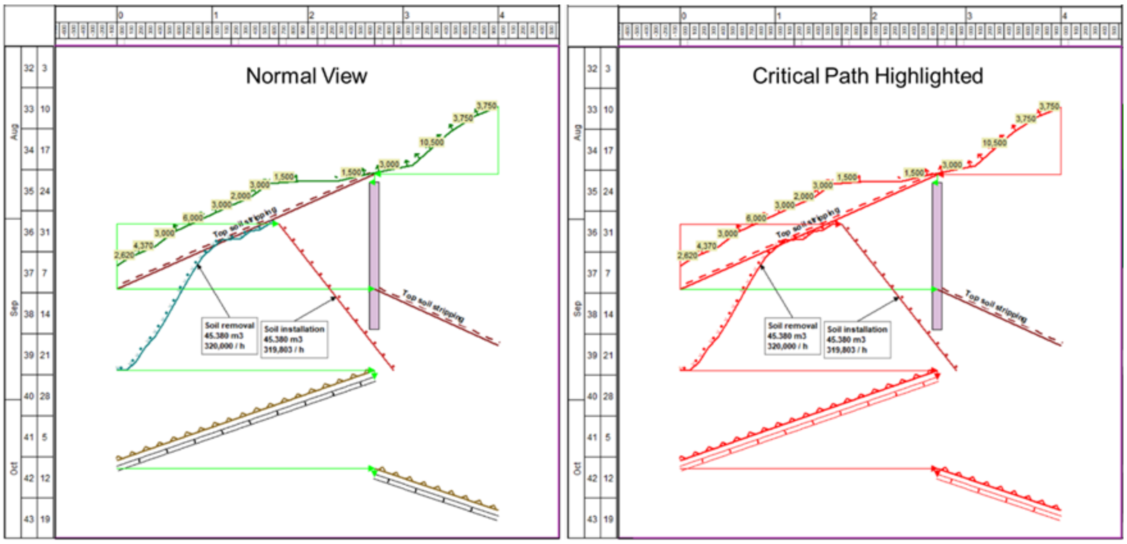

Figure 3.7. Highlighted Critical Path on the Time-Location Diagram in TILOS

The schedule in TILOS can be easily tracked and updated. Figure 3.8 shows an example of a schedule update. The activity highlighted in green is two days behind the planned schedule when it reaches the 2400 km mark. As a result, the schedule needs to be updated to show the impact on future activities. TILOS is capable of updating the remaining tasks automatically based on the input of completed tasks while still maintaining the baseline schedule for comparison.

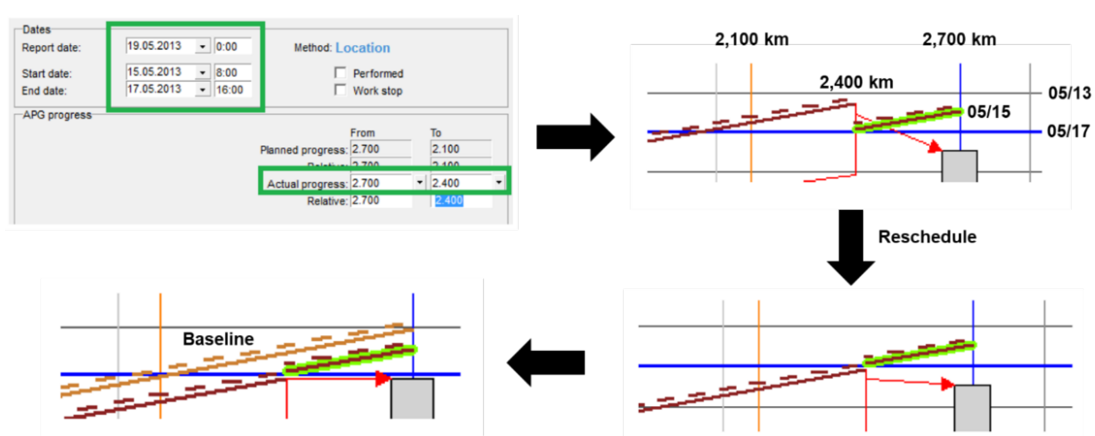

Figure 3.8. TILOS Progress Tracking Function

Another useful feature in TILOS is the clash detection function (see Figure 3.9). For a schedule with few activities, it is often not difficult to identify conflicts (intersecting lines) on the time-location diagram. When the number of activities increases, it becomes more difficult to make the same observation, even with proper color coding. The clash detection function generates warnings for every detected clash, and the user will be presented a list of all the clashes so they can be resolved.

