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Method for Base Estimation of Construction Time for Linear Projects in Front-end Project Phases

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Abstract: Even though horizontally linear projects have low complexity schedules, they are still not successful in meeting planned time. The deadlines are mostly based on estimations done in front-end project development when limited data are available. Early time estimation models in literature rely on few variables and, almost in all cases, one of them is the estimated cost. Early cost estimations can significantly deviate from actual costs and thus lead to unreliable time estimation. Time estimation models based on neural network and other alternative methods require databases and software, which complicates the process of time estimation. The purpose of this paper is to bridge the gap of scarce time estimation models and unreliable time estimates by developing a new method for time estimation. This research has been done on one large sewer system project. The case study shows how to extract several continuous activities for a pipeline project chosen from a sewer system. Moreover, a new algorithm for the calculation of project duration is devised based on the existing equation related to the linear scheduling method, and this algorithm works with continuous activities. The new method for construction time estimation is based on the extraction of linear continuous activities, usage of the algorithm for identification of minimal buffer between activities, and calculation of the project duration. To verify the algorithm, this method is used on another pipeline project from a sewer system. The limitation is that this method can be used only for base estimation. Further research needs to be done to include uncertainties and risks in the method.

Keywords: construction time estimation, linear projects, method, algorithm

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1 Introduction

1.1 Problem of construction time overruns and its economic impact

Various research reports give evidence that construction time overrun in construction projects is of very frequent occurrence (Bromilow, 1974; Bromilow et al., 1980; Chan and Kumaraswamy, 1995; Assaf and Al-Hejji, 2006; Mahamid, 2017). Delays and cost overruns in large public projects have significant implications from an economic as well as political point of view. Due to delays in project implementation, people have to wait for the provision of public goods and services longer than is necessary, therefore reducing the efficiency of available economic resources, limiting the growth potential, and reducing the competitiveness of the economy (Singh, 2010). Singh (2010) also emphasizes that delay in implementation will cause cost overrun for the project simply on account of inflation and overhead costs. Moreover, a long delay may cause depreciation of project assets, necessitating expenses on repairs or replacements. For European Union (EU)-funded projects, not meeting construction deadline invites very high penalties, up to 25% of the contract value (Ministarstvo regionalnoga razvoja i fondova Europske unije [MRRFEU], 2019), and still, reports of time overruns are frequent. The estimation of project time and cost for large construction projects is a characteristically complex exercise (Singh, 2010; Czarnigowska and Sobotka, 2014).

1.2 Difficulties in early time estimation of construction projects

Al-Khalil et al. (1997) reported that, in Saudi Arabia, early planning and design were the most important categories causing delays among the surveyed construction project owners. Similarly, Odeyiaka and Yusif (2002) and Abisunga (2014) found that the common reasons for time overrun in Nigerian building projects are, among others, planning and scheduling problems. Olawale and Sun (2010) reported that in the United Kingdom, time overruns are still quite common in construction projects and that the second most important factor inhibiting effective time control is an inaccurate evaluation of project duration. Car-Pusic and Radujkovic (2006) identified the problem of inaccurate estimations of project duration in the front-end phases, which are used for the determination of project deadline. Front-end planning, also known as preproject planning, is divided into three phases: feasibility, concept, and detailed scope wherein time estimates are made (Construction Industry Institute [CII], 2012). Estimating is a key front-end activity with a significant role in determining whether the project will be judged successful; yet, it rarely receives much attention in the literature (Edkins et al., 2013). Edkins et al. (2013) emphasized that front-end planning is an underresearched discipline and encouraged others to explore various specific topics, i.e., time and cost estimation. There are only few models of time estimation, and they are mostly based on project cost (Bromilow et al., 1980; Chan and Kumaraswamy, 1995; Car-Pusic and Radujkovic, 2006; Žujo et al., 2017). Most of these models are used to record what is likely to be achievable (i.e., duration) based on experience with past projects (Czarnigowska and Sobotka, 2014). The existing time predictive models are based on regression between cost and other project variables and duration (Bromilow et al., 1980; Kaka and Price, 1991 Chan and Kumaraswamy, 1995; Chan, 2001; Petruseva et al., 2019). However, some scholars are pointing to the fact that early cost estimates can be very inaccurate (Assaf and Al-Hejji, 2006). Furthermore, construction projects are capable of fluctuating as much as 10% or more of their cost value over periods as short as 6 months (Weidman et al., 2011), which makes "project costs" an even less-reliable parameter for time estimation.

Some scholars are claiming that construction activities and their embedded production rates should be emphasized more in time planning and time estimation (Lucko et al., 2014), especially for linear infrastructure projects (i.e., roads, tunnels, and highways). While front-end planning and early time estimation are not very highly researched topics in linear projects, there are numerous papers dealing with scheduling (Arditi et al., 2002; Mattila and Park, 2003; Duffy et al., 2011; Lucko et al., 2014). There is increasing interest in the linear scheduling method (LSM), and it is chosen by many scholars (Mattila and Park, 2003; Duffy, 2009; Lucko et al., 2014) as the best solution for time planning of linear infrastructure projects (i.e., pipelines and highways). Only few variables related to construction activities are needed to determine the project duration using LSM (Lucko et al., 2014), e.g., production rate and quantity of work, and these variables can be determined in the front-end phase through preliminary designs of construction projects.

Front-end planning and its inherent discipline of time estimation are found to be very potent and yet not sufficiently explored research areas. Existing early time estimation models have significant limitations, and scholars are emphasizing the need to provide alternative ways to estimate the construction project duration. Therefore, a new method for early time estimation will be presented in this paper. This method is based on production-related parameters and LSM. Section 2 addresses the current ways of estimating the time of construction projects and their limitations. Furthermore, in Section 2, existing LSMs are presented and their inability to be used in front-end planning is described. In Section 3, the research methodology is presented, which is followed by Section 4, in which the development of the new method is elaborated, along with an explanation of how to use the method. Contributions and limitations of the newly developed method are highlighted in Section 5. In the last section, concluding remarks and suggestions on possible further research are provided.

2 Literature review

2.1 Models for early time estimation

In the construction industry, previous experiences are usually used to estimate the project duration and the cost of a new project. The first early estimation of construction time performance of building projects was given in Australia in the late 1960s. After analyzing the performance of 329 Australian building projects in 1967, Bromilow et al. (1980) proposed the relationship between construction duration and the construction cost of the building projects to be of the following formula: $T = KC^{B}$, where T is the duration of the construction period from possession of site to practical completion, measured in working days; C is the final project cost in A$ million, adjusted to a price index; K is a constant describing the general level of time performance for an A$ 1 million project; and B is a constant describing how time performance is affected by project size as measured by cost. The equation describes the mean construction time as a function of the project cost. Afterward, Bromilow et al. (1991) conducted a similar survey on 140 roadwork projects and provided new values for the constants K and B, and many scholars provided Bromilow's time–cost (BTC) models for their countries (Car-Pusic and Radujkovic, 2006; Žujo et al., 2017). Chan and Kumaraswamy (1995) tested these relations on a small sample of infrastructure projects in Hong Kong (Table 1). The *R*-value indicates the coefficient of correlation, which is used as an indicator of the variability within each category and for comparison between categories.