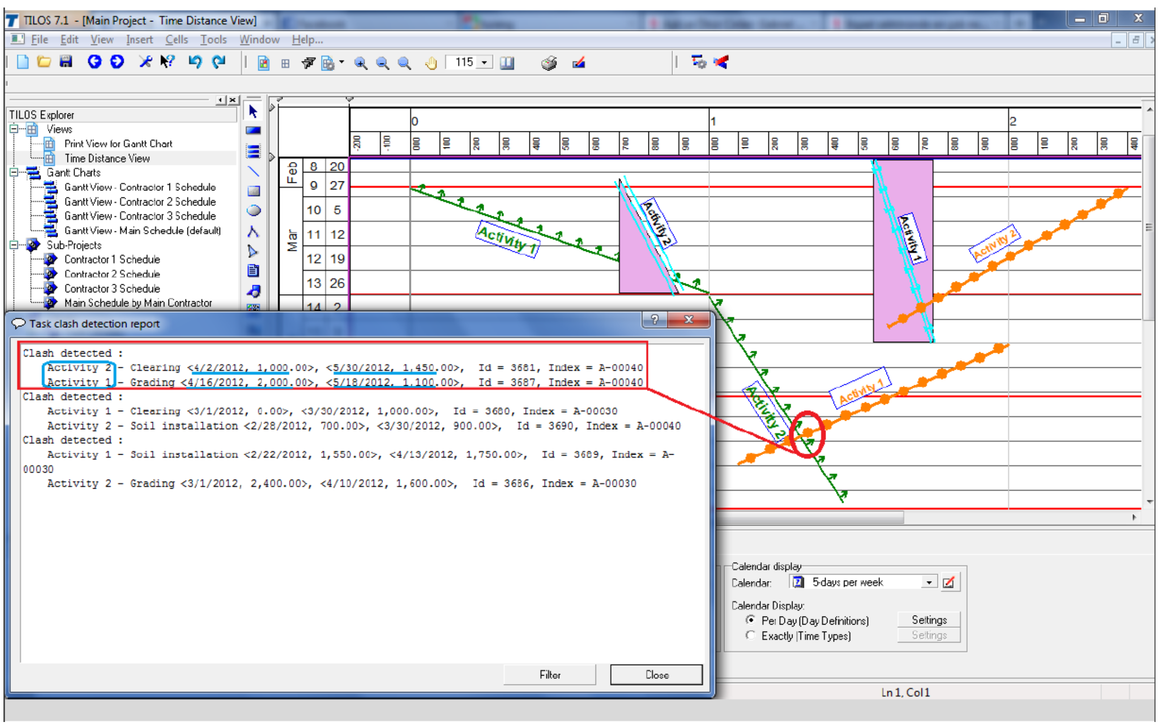

Figure 3.9. TILOS Clash Detection Function

3.5. Conclusion

Significant development has been made in the past two decades with LSM scheduling software. Interested users now have a full spectrum of different LSM programs to consider, from simple visualization tools to highly sophisticated programs that are comparable to other widely used network-based software. GraphicSchedule and TILOS are at two ends of the spectrum. Schedulers interested in implementing LSM programs should carefully consider the nature of the project before selecting the right tool. Using TILOS just for visualization may not be cost-effective, and the learning of extra functions may not be necessary. Both GraphicSchedule and TILOS have been used successfully in the United States by contractors. The experiences of these contractors will be the main focus of this study in the next phase.

4. LITERATURE REVIEW OF PROJECT PERFORMANCE MEASUREMENT FRAMEWORK

Introduction to various new technologies and tools is important for the survival of any industry in a fast-changing world. While the concept of LSM has long existed, it has not been widely adopted for linear projects, and only recently have various computerized tools capable of incorporating LSM been made available on the market, as noted in the previous chapter. Stakeholders of linear projects will be more likely to adopt LSM if they can visualize how the method can help improve the performance of their company or specific project. This chapter summarizes the background for the initial performance measurement framework of LSM proposed in this study. The research team completed the following objectives (also shown in Figure 4.1):

- Reviewed the state of practices related to measuring the performance of the linear construction projects.
- Reviewed the studies related to quantifying the benefits of using a BIM tool in the construction project.
- Proposed a performance measurement framework for LSM.

The results of the literature review discussed in this chapter provide extensive information on performance measures that will be further refined in the next phase of the study through interviews and surveys with construction professionals.

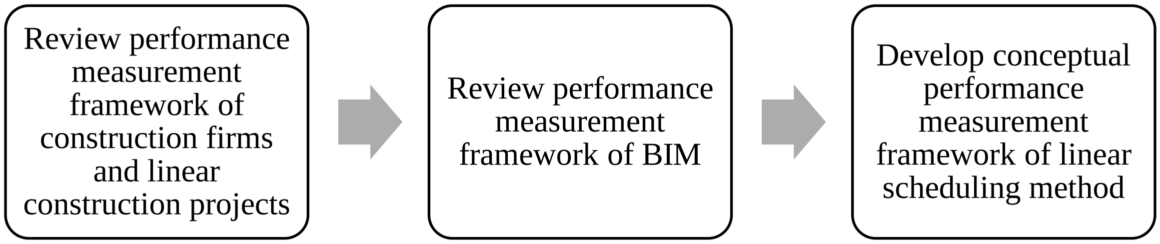

Figure 4.1. Research Process of LSM Performance Measurement Framework

4.1. Common Performance Measurement Framework in the Construction Context

Performance measurement has been recognized for many years as a method to monitor progress toward a goal. The benefits of performance measures include greater accountability to stakeholders, improved communication, increased organizational efficiency, greater effectiveness in achieving meaningful objectives, better understanding of the impacts of alternative courses of action, and ongoing improvement through feedback (National Academies of Sciences Engineering and Medicine, 2006). In transportation, performance measurement is used to “track and forecast the impacts of transportation system investments, monitor the condition of highway features, and gauge the quality of services delivered by an agency” (National Academies of Sciences Engineering and Medicine, 2006).

Successful transportation project management efforts can be measured in various ways; however, success is typically determined by the balance of scope, schedule, budget, and quality, as well as no unresolved project issues (National Academies of Sciences Engineering and Medicine, 2009). Examples of common program delivery performance measures are shown in Table 4.1.

Table 4.1. Examples of Program Delivery Performance Measures

Category	Example Measures
Cost	Project within budget (yes/no) Activity unit cost Percentage cost increase/decrease
Schedule	Contract milestones (e.g., completion date) Project on schedule (yes/no) Percentage schedule overrun
Scope	Number of change orders Activities performed versus planned Value of projects programmed versus delivered Number of projects programmed versus delivered
Quality	Performance specifications for capital improvements Levels of service for maintenance and operations activities Number of noncompliance reports

Source: Cambridge Systems Inc. (2002).

4.1.1. Main Project Evaluation Criteria

In a National Academies of Sciences Engineering and Medicine (2017) report that surveyed 41 state DOTs regarding program delivery performance, two typical performance metrics for almost all state DOTs' transportation projects were cost and scheduling metrics. The cost-related performance in the preconstruction phase usually compares the estimated versus approved project cost, while the projected versus actual expenses are calculated in the construction phase. Joshi and Lambert (2007) integrated equity metrics with traditional metrics for transportation project prioritization, where cost equity metrics ensure uniform distribution of the funds throughout the geographical region. Mladenovic et al. (2013) examined the use of key performance indicators (KPIs) for monitoring public-private partnership (PPP) transport projects and identified economic KPIs such as value for money, cost reduction based on total life-cycle cost, pricing of a certain risk, cost efficiency, and net present value. The Construction Industry

Institute developed a metric for quantifying the impact of rework on cost performance, which is expressed as a ratio of the total direct cost of rework to the total construction phase cost. Hwang et al. (2009) found that the impacts of rework differ in various project characteristics and that owner change and design error/omission have relatively greater cost impact than other sources of rework. The cost factor can also be considered as the business benefit derived from the completed project, measured as net present value (Chan, 2001).

In order to meet the schedule, the project must set the appropriate scheduling techniques, project change management (e.g., develop a formal process for dealing with change, risk management, and change awareness), and project closeout and audits (e.g., include a schedule for project closeout at the end of each phase). The schedule, or time performance, includes measuring whether the project is on time, ahead of schedule, or behind schedule. This performance measure has a close relationship with cost and quality performance. El-Rayes and Kandil (2005) developed a multi-objective optimization model that allows decision-makers to conduct time-cost-quality trade-off analysis in construction. Many studies have shown that construction projects suffer from a significant rate of delays in their schedules. For example, Thomas et al. (2006) found that 20.9 percent of 713 U.S. highway projects were delayed in their Transportation Research Board study. Another study identified unsettled or lack of project funding as the most influential factor for schedule delay (Larsen et al., 2016).

Project scoping involves the preparation of detailed project description and deliverables. A change in the project scope is a common source of cost overrun and schedule delays.

Scope performance includes the measurement of contract payments, change orders, and final expenditures in comparison with the original contract's projections (Utah Department of Transportation, 2016). Kermanshachi et al. (2017) developed a project scoping process framework of highway projects and found that less than 30 percent of the respondents used effective measures of project scoping. The study highlighted the importance of measuring the effectiveness of the scoping process, such as by comparing the State Transportation Improvement Program (STIP) budget to the engineer's estimate at letting and to the accepted contractor's bid, as well as comparing the STIP letting date to the actual letting date. Moreover, setting project-specific performance measures can improve the project objectives and scopes. For example, the goal of reducing congestion in a road project can be quantitatively measured through travel rate, mobility index, percentage of corridor congested, and other measures (Ramani et al., 2009).

Quality performance refers to how the project can be completed in accordance with the specification. For managing project quality, a National Academies of Sciences Engineering and Medicine (2009) report suggested several measures, such as constructability reviews, quality assurance, quality control, consultant performance, and risk management (e.g., ranking the factors and the likelihood of occurring and the impact). Larsen et al. (2016) found that project schedule, budget, and quality level are affected in different ways; thus, the identified issues should not be handled by focusing only on schedule or budget complications. The study revealed that the quality level of a public construction project was mostly influenced by errors or omissions in construction work. One way to measure quality performance is by the average number of nonconformance reports generated per month (Yeung et al., 2009).

4.1.2. Additional Project Performance Indicators

Apart from cost, time, scope, and quality, which remain the predominant project evaluation measures, researchers have attempted to develop both quantitatively and qualitatively more comprehensive measures to reflect the complexity of construction projects. For example, Chan (2001) conducted a systematic literature review and developed a framework for measuring the success of construction projects. The study added safety, participant satisfaction, user expectation/satisfaction, environmental performance, and commercial profitable/value as additional project performance indicators. More recent studies attempted to develop measures that affect the performance of project cost (Joshi & Lambert, 2007), schedule (Iyer & Jha, 2006), quality (Meng, 2012), and sustainability indicators (Mihyeon Jeon & Amekudzi, 2005).

Table 4.2 summarizes the additional performance indicators that are clustered based on whether they are people-centric or impact business value. While these criteria have been studied to improve the company or project performance, people-centric and specific business value criteria have not been used as consistent as cost, time, scope and quality measures. People-centric indicators focus on meeting customer expectations (e.g., Selden & MacMillan, 2006), engaging current employees and increasing their competencies (e.g., Omar & Fayek, 2014), and maintaining relationships with partners (e.g., Meng, 2012). Business value indicators consider performance measures related to the company's values that may be specifically important for their market image, such as concerns to sustainability (e.g., Amiril et al., 2014) or whether the company strives to advance in the technologies (e.g., Mladenovic et al., 2013).

Table 4.2. Performance Indicators Affecting Cost, Time, Scope, and Quality Performance Construction

Reference	Context	People-Centric					Business Value			
		User satisfaction	Internal satisfaction	Individual competence	Organizational competence	Collaborative partnership	Safety	Environmental performance	Social and equity	Innovation
Chan (2001)	Construction project success	√					√	√		
Johanson et al. (2001)	Construction performance drivers	√		√	√					
Said et al. (2003)	Performance consequences of nonfinancial measures	√			√		√			√
Kim and Arditi (2010)	Performance of minority/ disadvantaged/women business enterprise in transportation projects	√	√	√	√		√			√
Construction Best Practice Program (2002)	Construction industry performance	√					√			
Yu et al. (2007)	Performance measurement for construction companies	√	√	√	√					