Chan and Kumaraswamy (1995) provided additional simple parametric time estimation models based on simple regression between time and one other parameter (i.e., Time – Total floor area; Time – Number of storeys) and they also performed multiple linear regression (MLR) to provide models based on two parameters (i.e., Time – Cost – Total floor area model). Some researchers suggested that with more independent variables (parameters), more precise estimates can be provided (Nkado, 1992; Chan and Kumaraswamy, 1999; Hoffman et al., 2007). Hofmann (2007) provided an MLR model based on six parameters (i.e., project delivery method, work type, and so on). Czarnigowska and Sobotka (2014) used 25 parameters in their MLR, and Chan and Kumaraswamy (1999) also used >10 parameters to provide best-fit estimation. In addition to simple linear regression and MLR, there are other methods for time estimations based on construction project parameters, i.e., artificial neural network (ANN) model (Bhokha and Ogunlana, 1999), neurofuzzy model for time and cost estimation (Boussabaine, 2001) using both fuzzy concept and neural networks, time prediction model based on locally linear neurofuzzy (LLNF) model, being trained by a locally linear model tree (Vahdani et al., 2016.). Furthermore, there are some experience-based time estimation models, such as multiphase integrated automation systems (MITOS), developed by Kanoglu (2003) based on a large amount of information and few computer software. Žujo et al. (2017) developed five hybrid models, and the most accurate one was the BTC–general regression neural network (GRNN) model, which uses the BTC model as a process-based model and the GRNN as a data-driven model.

Tab. 1: Time–cost performance for civil engineering projects in the expanded Hong Kong sample

Project type	*K*	B	*R*	Total projects
Total civil works	250.5	0.206	0.79	148
Roadworks	251.2	0.225	0.87	57
Other civil works	262.5	0.185	0.69	91

Source: Chan and Kumaraswamy (1995).

Time–cost regression parametric models have some advantage over other (alternative) models, such as "black box" expert systems or neural networks, because regression models are expressed as equations, and to use them, one does not need to dispose of the whole database or software (Czarnigowska and Sobotka, 2014). On the contrary, one of the significant limitations of the "time–cost" model is also that it can be applied only in the area or country of its origin because of specific economic characteristics, which are reflected on the value of model constants (Žujo et al., 2017). Furthermore, a study in Indonesia found that cost overruns occur more frequently and are a more severe problem than time overruns (Kaming et al., 1997), and it is also proven that the relationship between the early estimated cost and the actual value of works may be rather loose (Czarnigowska and Sobotka, 2014). Current studies show that time–cost models provide unreliable time estimation and, on the other side, alternative time prediction models require quite an effort and specific knowledge.

2.2 Defining the construction project duration through major construction activities

Models for early time estimation based on multiple variables can be split into two groups: those that are orientated on project parameters, and those that are oriented on a set of activities (Car-Pusic and Radujkovic, 2006). Gray and Little (1985) have shown that there are several time-leading phases and processes in every construction project. If these construction processes can be estimated consistently in the early design stage, the probability of mistake will be minimized (Chan and Kumaraswamy, 1999). Chan and Kumaraswamy (1999) confirmed by survey that there is general agreement among practitioners on the categorization of primary work packages for building projects and the work sequencing of these packages. Nkado (1992) defined the activities for the construction of new buildings. Activities can be categorized into major work packages to form an outline of the construction program (Nkado, 1992), as presented in Figure 1.

Nkado's (1992) masterplan underlines the duration of construction projects, which he presented through traditional scheduling techniques (critical path method [CPM]; and bar chart) for the determination of construction time. Similarly, Chan and Kumaraswamy (1999) proved that construction duration can be determined by the durations of work packages and their lag times (e.g., buffers between start of adjacent work packages). Harmelink and Rowlings (1998) and Duffy (2009) stated several major construction activities (e.g., work packages) for pipeline projects that represent the most important contributors of project duration. In both papers, LSM is used to portray these planned activities.

2.3 Planning linear projects with LSM

Projects that are horizontally linear, vertically linear, or feature repetitive operations are ideally suited for LSM (Arditi and Albulak, 1986; Harris and Ioannou, 1998; Lucko and Gattei, 2016.). There are numerous linear scheduling techniques based on the time–location diagram, in which one axis represents the time and the other represents the location (Figure 2). The two most known linear scheduling methods are the "line of balance (LOB)" method and the LSM (Su and Lucko, 2015). These two methods both use the coordinate system of work and time, but fundamental differences exist in activity representation, project start, and productivity between the LOB and LSM models (Su and Lucko, 2015, 2016). The reason is that the concept of LOB is rooted in the activity-on-arrow (AOA) network, while LSM resembles the activity-on-node (AON) approach and thus differences appear in activity presentation (e.g., two parallel lines in LOB vs one line in LSM) and related graphical and mathematical expressions (i.e., activity slope in LOB denotes delivery rate, while slope in LSM denotes production rate) (Lucko and Gattei, 2016). Furthermore, LOB emphasizes the principles of "optimum crew size" and "natural rhythm" (Damci et al., 2013), while activities in LSM are presented through a single line and the work tasks within are not specifically separated but can be read off the work axis in integer or noninteger points in time (Lucko and Gattei, 2016). LSM is slightly better known (Su and Lucko, 2015).

A reason why linear scheduling (LS) has not become a popular method, similar to CPM has, because there is no unanimously accepted method for identifying the critical path (Kallantzis and Lambropoulos, 2004b). Lately, the most pronounced topic related to LSM is determination of the controlling activity path (CAP) (Harmelink and Rowings, 1998; Yamin and Harmelink, 2001), controlling sequence (Harris and Ioannou, 1998; Mattila and Park, 2003), and critical path (Kallantzis and Lambropoulos, 2004b, Lucko, 2007, 2008), with the joint purpose of reducing deficiencies in LSM scheduling. Kallantzis and Lambropoulos (2003) proved using an example that CAP and controlling sequence provide different solutions from CPM-based critical path and thereafter provided their own Kallantzis–Lambropoulos Repetitive Project Model (KLRPM), which is compatible with CPM, even though KLRPM is purely a graphical method (unlike CPM). To relate the linear schedule in KLRPM with CPM, network plan activities were allowed to make interruptions and violate the resource continuity constraint even though it is against the logic of the linear methods in general (Kallantzis and Lambropoulos, 2004b). Ioannou and Yang (2004) stated that the term ''path'' implies that activities succeed each other in a finish-to-start manner, so that each activity, if delayed, ''pushes'' the activities in front of it and thus delays the