Reference	Context	People-Centric					Business Value			
		User satisfaction	Internal satisfaction	Individual competence	Organizational competence	Collaborative partnership	Safety	Environmental performance	Social and equity	Innovation
Iyer and Jha (2006)	Success factors affecting schedule performance of construction projects			√	√					
Mihyeon Jeon and Amekudzi (2005)	Indicators and metrics for sustainable transportation systems	√					√	√	√	
Mladenovic et al. (2013)	Performance objectives of PPP transport projects	√		√		√	√		√	√
Takim and Akintoye (2002)	Indicators for construction project performance	√					√			
Meng (2012)	Effect of relationship management on construction project performance					√				
Wagner (2013)	Performance of public engagement in	√				√			√	

Reference	Context	People-Centric					Business Value			
		User satisfaction	Internal satisfaction	Individual competence	Organizational competence	Collaborative partnership	Safety	Environmental performance	Social and equity	Innovation
	transportation planning									
Shelton and Medina (2010)	Criteria to prioritize transportation projects						√	√	√	
Ramani et al. (2009)	Sustainable transportation performance measures	√					√	√	√	
Amiril et al. (2014)	Sustainability performance for railway project					√	√	√	√	√

The five performance indicators of people-centric and four performance indicators of business value identified from the literature are described as follows:

- **User satisfaction** measures the satisfaction of everyone who uses the constructed facilities (Chan, 2001) and the working partners, such as clients, designers, or contractors. 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 & Arditi, 2010; Yu et al., 2007).
- **Internal satisfaction** refers 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 & Arditi, 2010) or the employee turnover rate (Yu et al., 2007).
- **Individual competence** includes 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 & 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.

- **Organizational competence** includes 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 & Jha, 2006).
- **Collaborative partnership** 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.
- **Safety** factors focus on completing the project without major accidents or injuries (Bubshait & 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.

- **Environmental performance** is a major indicator of performance. Construction projects impact the environment across their life cycle (Shen & 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).
- **Social well-being 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 & Medina, 2010). Mihyeon 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.
- **Innovation and technology transfer** are important performance objective categories identified in both the public and private sector of 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 & Arditi, 2010).

4.2. Performance Measurement Framework for BIM

This section presents the findings from the literature review of the performance measurement frameworks used to quantify the benefits of BIM tools. An assessment of how the concepts of BIM performance measurement can be adopted to establish the performance measurement of LSM is provided. BIM is a powerful visual representation tool that can combine 3D visualization models with schedule and cost features. Based on some similar characteristics between the new technologies of BIM and LSM tools, as well as BIM's capabilities to provide better visualization and identify issues to save project time and cost, this study examined the literature that has been conducted to quantify the benefits of BIM.

Coates et al. (2010) presented the case study of BIM adoption of a project that focused on a set of KPIs developed and tested in the project. The weighting of the KPIs was developed from an architectural business perspective. The identified KPIs were manhours spent per project; speed of development; revenue per employee; IT investment per unit of revenue; cash flow; better architecture; a better product; reduced costs, travel, printing, document shipping; bids won or win percentage; client satisfaction and retention; employee skills; and knowledge development. Thus, KPIs can form a method of comparing the success of different BIM adoptions in terms of measuring the project quality, standardizing information and the measurement process, setting benchmarking targets, and recording the effectiveness of an action.

Barlish and Sullivan (2012) developed a methodology to analyze the benefits of BIM, then applied projects to the methodology to quantify outcomes, and subsequently presented a more holistic framework of BIM and its impacts on project efficiency. The metrics were divided into two groups: (a) cost, or investment, metrics, which include design and construction costs; and (b) benefit, or return, metrics, which include requests for information, change orders, and duration improvements.

Lu et al. (2013) empirically measured the benefits of BIM as a learning tool in real-life construction tasks. Their model was expected to help promote BIM's value in the AEC industry. The study identified learning curves of two situations—construction tasks with and without BIM—by following a series of analytical processes. Performance data are in staff-hours/cycle (e.g., staff-hours/m^2). *Cycle* in this report refers to a repetitive construction task.

Li et al. (2014) focused on the methodological quantification (through a case study) of BIM's benefits in building construction resource management and real-time cost control in contrast to traditional non-BIM technologies. The study showed BIM functionalities in different phases: design review, construction simulation, and materials management. The performance measurement included (a) duration—comparing the original duration with optimized duration after BIM optimization and calculating the time savings in day unit; and (b) issues—identified by implementing BIM (in # unit) before construction and during construction, measuring the time per each issue, and calculating the total time savings (in day units) and cost savings (cost-saving [percent] = cost-saving [$]/total MEP construction cost [$] * 100 percent [in percent unit]). In addition to quantitative information, qualitative data were collected through user interviews across different implementations that asked about BIM's credibility, the workload comparison of BIM and non-BIM methods, the difficulty of learning BIM tools, and the possibility of its future use.

Aziz et al. (2016) reviewed the opportunities acquired by the organization that implemented BIM in facilities management (FM) for the benefit of the quality of life in the workplace. The authors identified the following benefits from integrating BIM in FM: (a) effective operational cost; (b) shorter time for decision-making; (c) resource for decision-making; (d) better documentation system; (e) collaboration and work flexibility; and (f) updated information and clash detection.

Liu et al. (2017) developed and validated a list of metrics that are suitable for the proposed BIM benchmarking application. They developed the metrics based on a literature review, interviews, and a pilot survey of a BIM expert group, and then they administered the survey to BIM practitioners. The performance measures were placed into two categories: the BIM model and the BIM modeling process. In the BIM model, the measures included (a) quality—for example, how closely the model deliverables meet owner contract requirements and the basis of the design; (b) accuracy—how closely the BIM geometry/data represent as-built conditions in the field; (c) usefulness—for example, how often the model is accessed for different purposes; and (d) economy—for instance, if the model is developed at the lowest cost and hardware requirement. In the BIM modeling process, the measures included (a) productivity—for example, how fast a BIM is developed on average; and (b) effectiveness—for instance, how well a BIM is developed on average (if the model keeps changing over time, it could be a sign of ineffective development).