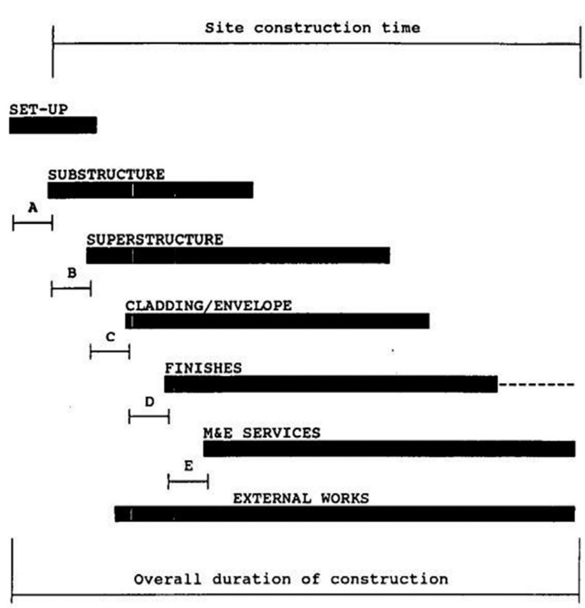

Fig. 1: Simplified outline of the construction plan based on condensed work packages.

Source: Nkado (1992).

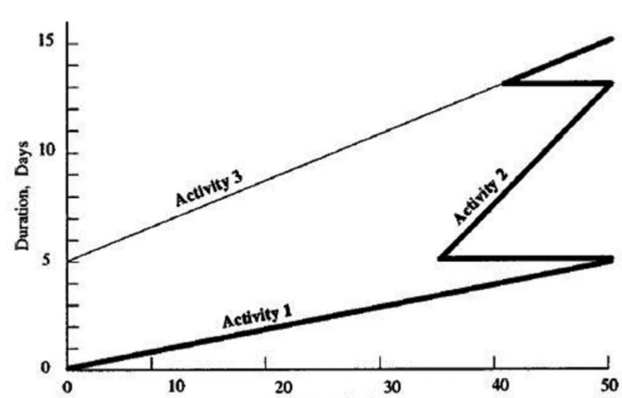

Fig. 2: Example of controlling activity path (CAP) in time–location diagram.

Source: Mattila and Park (2003).

project and that this is not true for the LSM-related "critical path". Hence, in resource-restraint-based scheduling, (i.e., LOB and LSM), wherein resource continuity is the underlying assumption, the concept of a critical path breaks down (Ioannou and Yang, 2004). Lucko (2007, 2008) developed the "Productivity Scheduling Method" (PSM), which is based on singularity functions, and thus mathematical expressions are provided for activities in the LSM schedule. Furthermore, calculations for criticality and floats based on singularity functions (Lucko, 2009) are developed. Ammar (2013) presented an integrated LOB–CPM approach, which is based on plotting the initial plan through equations based on the LOB method and calculating the critical path using the CPM approach in an equivalent CPM plan. Even though Lucko (2008) and Ammar (2013) showed that it is possible to get the same critical path in LSM and CPM, Su and Lucko (2016) emphasized that the CPM network technique for repetitive and linear projects has major disadvantages, i.e., large number of activities, or tasks, to represent the project, which makes it extremely difficult to visualize the project, does not guarantee maintaining the continuity of work, not considering the location in which the construction activity takes place, and so on.

The mentioned LSM-related issues are based on an analysis of a fully developed time–location diagram and for activities with varying production rates. In these detailed schedules, activities are represented by a polyline (varying production rates) rather than a straight line, and they are not suitable for front-end phases of the project, wherein early time estimation takes place.

2.4 LSM for early estimation of construction time?

Harmelink (1995) provided the classification of activity types in LSM, and there are four types of linear activities: continuous full-span activities; intermittent full-span linear activities; and two types of partial-span linear activities. LSM was created within construction and was originally intended for geometrically linear projects, such as highways and pipelines (Su and Lucko, 2016). Those types of projects are, by nature, characterized by a set of continuous full-span linear activities, the carrying out of which involves the whole development of the site without interruption (Abbondati et al., 2016). These early LSM and LOB schedules often consisted of several repetitive or linear continuous activities (Peer and Selinger, 1972; Arditi et al., 1986), wherein activities were presented in time–location diagrams as straight lines (LSM) or double lines (LOB).

Graphically based LSM, LOB method, and repetitive scheduling method (RSM) use classic geometry for analyzing linear and repetitive schedules (Lucko, 2007) and thus are not suited for early estimation (e.g., requires fully developed time–location diagram). Some attempts were made to set basic equations for RSM (Reda, 1990) and LOB (Al-Sarray, 1990), but there were no clear and simple equations for project duration. Lucko (2007, 2008) developed the PSM and explained in seven steps how to use the sets of singularity functions to derive activity duration, buffers, and critical path. Even though PSM (Lucko, 2008) brought great advancement in linear scheduling, the numerous sets of singularity functions needed to describe the several activities and buffers, as well as the focus on criticality, make PSM not well suited for time estimation. The integrated LOB–CPM approach (Ammar, 2013) is based on overlapping activities that have continuous progress rate and thus is more feasible in the front-end phase than PSM. Nevertheless, lengthy LOB calculations for the initial plan, along with the necessity to use two methods (LOB and CPM) to provide assessment of project duration, is more tailored to detailed scheduling than for early estimation.

On the other side, for this type of simplified linear schedule based on linear continuous full-span activities, it is possible to use the "old" equations for the calculation of construction time, provided by Peer and Selinger (1972), which define the basic construction time (T_b) as follows:

$$T_\mathrm{b} = k(m+n-1) + \sum_{i=1}^{n} t_i \quad (1)$$

m = number of sections; n = number of production lines; and t_i = waiting interval after line i, dictated by the production process.

Equation (1) is very similar to Equation (2) for calculation of the total project time in LSM, presented by Radujkovic (2012), wherein the variables are depicted using plain and simple graphical representation (Figure 3) and therefore are easy to comprehend.

$$T_\mathrm{t} = t_\mathrm{p} + \sum_{1}^{n-1} y + (m \times v_\mathrm{n}) \quad (2)$$

T_t = total time; t_p = preparation time; y = buffer time between two adjacent activities; m = number of location units; v_n = production rate; $m \times v_n$ = duration of the last activity; and n = number of activities.