Pärn et al. (2017) presented a thorough review of published literature on the latest research and standards development that impact BIM and its application in FM during the operations and management phase. The study found the challenges facing the FM sector include the need for greater consideration of long-term strategic aspirations; data integration issues; augmented knowledge management; enhanced performance measurement; and enriched training and competence development for facilities managers to better deal with the large range of services covered by FM. Table 4.3 summarizes the literature review on BIM performance metrics. The categories for indicators are similar to general company performance categories but also include the added category of technology-related, which focuses on reliability, capacity, and early issues identification.

Table 4.3. Performance Metrics for Quantifying the Benefits of BIM

Performance Indicator	Example Metric	Reference
Fundamental indicator		
Cost	Manhours spent per project; revenue per head; overall savings with BIM in design and construction; change orders (cost of change/total cost of project)	Coates et al. (2010), Barlish and Sullivan (2012), Aziz et al. (2016), Pärn et al. (2017)
Speed	Speed of development; schedule (actual duration to standard duration)	Coates et al. (2010), Barlish and Sullivan (2012), Pärn et al. (2017)
Quality	Better architecture, reduction in buildability issues, ratio of number of warnings to number of objects	Coates et al. (2010), Liu et al. (2016)
Technology-related		
Tool reliability	Quantity takeoff accuracy; level of corrections; level of credibility	Coates et al. (2010), Li et al. (2014), Liu et al. (2016), Pärn et al. (2017)
Visualization capability	Reduction of printing and document shipping; number of objects per square foot or objects created per month	Coates et al. (2010), Liu et al. (2016), Pärn et al. (2017)
Early issue identification	Reduction of mistakes; class detection; automated model checking; object changes per month	Coates et al. (2010), Aziz et al. (2016), Liu et al. (2016)
People-centric		
Information sharing	Reduction of travel cost; quantity of request for information (RFI)/assembly	Coates et al. (2010), Barlish and Sullivan (2012), Aziz et al. (2016), Liu et al. (2016), Pärn et al. (2017)
User satisfaction	Client satisfaction and retention	Coates et al. (2010)
Internal satisfaction	Staff reaction and acceptance; knowledge level and related BIM training; learning curve; learning tool in real construction tasks; workload reduction; future use	Coates et al. (2010), Lu et al. (2013), Li et al. (2014)
Collaboration	Simultaneous work by multiple disciplines	Coates et al. (2010), Aziz et al. (2016), Pärn et al. (2017)
Business value		
Competitiveness	Bids won or win percentage	Coates et al. (2010), Aziz et al. (2016)
Innovation	IT investment per unit of revenue	Coates et al. (2010)

4.3. Proposed Performance Measurement Framework for LSM

4.3.1. Adopting the Rules of KPIs

The development of appropriate performance measures is an important task and should follow good rules governing the establishment of measures. Table 4.4 summarizes various guidelines focusing on setting specific, measurable, achievable, realistic, time-based (SMART) rules that need to be met prior to selecting any KPI. It was indicated earlier that the previously identified performance measures commonly used in a construction context are insufficient to be used as a framework for measuring the success of LSM. Based on the growing trend of relationship-based approaches in construction, recent studies categorized performance measurement into (a) result-oriented objective measures, (b) result-oriented subjective measures, (c) relationship-oriented objective measures, and (d) relationship-oriented subjective measures, as summarized by Yeung et al. (2009). In the result-oriented category, cost performance, time performance, and scope of rework are some examples of objective measures, while subjective measures include quality performance, professional image establishment, satisfaction, and innovation. In the relationship-oriented category, the occurrence and magnitude of litigation, dispute, and claim are considered objective measures, while trust, effective communications, business relationship, and reduction of paperwork are examples of relationship-oriented subjective measures. Among these KPIs, Yeung et al. (2009) identified client satisfaction, cost performance, quality performance, time performance, effective communications, safety performance, trust and respect, and innovation and improvement as the important KPIs to use to evaluate the success of relationship-based projects in Australia.

Table 4.4. Integrated KPI Rules

Indicator Category	Indicative Rules
Accuracy	The indicator should consider the precision level needed while measuring
	The indicator should consider the difficulty level, represented by either the frequency or ease of measurement
Frequency	The indicator should frequently (i.e., annually) track the asset's performance throughout the planning horizon
	The indicator's rate of change should be highly considered (i.e., the KPI should experience a periodical difference in the asset state)
Financial	The indicator should consider the costs needed for frequently measuring and controlling the asset
Ownership	The indicator should have an owner who is held liable/responsible for it
Portability	The indicator should fit multiple assets with different features and attributes such as deterioration rates, useful lives, and construction years
Subjectivity	The indicator should be objective and should include a predefined set of rules for measuring an asset attribute to guarantee a consensus agreement among different parties
Understandability	The indicator should consider the ease of understanding and tracing the triggers behind a sudden rise/fall throughout the asset's life cycle

Source: Samra et al. (2018).

4.3.2. KPIs for the Benefits of LSM

This section proposes the initial performance measurement framework for LSM based on the comprehensive literature review related to the framework of linear construction projects and BIM tools. The proposed LSM performance framework is shown in Table 4.5.