Examining Equation (2), the total project time is calculated as a sum of preparation time, buffer time between activities (e.g., y_1 is the buffer between activities A1 and A2), and the duration of the last activity. Time and work (or distance) buffers indicate the required time lag between

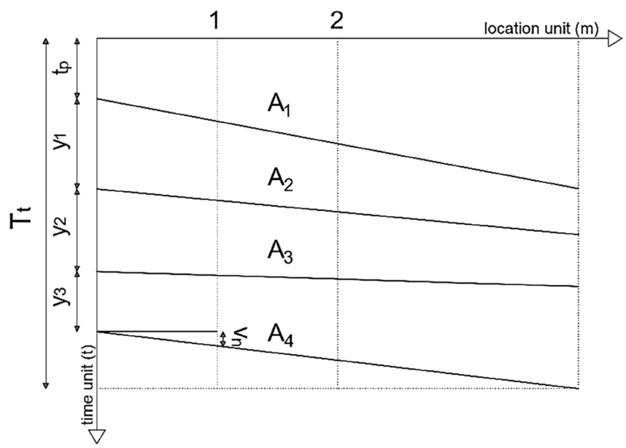

Fig. 3: Graphical representation of the equation of total project time in LSM for continuous full-span activities.
Source: Radujkovic (2012).

activities, which ensures the continuity of work (Kolhe et al., 2014; Su and Lucko, 2015). The placement of buffers in time–location diagrams (e.g., on activity start and finish) is dependent on the slope of every two adjacent activities (Ammar, 2013; Lucko and Gattei, 2016), and the slope of the activity is proportional to the activity's production rate. Time buffer can be simply added on the y-axis, while work buffers can be achieved by converting it into a time buffer via the LSM slope (Su and Lucko, 2015). If two activities are linked with both a minimum time and a minimum distance constraint in that situation, one of them would prevail and set the determinant buffer between them (Kallantzis and Lambropoulos, 2004a), meaning that in the time–distance diagram, buffer can always be added on the y-axis in the form of time buffer.

As already elaborated, to achieve viable duration in situations of converging activities (i.e., activities A2 and A3 in Figure 3), buffer time (i.e., y_2) should be placed at the end of the predecessor activity where two activities are closest in terms of time and location (Lucko, 2008; Ammar, 2013). With reference to Figure 3 and Equation (2), the buffer time y is placed on the start of each consecutive activity (y_1, y_2, and y_3 in Figure 3). Thus, to use Equation (2) in its current form, it is necessary to develop a detailed time–location diagram and refine it through several steps to derive viable buffers (y) between the start of each pair of consecutive activities and then to read the value of buffers (y) from the y-axis. Equation (2) is simple, related to production variables, and could provide the much-needed alternative method for time estimation, but in this form, it cannot provide reliable and rapid time estimation.

The question then is how to determine a set of continuous full-span linear activities and buffers between each pair of adjacent activities without the need for developing detailed graphical linear schedules? Is it possible to develop a mathematical expression to remove the need for developing the time–location diagram? In other words, the question is how to exploit the benefits of LSM for time estimation in a project's front-end phase?

2.5 Research justification

Front-end planning is an underresearched discipline in literature, and early time estimation is part of front-end planning. Shortage of early time estimation models is especially present for linear infrastructure projects such as pipelines and roads. In the project front-end phase, little information is known, and the estimated project cost is one of them. Early estimated cost is part of almost every early time estimation model. Usually, the early estimated cost significantly differs from the cost at the end of the project; thus, cost is not a very reliable parameter for time estimation. Alternative models for time estimation can be more reliable, but they require specific knowledge and software. Existing scheduling methods (i.e., LSM or PSM) and the accompanying means to determine project duration are too lengthy or too complex to be used for quick estimation in the project front-end phase. Therefore, the gap of scarce early time estimation models and unreliable time estimation is evident. To fully exploit LSM for early time estimation, some of its aspects described in the previous section should be examined in more depth. Goal is to enable the usage of existing simple LSM-based equation without the need of graphical aid (i.e., time–location diagram). The production point of view that is supported by this new method could lead to much-needed improvement in early time estimation.

3 Methodology – method development through case study approach

In this section, we will present the methodology containing several steps, which resulted in the development of the new method for early time estimation of linear projects. A case study approach is chosen because the purpose is to examine the LSM in detail and further develop LSM-related equation for the project duration. The goal is to extract specific elements from a known scheduling method, and the case study method is appropriate when the goal is to examine some phenomenon in detail. This case study is done on one large sewage system, organized in lots (Figure 4), each lot containing several pipelines. Pipelines are considered a linear project, determined mainly by linear activities. Analyzing the works in technical documentation, for the development of the method, one pipeline that represents the most complex situation in the whole sewage system (e.g., highest number of different linear activities) is selected. The method is thus suitable for all other, less-complex pipeline projects. After the method was developed on one pipeline project, we verified it on another pipeline, thus showing how the use the method.

3.1 Step 1 – sewer system analysis and selection of representative project

The sewage system examined in the paper is classified as a separate sewer system. In a separate sewer system, the sanitary wastewater from the household and the wastewater of service-industrial zones are drained by fecal sewage, while the precipitation water is drained by the presewerage system, which is partially built. The sewer system that was studied consists of three lots. Lot 1 contains nine projects; Lot 2 has seven projects, and Lot 3 has six projects. Technical description, bill of quantity, and drafts are given for all projects. After a thorough research of each pipeline project, the most complex one has been identified and taken into further consideration for method development. The representative project that was chosen included all types of work and related activities that were seen in the technical documentation of all other pipeline projects.

3.2 Step 2 – detailed linear schedule based on several linear continuous activities

For this project, several linear continuous activities were derived from technical documentation, and the average production rates were determined for each activity. These activities are used for the development of the detailed LSM schedule. These activities are roughly predictive for the total project duration because they present the majority of the work. Some minor and less time-consuming activities were not considered. The activities were sequenced in the order in which they are typically performed. By using the software TILOS, a basic linear schedule was planned.

3.3 Step 3 – identifying important elements for development of algorithm based on LSM-related equation

In the process of schedule optimization, the developed linear schedule (e.g., time–location diagram) was thoroughly analyzed. Three possible relations between a pair of two adjacent activities in the time–location diagram were found and classified. The slope of the activity in the time–location diagram is proportional to its production rate, and based on the relation of the production rates of two activities, these different relations occur. The related mathematical expressions for buffer y for each of the three identified situations are presented in Figure 5 and Table 3.

3.4 Step 4 – developing the algorithm and the method for time-based estimation of linear construction project

Based on the mathematical expressions derived for buffer y, the algorithm for determination of the buffer value between two adjacent linear activities is developed. When this newly developed algorithm is placed in the existing equation for total project duration (Equation (2)), the final equation (Equation (6)) for determination of the linear project construction time is derived. This equation is an extension of the existing equation for calculation of the project duration (Equation (2)), which is based on the buffer y and the duration of the last activity. This new equation, along with the initial steps of determining several major linear activities and their related production variables, constitute a new method for early time-based estimation.