Table 4.5. Conceptual LSM Performance Framework

Indicator	Metric	Unit	Source	Easiness to Obtain
Cost				
Design cost	Additional LSM cost of A&E services/cost of total design non-LSM and LSM scope awarded	Percentage	O, C, D	Hard
	Software/hardware costs	Percentage	O, C, D	Hard
Construction cost	Additional LSM cost of construction/cost of total construction non-LSM and LSM scope awarded	Percentage	O, C	Hard
	Constructability	Description	O, C, D	Hard
Other costs	Avoidance log and associated costs	Percentage	O, C, D	Hard
	Offsite prefabrication manhours from contractors	Percentage	O, C, D	Hard
	Reconciliations of savings from contractors using LSM	Percentage	O, C, D	Hard
	Reconciliations of savings from designer using LSM	Percentage	O, C, D	Hard
Time				
Schedule	Actual duration/standard duration	Percentage	O, C	Easy
Change order	Percent of standard costs	Percentage	O, C, D	Easy
Productivity	How fast the LSM is developed on average	Description	O, C, D	Medium
Quality				
Tool reliability	Ratio number of issues identified using LSM vs. non-LSM	Percentage	O, C, D	Medium
	Consistency of LSM with other scheduling tools	Likert scale	O, C, D	Easy
	LSM tool credibility, and how well the schedule is developed on average	Likert scale	O, C, D	Easy
	Workload comparison of LSM and non-LSM methods	Likert scale	O, C, D	Easy
	Material management (e.g., quantity takeoff accuracy)	Description	O, C, D	Easy
	Conflict detection, design analysis and optimization	Description	O, C, D	Medium
Contractor quality	Contractor accountability	Description	O	Easy
	Contractor verification	Description	O	Easy
Reporting quality	Quality of analytical reporting	Description	O	Easy

Indicator	Metric	Unit	Source	Easiness to Obtain
Communication				
Usefulness	How frequently the LSM is accessed	Number of access	O, C, D	Medium
	Ease of construction documentation creation	Description	O, C, D	Medium
	Reliability of LSM for user	Description	O, C, D	Medium
Engagement	Coordination meeting attendance	Description	O, C, D	Medium
Socio-equity	How the LSM can be utilized when addressing social and equity issues	Description	O	Hard
Request for information	Quantity of RFIs in LSM vs. non-LSM	Percentage	O, C	Medium
Competitiveness				
Client satisfaction	Client satisfaction and retention	Likert scale	O, C	Easy
	Possibility of LSM future use	Likert scale	O	Easy
Bids won	Bids won or win percentage	Description	C	Medium
Skill development	Employee skills and knowledge development	Staff-hours/m^2	O, C	Easy

O: Owner, C: Contractor, D: Designer

Performance indicators that can best support the quantification of LSM benefits should include the following principles:

- *Cost*—includes impacts of implementing LSM on costs at different project phases and elements.
- *Time*—relates to how this method can improve productivity levels and impacts the completion date.
- *Quality*—includes performance of the tool and the users in delivering the tasks.
- *Communication*—measures how well the LSM can better communicate the project progress to different stakeholders.
- *Competitiveness*—measures the capabilities of the tools to improve the competitiveness of the users.

Performance measures identified from the existing practice and literature review of linear projects and BIM were adopted when suitable for use within the LSM context. The performance indicators were broken down into 30 performance metric levels, with the possible unit of measurement, suggested source of information, and estimated easiness level based on literature and assumptions. Metrics and unit of measurement are critical to ensure that performance can be quantified. Sources of information for each metric should be identified in advance since different projects have different conditions and varying degrees of stakeholder visibility. For example, an owner utilizing new project management tools may have a low degree of visibility to contractors' actual savings, safety rates, and reduced headcount in the field and office, while only the contractor may know field labor productivity rates (Barlish & Sullivan, 2012). Thus, cost-related performance metrics are currently categorized as hard to obtain since actual savings become proprietary due to the nature of the business. Time performance can be measured quantitatively, and the data are generally available to all parties; thus, it is assumed that the time performance metrics are readily obtainable. Many performance metrics for quality, communication, and competitiveness, although they also can be quantified, are based on stakeholders' individual subjectivities affected by different degrees of visibility based on their experience and roles. Therefore, the level of easiness to obtain data for quality, communication, and competitiveness performance ranges from easy to hard.

4.4. Conclusion

This chapter summarized the extensive literature review pertaining to the use of BIM in the performance measurement of construction firms and some highway construction projects. The literature review results presented in this chapter provide the background of a conceptual performance measurement framework for quantifying the benefits of adopting LSM in projects. The performance measures in the context of LSM inform the decision-making process among the stakeholders interested in adopting the method and communicate more effectively the consequences of the investments.

Based on this initial study, the researchers suggested five performance criteria (cost, time, quality, communication, and competitiveness), 16 performance indicators, and 30 performance metrics to measure the benefits of LSM. Additionally, the proposed framework includes the potential unit of measurements, source of information, and level of easiness to obtain data. While assumptions were made based on the literature review, the framework will need to be further refined using a case study approach through interviews and surveys with the relevant stakeholders, including existing and potential

LSM users. The future study should identify the trade-offs between the importance level of performance measures, how much information is available, and how difficult it is to obtain the available information.

5. SURVEY QUESTIONNAIRE

5.1. Introduction

Using the information gained from the literature review, the research team will conduct two sets of activities, namely an online survey and follow-up interviews, to further assess current practices in the adoption of LSM and its benefits. The survey questionnaire will be designed to capture the expertise and knowledge of design and construction professionals with various levels of experience using LSM in transportation projects. In developing the survey questionnaire, the research team will aim to identify the following:

- General steps in the adoption of LSM and their relationships 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 LSM with respect to the proposed LSM performance framework shown in Chapter 4.
- Appropriate contacts for targeted interviews and case studies.

5.2. Methodology

Completing the survey is expected to take between 30–45 minutes. Before administrating the survey, the project team will pretest the web-based survey by asking two members of the advisory team to complete the survey online and provide feedback.

After the survey is finalized, it will be distributed to potential participants using the online platform. Potential respondents will be identified by reviewing a list of WSDOT past and current projects and identifying those in which LSM is used. The project team will target at least two projects of a small-medium size and two projects of a large mega-complexity level (four projects total). For each project, the survey will be sent to the following individuals within each of the three major parties involved in the project:

- Owner: field engineers, project planners, project managers.
- Consultant: project planners and project managers.
- Contractor: field engineers, project planners, and project managers.