3.5 Step 5 – verification of the newly developed method

We used the developed method on another pipeline project situated in a different lot from the same sewer system for which we first extracted several major linear activities along with their quantities of work. We added the same average production rates as we did for the first pipeline. Then, we determined the activity buffers using the new algorithm and related equations and we rapidly calculated the project duration. The project duration that was read from the detailed time–location diagram made for this pipeline was the same as that calculated with our early time-based estimation algorithm, showing that this new method can work as a means of rapid early time estimation.

4 Developing a method for calculation of total construction time

4.1 The set of leading activities as main construction time-related characteristic of project

Based on the location, the terrain condition, the quantities of work derived from technical documentation, and the presumed average machinery production rate, all major linear activities are determined. Some minor, non-time-consuming and partial-span activities are excluded, and thus, the set of linear full-span continuous activities is determined.

The major activities of the representative project are as follows:

1. Pulverizing and grinding of existing roadway
2. Mechanical excavation
3. Manual excavation
4. Replacement of low foundation material
5. Planning and compacting/trimming, leveling, and grading the landfill base
6. Spreading filter pedestrian finishing base
7. Installation of manholes
8. Lowering pipe into trench
9. Spreading filtered, single-sized, rounded gravel as a protection dam above the pipes
10. Backfill
11. Embankment – road compacting
12. Base pavement – base course layer
13. Surface pavement – binder and wearing course

4.2 Developing a detailed linear schedule with linear continuous activities

Since sewer projects typify manholes (physically breaking the project into spreads), they were used as stations (work units), whereby the quantity would be distributed. By using the linear interpolation method, distribution of the quantities of work (Q) was carried out through project stations for each type of work, i.e., each major activity. The result is that all activities are converted to continuous full-span activities, and thus, the locations are reduced to only one linear location (work unit) covering the whole length of the pipeline project. The method used to draft the time–location diagram was the LSM, in which the linear continuous activities are represented with one straight line and their slope denotes the activity's unit production rate. Every activity was manually planned (e.g., composition of the work group was set, and their average resource production rates were assigned), and their duration was calculated. Thus, the duration for every activity was calculated from the quantity and average work group (resource) production rate, as shown in the following equation.

$$T_a = \frac{Q}{U_p \times n} \tag{3}$$

where Q is the quantity of material, divided by the number of work groups n, and U_p, the production rate of one work group per day (i.e., cubic meters per day: m^3/day). In this paper, the focus is on how to rapidly produce the time estimation of project duration with continuous full-span activities and their related variables, which are derived from available technical documentation.

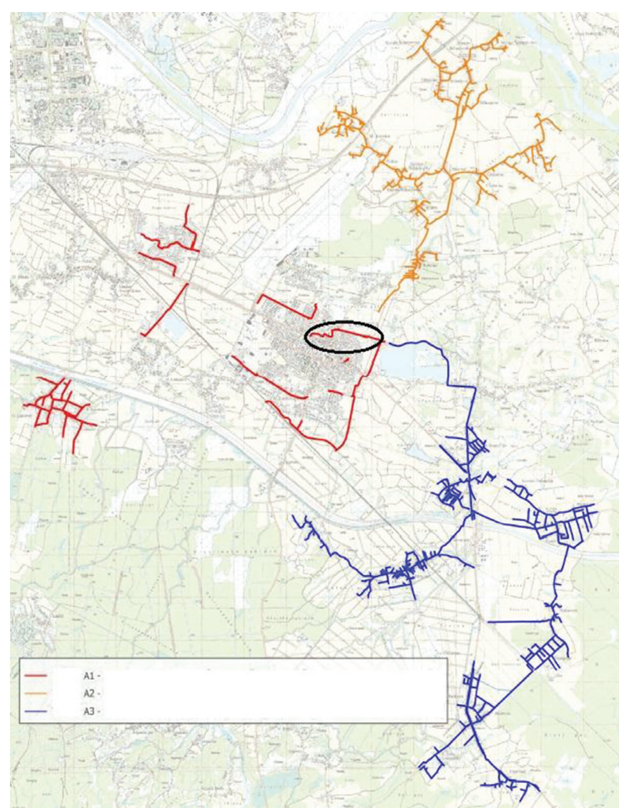

Fig. 4: Representative pipeline project from the analyzed sewer system.
Source: project technical documentation

4.3 Identifying possible types of task links and optimizing the linear schedule

After following hard sequence logic for making the initial detailed schedule, a first version of the project masterplan was created. For more realistic project duration, optimization of the schedule must be carried out. A chance for shortening the duration was observed (the commencement of certain activities can be placed earlier) by applying buffers between the starts or the ends of adjacent activities (i.e., same as using the start–start or finish–finish type of link in the CPM plan).

Depending on the production rate between activities (e.g., relationship between slopes of two adjacent activities in the time–location diagram), a minimum time lag k of 1 day was placed between every two adjacent activities. Time lag k is set either at the start of the predecessor activity if the production rate of the successor activity is smaller or the same as the predecessor's (i.e., Situations 1 and 2, where the lines diverge in the time–location diagram) or at the end of the predecessor activity if the production rate of the successor activity is greater than the predecessor's (i.e., Situation 3, where the lines converge in the time–location diagram). The result is that every activity has a time lag k set on the point where adjacent activities are the closest in terms of time and place. The goal of placing the buffer is to prevent overlap between activities and to make a realistic masterplan. It is necessary to highlight the fact that the minimum time lag k represents both time and distance buffers (distance buffer, if it exists, can be converted to time buffer via slope).

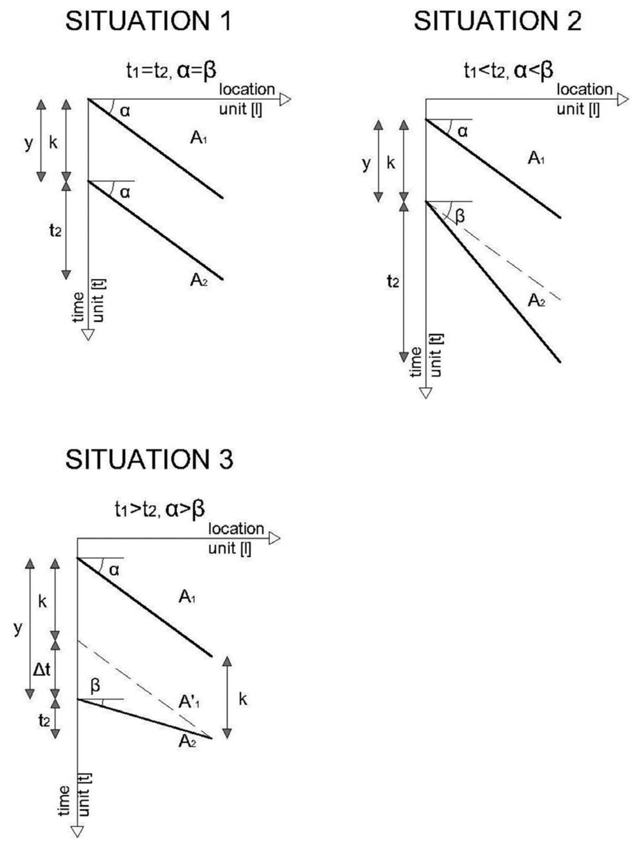

Fig. 5: Task links and the three possible variations between two activities.