5.3. Draft of the Survey Questions

A proposed list of survey questions is provided in Table 5.1. The first section of the survey covers background information about survey respondents, including job title, affiliations, project experience, and level of familiarity with LSM. The subsequent sections of the survey cover technical aspects of LSM and include the following subsections:

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

Table 5.1. Preliminary List of Survey Questions

Theme	Question	Format
Background information about participants	What is the contractual role of your organization in construction projects?	Multiple choices
	What is the size of your company in terms of the collective value of contracts?	Multiple choices
	What is your job title?	Open-ended (short answer)
	How many years of experience do you have in your role?	Multiple choices
	How familiar are you with LSM?	Likert-type scale
LSM processes and procedures	Does your organization use LSM?	Multiple choices
	If yes, when did your organization first use LSM?	Multiple choices
	If no, did your organization ever consider using LSM?	Multiple choices
	If your organization did consider using LSM, why was it not adopted?	Multiple choices
	If your organization uses LSM, which group or individual (job title) is in charge of planning and implementing LSM?	Open-ended (short answer)
	If your organization uses LSM, do you have formal processes for using it?	Multiple choices
	Can you share your LSM processes?	File upload
	In which type of projects (example, tunnel, highway, etc.) does your organization use LSM?	Multiple choices
	At which phase of the project does using LSM start?	Multiple choices
	At which phase of the project does using LSM end?	Multiple choices
Benefits and challenges	What are the benefits of using LSM? Please select the top three benefits by project outcome affected (cost, time, quality, safety).	Multiple choices
	Can you share examples and include project documents?	File upload
	What are the challenges of using LSM? Please select top three challenges by project outcome affected (cost, time, quality, safety).	Multiple choices
	Can you share examples of your organization overcoming these challenges and include project documents?	File upload
	Do the benefits of using LSM offset its challenges?	Multiple choices
Tools and resources	Which software program do you use for LSM?	Multiple choices
	Who (job titles) within your organization is involved in developing and implementing linear scheduling plans?	Open-ended (short answer)
	Who (job titles) outside of your organization (other parties in the project) is involved in developing and implementing linear scheduling plans?	Open-ended (short answer)
	Can you share examples and include project documents?	Open-ended
	How often do you update your LSM plans during the course of the project?	Multiple choices
Other	Generally speaking (in the construction industry), do you think LSM is going to thrive or fade away?	Multiple choices

5.4. Conclusion

The survey will help capture information on the general steps in the adoption of LSM, resources (information, personnel, tools) required for completing each step, and related benefits and challenges. The research team will identify appropriate contacts for targeted interviews and case studies.

6. INTERVIEW QUESTIONNAIRE

6.1. Introduction

The goal of follow-up interviews will be to confirm survey results and obtain additional information beyond what was gained from the online questionnaire, including information on linear scheduling activities and specific tools that are used in each activity.

6.2. Interview Methodology

The research team will follow a case study approach in conducting the interviews. Using the survey results, the project team will select one project of a small-medium size and one project of a large mega-complexity level for follow-up interviews. Up to two individuals from each of the three major parties involved in each project (owner, consultant, and contractor) will be interviewed, resulting in 10–12 interviews (two projects, three organizations in each project, and two individuals from each organization). Interviews will be selected to cover different job titles, including field engineers, project planners, and project managers. A list of some potential candidates for the interviews is given in Appendix II.

6.3. Draft of the Interview Questionnaire

A proposed list of interview topics is provided in Table 6.1. In terms of the contact, the interview will follow the topics covered in the survey, but in an open-ended format to facilitate discussions.

Table 6.1. Preliminary List of Interview Questions

Theme	Question	Format
Background information about participants	What is your job title?	Open-ended (short answer)
	How many years of experience do you have in your role?	Multiple choices
	How familiar are you with LSM?	Likert-type scale
LSM processes and procedures	Which group or individual (job title) is in charge of planning and implementing LSM?	Open-ended
	What are the major steps in developing LSM in a project?	Open-ended
Benefits and challenges	What are the benefits of using LSM? If possible, please break down benefits by project phases.	Open-ended
	What are the benefits of using LSM? If possible, please break down benefits by project outcome affected (cost, time, quality, safety).	Open-ended
	Can you share examples and include project documents?	Open-ended
	What are the challenges in using LSM? If possible, please break down benefits by project phases.	Open-ended
	What are the challenges of using LSM? If possible, please break down benefits by project outcome affected (cost, time, quality, safety).	Open-ended
	How does your organization overcome these challenges?	Open-ended
	Can you share examples and include project documents?	Open-ended
	Do the benefits of using LSM offset its challenges? Please explain how.	Open-ended
Tools and resources	Who (job titles) within your organization is involved in developing and implementing linear scheduling plans?	Open-ended (short answer)
	What is the role of each individual (in terms of information input and expertise) in developing and implementing linear scheduling plans?	Open-ended
	Who (job titles) outside of your organization (other parties in the project) is involved in developing and implementing linear scheduling plans?	Open-ended (short answer)
	What is the role of each individual (in terms of information input and expertise) in developing and implementing linear scheduling plans?	Open-ended
	Can you share examples and include project documents?	Open-ended
Other	Generally speaking (in the construction industry), do you think LSM is going to thrive or fade away? Why?	Open-ended

6.4. Conclusion

Interviews will allow researchers to collect and synthesize practical information from projects in which LSM is used. The interviews will help further develop the general steps in the adoption of LSM, resources (information, personnel, and tools) required for completing each step, and related benefits and challenges.

7. CONCLUSIONS

WSDOT has launched an initiative to evaluate, develop, and implement best practices for linear scheduling of transportation projects. Linear scheduling may be 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 includes surveys and interviews of key WSDOT project personnel as well as pilot use of linear scheduling with off-the-shelf software in a selected project.