$$\alpha = \tan^{-1}\left(\frac{\frac{\Delta Q}{U_p}}{\Delta l}\right), \tag{4}$$

4.4 Defining the key LSM-related equations

The main issue in using the existing LSM-related Equation (2) in early time estimation is the problem of determination of the value of buffer y without a fully developed graphical schedule (e.g., time–location diagram). Buffer y is presented in Equation (2) and Figure 3 as the lag between the start points of adjacent activities. To derive the relation to the existing Equation (2) for the project duration, different relations between pairs of adjacent activities and the related buffer y are mathematically formalized (Table 2) as if the buffers are always set at the activity start. We have shown in Figure 5 that for determination of buffer y, it is necessary to consider the relationship between the slopes of the pair of adjacent activities. We determined the equation for calculation of the slope of that activity in LSM which is represented as the angle between the activity and the x-axis (e.g., slope of the activity):

where ΔQ represents the quantity, U_p is the production rate of the activity per day (i.e., m^3/day), and Δl is the station length for which the activity will be executed (e.g., length of the whole pipeline).

For the three situations explained in the previous section and portrayed in the time–location diagram (Figure 5), equations are developed (Table 2) for the duration of adjacent activities and for buffer y, which consists of two separate parts. Part k is the minimum time lag, which must be set to the start or the finish of the preceding activity and part Δt represents the residual part of activity buffer y, which is the consequence of the finish-to-finish link (i.e., Figure 5, Situation 3). Thus, buffer y is either the same as the minimum time lag k (Situations 1 and 2 in Figure 5) or it is determined as the sum of the minimum time lag k and the residual time ΔT (Situation 3 in Figure 5). With the expressions provided in Table 2, it is possible to amend Equation (2) for calculation of the project duration.

Tab. 2: The equations for calculation of time buffer and duration of two adjacent activities

Situation 1. $\alpha = \beta$ Production rate: tasks A1 and A2 are equal. Recommended task link: Start– Start (S–S) Total duration: $T = k + t(A_2)$ Time buffer: $y = k$	Situation 2. $\alpha < \beta$ Production rate: task A1 is faster than task A2. Recommended task link: Start– Start (S–S) Total duration: $T = k + t(A_2)$ Time buffer: $y = k$
Situation 3. $\alpha > \beta$ Production rate: task A2 is faster than task A1. Recommended task link: Finish– Finish (F–F) Total duration: $T = k + t(A_1) - t(A_2) + t(A_2)$ Time buffer: $y = k + \Delta t = k + t(A_1) - t(A_2)$	

4.5 Developing the algorithm for the total time of a linear construction project – key elements of the developed method

If buffer y can be provided in the form of a mathematical expression that could derive the realistic value of buffer y (e.g., the same value as in the optimized time–location diagram), it is possible to amend Equation (2) and thus calculate the total project duration without the need to graphically develop the time–location diagram. By adding the developed mathematical expression (Table 2) in the existing Equation (2), the result is a newly developed algorithm for the determination of time buffer y and the total project duration:

$$T_t = t_p + \sum_{1}^{n-1} y + t_n \qquad (6)$$

where t_p = preparation time; T_t = total time; t_n = duration of the last activity; and Sy represents the sum of all buffers.

Buffer y is determined by the following conditions:

$$\alpha \le \beta \Rightarrow y = k; \qquad (6.1)$$

$$\alpha > \beta \Rightarrow y = k + \Delta t = k + t_1 - t_2 = k + \frac{Q_1}{U_{p1}} - \frac{Q_2}{U_{p2}}; \qquad (6.2)$$

$$\alpha = \tan^{-1}\left(\frac{\Delta Q_1}{\frac{U_{p1}}{\Delta l}}\right); \ \beta = \tan^{-1}\left(\frac{\Delta Q_2}{\frac{U_{p2}}{\Delta l}}\right) \text{on location } \Delta l. \qquad (6.3)$$

α = production rate (slope) of the predecessor activity; β = production rate (slope) of the successor activity; and k = minimum time lag.

This new algorithm (Equation (6)) provides the means to determine the activity's buffer time based on the slope relations of two adjacent activities, meaning that we first need to determine the slopes α,β for each adjacent activity using Equation (6.3). Then, by comparing each pair of adjacent activities using Equations (6.1) and (6.2), all the buffers y are determined. The last step is to insert the values of the buffers and the duration of the last activity. This algorithm provides the means to determine the construction time for linear projects with continuous full-span activities without the need to develop a detailed graphical LSM time–location diagram.

4.6 Application of the new method for calculation of the construction time of a linear project

For every activity of the observed pipeline, the quantity of work Q, the average production rate Up, and the work unit Δl (e.g., station length) are determined from the existing project documentation. Based on these three variables, the slopes α,β can be calculated using Equation (6.3). Depending on which pair of adjacent activities we observe, the activity slope is observed as preceding or succeeding except for the fixed first and the last activities.

$$\alpha_1 = \tan^{-1}\left(\frac{\Delta Q_1}{\frac{U_{p1}}{\Delta l}}\right) = \tan^{-1}\left(\frac{2662.807}{\frac{292.08}{920}}\right) = \tan^{-1}\ (0.009909) = 0{,}568°$$

$$\beta_1 = \alpha_2 = \tan^{-1}\left(\frac{\Delta Q_2}{\frac{U_{p2}}{\Delta l}}\right) = \tan^{-1}\left(\frac{2949.962}{\frac{669.76}{920}}\right) = \tan^{-1}(0.004787) = 0{,}274°$$

$$\beta_2 = \alpha_3 = \tan^{-1}\left(\frac{\Delta Q_3}{\frac{U_{p3}}{\Delta l}}\right) = \tan^{-1}\left(\frac{737.49}{\frac{669.76}{920}}\right) = \tan^{-1}(0.001199) = 0{,}069°$$