The objective of Phase I of this study included synthesizing the potential application of LSM for transportation projects. The secondary objectives included identifying lessons learned, strategies for effective use, and knowledge gaps. Through Phase I, the research team identified the need to examine more LSM projects, investigate commercial software, and refine the LSM performance metrics. While some of this work was identified as tasks to expand on during Phase II, parts are included in this report.

The findings from this synthesis show that 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. Five case studies sponsored by state DOTs in the United States that evaluated the use of LSM in roadway constructions were found. The researchers concurred that for linear projects, LSM improved schedule overview and facilitated better communication. The work continuity was ensured, and project control was enhanced by adopting LSM as the scheduling method. However, it was noted that none of the five case studies were recent, which shows the necessity of the current study to assess the present status of LSM research and application. An overview of existing LSM scheduling software was also provided in this synthesis. GraphicSchedule and TILOS were shown to have the potential to support the implementation of LSM in the WSDOT community.

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APPENDIX I

List of Questions and Comments from WSDOT Webinar on March 13, 2019

Topic	Topic Description	Participant Questions and Comments
Example projects	The application of LSM in real projects	Has your research uncovered any application where LSM has been used in parallel (more than one location on a corridor at the same time)?
		Please select a variety of projects in size and complexity, not just mega projects.
		Will any part of the research include LSM application in a practical solutions/design approach?
		Contractors have projects that specify CPM to be used for the submittal of project schedules; how long until we see WSDOT projects specifying linear schedule?
		Are there highway projects complete that used linear scheduling?
Performance metrics	The potential benefits and challenges in adopting linear scheduling method	In other words, additional work for the project offices that doesn't eliminate existing processes. Why would we do this?
		Resources and costs can be tracked, depending on the sophistication of the software tool. More features = more money.
		We speak to the quantification, but what about the qualitative aspects, which are key in developing meaningful KPIs?
		Cost and budget are important to be included so you can do earned value analysis in the same place.

Topic	Topic Description	Participant Questions and Comments
		Do you see linear scheduling as a way to reduce risk?
Research specific	The progress and methodology of research	The pilot projects selected—will one of them include a structure?
		GPM = Graphical Path Method?
		Graphical Path Method....GPM?
		Since linear scheduling has been around for 20 years, there must have been other research conducted on this subject; has this team reviewed any prior research that would eliminate duplication of effort?
		Suggest you expand your literature research to include PMI.org and AACEi.org.
		Why not include GPM in this study, as a good fit for a large number of WSDOT projects?
		Will we be getting a copy of this study?
Software	The available linear scheduling software on the market and its capabilities	I was wondering if this approach could be used for modeling disaster recovery scheduling for infrastructure?
		This seems to be the same as trying to keep offices from using MS Project and P6. Two different tools compounding problems of communication.
		This seems very interesting and somewhat concerning that several of the questioners are concerned about additional work burdens instead of possible advantages of a new tool. Have you considered somewhat novel approaches such as scheduling ferry maintenance during journeys or dock repairs during intermittent

Topic	Topic Description	Participant Questions and Comments
		operation? I can see some possible new ways to obtain insights into improving efficiencies in the scheduling of efforts.
		What is the software used for linear scheduling?
		Can you tell us who the local vendor is?
		From what has [been] presented, the project offices will become burdened with another tool to use.
		How are costs/budgets reflected in this method?
		I am wondering how involved a linear schedule gets when you have a large project with hundreds of activities that occur both within a segment of the project and throughout the project lifespan.
		Is it going to be separate software like P6 or other software? If it is, are we combining the features many features from different software to make this one unique (advanced) than software in the market?
		Linear looks to be more of a reporting tool than a scheduling tool. We have reports available now.
		Linear schedule presentations always show the report, but they don't show the data required to maintain the schedule. What data is required to produce the schedule?
		Linear scheduling can be helpful in identifying crew/discipline conflicts.

Topic	Topic Description	Participant Questions and Comments
WSDOT specific	The potential impacts of this research to WSDOT projects in the future	If this is being investigated to be part of the current PMRS processes, why is the PMRS group not involved?
		Is it expected that WSDOT will implement linear scheduling requirements for contractors on projects?
		Is this being viewed as a replacement to the current method of scheduling project in WSDOT, and is this being coordinated with the WSDOT PMRS group who is responsible for this type of work?
		Most WSDOT projects I encounter are at a singular location such as a widening or resurfacing at a small distance. Is LSM applicable to this, or is it more justifiable on long stretches of improvement?
		Would WSDOT be generally open to a no cost change order to convert to linear scheduling if the project fits the profile of what might work best as the scheduling option?
		WSDOT often mandates the schedule type within the contract. Will linear scheduling be added as a scheduling option or even contract specific schedule type in the near future, or will we be waiting for the end of the research?

APPENDIX II

List of Potential Candidates with Linear Project Experience for Phase II Interview

<table>
<tr><th>Candidate</th><th>Linear Project Experience</th><th>Referral</th></tr>
<tr><td>Whitney Ruth (Director of Scheduling, Global Critical Facilities Group)</td><td>Bay Area Rapid Transit light rail project.</td><td rowspan="2">Lorne Duncan (President & CEO, Petroglyph)</td></tr>
<tr><td>Andy Fairbairn (Lead Scheduler, PARSONS)</td><td>Long-time user of TILOS.</td></tr>
<tr><td>Kristine Mason (Construction Consultant, Tarr Whitman Group, LLC)</td><td>East Link Light Rail E330 Downtown Bellevue Tunnel</td><td rowspan="2">Kiley Rempp (Engineer I, HNTB)</td></tr>
<tr><td>Kyle Kankanton (Construction Consultant, Tarr Whitman Group, LLC)</td><td>East Link Light Rail E335 Downtown Bellevue to Spring District</td></tr>
</table>