Having determined all the activity slopes, we can use Equations (6.1) and (6.2) to determine all the buffers y and then use Equation (6) to calculate the construction time of the linear project. Here, we present the calculation for our observed representative linear project:

$$T_t = y_1 + y_2 + y_3 + y_4 + y_5 + y_6 + y_7 + y_8 + y_9 + y_{10} + y_{11} + y_{12} + t_{13}$$

$$\begin{aligned} T_t = &\left(k + t_{cut} - t_{Mechanical}\right) + \left(k + t_{Mechanical} - t_{Manual}\right) \\ &+ \left(k + t_{Manual} - t_{Replacement}\right) + k \\ &+ \left(k + t_{Trimming} - t_{Spreading\ filter}\right) + k + k + k \\ &+ \left(k + t_{Lower\ pipe} - t_{Spreading\ gravel}\right) + k \\ &+ \left(k + t_{Backfill} - t_{Embankment}\right) + k + t_{Surface} \end{aligned}$$

$$\begin{aligned} T_t = &\left(k + \frac{\Delta Q_{Cut}}{U_{p\text{-}Cut}} - \frac{\Delta Q_{Mechanical}}{U_{p\text{-}Mechanical}}\right) + \left(k + \frac{\Delta Q_{Mechanical}}{U_{p\text{-}Mechanical}} - \frac{\Delta Q_{Manual}}{U_{p\text{-}Manual}}\right) \\ &+ \left(k + \frac{\Delta Q_{Manual}}{U_{p\text{-}Manual}} - \frac{\Delta Q_{Replacement}}{U_{p\text{-}Replacement}}\right) + k \\ &+ \left(k + \frac{\Delta Q_{Trimming}}{U_{p\text{-}Trimming}} - \frac{\Delta Q_{Spreading\ filter}}{U_{p\text{-}Spreading\ filter}}\right) + k + k \\ &+ k + \left(k + \frac{\Delta Q_{Lower\ pipe}}{U_{p\text{-}Lower\ pipe}} - \frac{\Delta Q_{Spreading\ gravel}}{U_{p\text{-}Spreading\ gravel}}\right) + k \\ &+ \left(k + \frac{\Delta Q_{Backfill}}{U_{p\text{-}Backfill}} - \frac{\Delta Q_{Embankment}}{U_{p\text{-}Embankment}}\right) + k + \frac{\Delta Q_{Surface}}{U_{p\text{-}Surface}} \end{aligned}$$

$$\begin{aligned} T_t = &\left(1+10-5\right)+\left(1+5-2\right)+\left(0+2-1\right)+1+\left(+1+1-1\right)+1 \\ &+1+1+\left(1+24-2\right)+1+\left(1+3-1\right)+1+3 = 46 \text{ days} \end{aligned}$$

Organization of the relevant variables related to linear activities can be done in the form of a table (Table 3).

The project duration of this representative project was the same as that read from the *y*-axis of the optimized final LSM schedule (e.g., time–location diagram).

4.7 Verification of the developed method

This newly developed method consists of four steps; the first is the determination of several linear activities; the second step is to distribute the quantities of work through each station (i.e., make all activities continuous) and calculate the production-related variables (i.e., slope of activity) for every activity; third is the determination of buffer *y* for every pair of adjacent activities based on the developed algorithm; and the fourth step is calculation of the project duration based on the equation for total project duration. These four steps are purely mathematical and can be done in the project front-end phase based on little available information. For the purpose of verification of this method, we chose another pipeline project from the same sewer system and we assumed the same working groups with the same production rates. For this project too, we determined the linear activities, which were the same as in our first observed pipeline. As we stated earlier, we chose the most complex pipeline project as the representative to enable other projects (i.e.,

Tab. 3: Linear continuous activities of the analyzed pipeline project and their related variables

	Leading activities	First three variables determined from technical documentation							
		ΔQ	**U_p**	**Δl**	**α, β ($\tan^{-1}$)**	**t_n (days)**	**Task link**	**k**	**y**
1	Pulverizing and grinding of existing roadway asphalt or concrete curtain	2662.807	292.08	920	0.009909	10	F-F	1	**6**
2	Mechanical excavation	2949.962	669.76	920	0.004787	5	F-F	1	**4**
3	Manual excavation	737.49	669.76	920	0.001199	2	F-F	0	**1**
4	Replacement of low foundation material	474.896	878.40	920	0.000588	1	S-S	1	**1**
5	Trimming, leveling, and grading of the landfill base	1637.047	2927.9	920	0.000608	1	F-F	1	**1**
6	Spreading filter pedestrian finishing base	248.39	878.40	920	0.00030	1	S-S	1	**1**
7	Installation of manholes	47	2.00	920	0.012771	24	S-S	0	**0**
8	Lowering of pipe into trench	849.38	36.40	920	0.025358	24	F-F	1	**23**
9	Spreading rounded gravel above the pipes	1273.79	878.40	920	0.001576	2	S-S	1	**1**
10	Backfill	2815.45	1152.9	920	0.002654	3	F-F	1	**3**
11	Embankment- road compacting	941.31	1112.6	920	0.000920	1	S-S	1	**1**
12	Base pavement- base course layer	2344.797	1145.4	920	0.002225	3	S-S	1	**1**
13	Surface pavement- binder and wearing course	2344.797	1145.4	920	0.002225	**3**			
							Total time		**46d**

this project) to use the same linear activities to rapidly make time-based estimation for every other project. In Table 4, all the variables are calculated for this second pipeline project.

Verification of the developed method with this second pipeline project clearly portrays the usefulness of the developed method, which is a relatively easy and rapid way for early estimation of the construction time of a linear project in the project front-end phases.

5 Discussion

This new method requires few simple steps to provide total project duration and, compared to existing scheduling methods, requires less effort to obtain the project duration, which can be seen from the comparison given in Table 5.

It is easy to transform "repetitive" activities (activities spreading through several work units) into simpler linear continuous full-span activities with LSM because LSM uses a continuous measure of the work product (Lucko and Gattei, 2016). On the other side this transformation is more complicated with LOB method because there are six different LOB equations required to transform one "repetitive" activity into one overlapping (e.g. continuous) activity which can be seen in first step of LOB-CPM method (Ammar, 2013). Ammar (2013) presented overlapping activities that do not fully adhere to LOB logic (e.g., a simplified LOB diagram is made), and this makes Steps 2 and 3 of the LOB-CPM approach similar to Steps 2 and 3 in the new method presented in this paper. The buffer time in the LOB-CPM approach is placed at the activity start or end (Ammar, 2013), similar to the minimum time lag k being placed in the new LSM-based method. It is clear that some similarities exist between the integrated LOB-CPM approach and the new method for early time estimations, but it is obvious that this new LSM-based method is simpler and requires less effort to provide several activities and buffers.

The new method for early time estimation presented in this paper relies on simple equations to calculate the project duration, along with an algorithm to determine buffer y, and it is suited for a simplified masterplan, wherein activities have one predecessor and one successor. The integrated LOB-CPM approach (Ammar, 2013) works with activities of multiple predecessors and successors and requires a compatible CPM network to be made, and based on this network, the CPM analysis is conducted. This requires additional time and effort. On the other side, the PSM provided by Lucko (2007, 2008) is based on singularity functions and requires a set of equations for each of the seven steps. The PSM is robust and can solve complex scheduling problems which occurs when time-location diagram contain activities with varying production rates and multiple predecessors and successors (Lucko, 2008). However, PSM method requires additional effort because it needs multiple steps and multiple singularity functions to provide project duration even for simple schedules. The method presented in this paper is tailored to produce the total project duration for a simplified masterplan and is thus tailored for early time estimation, while the existing PSM (Lucko, 2007) and integrated LOB-CPM (2013) approaches are more robust and suitable for detailed scheduling and criticality analysis.

Tab. 4: Leading activities and their related variables of another pipeline project from the same sewer system

	Leading activities	ΔQ	U_p	Δl	α, β (tan^{-1})	t_a (days)	Task link	k	y
1	Pulverizing and grinding of existing roadway asphalt or concrete curtain	4500	292.08	2113	0.0073	16	F-F	1	**8**
2	Mechanical excavation	5653.52	669.76	2113	0.0040	9	F-F	1	**7**
3	Manual excavation	1413.38	669.76	2113	0.0010	3	F-F	0	**2**
4	Replacement of low foundation material	559.98	878.40	2113	0.0003	1	S-S	1	**1**
5	Trimming, leveling, and grading the landfill base	1610	2927.9	2113	0.0003	1	S-S	1	**1**
6	Spreading filter pedestrian finishing base	209	878.40	2113	0.0001	1	S-S	1	**1**
7	Installation of manholes	133	2.00	2113	0.0197	42	S-S	0	**0**
8	Lowering pipe into trench	2113.6	36.40	2113	0.0275	59	F-F	1	**58**
9	Spreading rounded gravel above the pipes	1071.1296	878.40	2113	0.0006	2	S-S	1	**1**
10	Backfill	2480	1152.9	2113	0.0010	3	F-F	1	**2**
11	Embankment- road compacting	2080	1112.6	2113	0.0009	2	S-S	1	**1**
12	Base pavement- base course layer	5195	1145.4	2113	0.0021	5	S-S	1	**1**
13	Surface pavement-binder and wearing course	5195	1145.4	2113	0.0021	**5**			
						Total time: **88 days**			

Tab. 5: Comparison of the new LSM-based method for time estimation with the two existing methods

Integrated CPM–LOB model (Ammar, 2013)	PSM (Lucko, 2007, 2008)	LSM-based method for early time estimation
1) *LOB calculations* This step consists of (at least) four (sub)steps. First is to draw a unit network (of repetitive activities for single work unit); second is to estimate the crew size for each activity; third is to establish a target rate of output (this (sub)step can be further divided into smaller steps); fourth is to derive the LOB diagram.	1) *Initial equations* The execution of PSM starts with describing all activities in the Macaulay bracket notation (e.g., singularity functions). However, no links are considered for the initial equations (one equation for each activity).	1) *Activity list* Based on available technical documentation, devise the list of linear activities of the projects, along with their parameters of work quantity and work group productivity (average). Work quantity is spread through work units using linear interpolation to make every activity continuous. Their sequence must be established unambiguously.
2) *Calculating activity duration* Overlapping activities are generalized to represent repetitive activities. For this generalization to be possible, the duration is assumed constant in all units of a repetitive activity.	2) *Buffer equations* In the second step, the singularity functions for buffers are set up (one equation for each buffer).	2) *Calculating activity durations and slopes* Calculate durations and unit production rates (e.g., slopes) for every linear continuous activity.
3) *Specifying logical relationships using overlapping activities (buffer time)* To specify relationships, the actual progress rate of each activity is compared with that of its successors. Three scenarios can be encountered: diverging, converging, and parallel activities. Based on the scenario, the buffer time is placed on the first or the last unit.	3) *Initial stacking* In the third step, the initial activity and buffer equations are stacked up in the order of precedence with the set of singularity functions (one equation for each activity).	3) *Using the newly developed algorithm for determination of buffers between activities* Pair of activities can converge, can diverge, or be parallel depending on the relation of production rates of two adjacent activities. Depending on this relation, the equation for every buffer y is determined, and calculation of the buffer is performed.
4) *Time scheduling* 1. Forward pass – the early timings (belong to the first and last units only) are determined for each activity. 2. Backward pass – the late timings (belong to the first and last units only) are determined for each activity.	4) *Minimum differences* In the fourth step, the differences between neighboring predecessor buffer equations and successor equations are taken and the minima of these difference equations are determined across all positive values of x (one equation for each activity–buffer link).	4) *Using the newly developed algorithm for calculation of project duration* Based on the determined buffer times, the project duration is calculated as the sum of the buffers and the duration of the last activity.
5) *Criticality analysis*	5) *Differentiation* Differences are differentiated using equations to confirm the nature of the vertices (set of equations)	
	6) *Final consolidation* In the sixth step, the vertex distances between a neighboring predecessor buffer equation and successor equation are compared to identify the overall minimum distance (set of equations).	
	7) *Criticality analysis* The equivalent of a critical path from CPM is calculated (set of equations).	

6 Conclusion, limitations, and practical implications

In this paper, we have presented the problem of construction time overruns and its relation to early time estimation. We analyzed the state of early time estimation models, and we found a few models with low usefulness, especially for linear projects with continuous linear activities. We described the state of the art of project planning and scheduling of projects with continuous full-span activities, such as roads and pipelines. The LSM was found to be the most useful for planning these types of projects. To be able to exploit the benefits of LSM for time estimation in project front-end phases, we developed a new method. We explained the process of method development and how it can be used. With this method, there is no need to develop a graphical linear schedule, and the result of construction time obtained using this method is the same as the duration provided by the developed LSM time–location diagram.

The first limitation of the presented method is that it can serve only for base estimation because it includes only major construction activities without adding risk and uncertainties in the estimation process. The accuracy of time-based estimation is not tested, since the method has not yet been used for early time estimation on real projects. Despite these limitations, this method can help practitioners and scholars to easily determine the duration of a linear project and to relate the project quantities of work and the average production rates of work groups with the total project duration. In the process of verification, we showed that this method enables rapid early time-based estimation of linear projects. Different variants of work groups and their production rates can be tested in a simple manner and, thus, this method can contribute to construction project management-related tasks, e.g., controlling the speed of contractor works during onsite activities, and equipment utilization versus contract plan. The algorithm and the method developed in this paper represent a basis for creating a base estimation model for early time estimation of linear projects oriented on a set of activities. For further development of the model, risks will be included to improve its accuracy and enable more reliable early time estimation.

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