A Proposed Curriculum for Teaching the Tri-Constraint Method of Generative Construction Scheduling

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Abstract –

Typical construction project management and production management courses teach the critical path method, in which only the precedence constraint is considered while scheduling activities. By contrast, the tri-constraint method is an object-based scheduling method that considers activity precedence, resource constraints, and spatial availability. However, the tri-constraint method is only taught at few universities to date. This paper outlines the creation of a new curriculum to teach the theory and application of the tri-constraint method. The paper describes a proposed five-lesson, flipped-classroom curriculum for teaching the tri-constraint method. In class one, we introduce students to the limitations of the critical path method. In class two, we teach the fundamental algorithm behind the tri-constraint method. In classes three to five, we demonstrate how the tri-constraint method can be scaled using a BIM-based smart scheduler, in partnership with the software company ALICE Technologies Inc. During this period, students learn how to model constraints, generate millions of schedules, and explore tradeoffs and interventions for further schedule optimization. The paper concludes by describing how the curriculum was implemented in Autumn Semester 2020, summarizing preliminary qualitative feedback from the students, and reflecting on future improvements. The proposed curriculum is now available for usage or adaptation by the broader construction informatics research community to be integrated into construction project and production management courses.

Keywords –

Education; Generative construction scheduling; Tri-constraint method; Critical path method; Automation

1 Introduction

Creating a schedule is one of the most important steps in the planning phase of a construction project: in the planning phase it shows the scope of the work, enables coordination of all project participants and is the basis for estimating costs and the duration of the project; in the execution phase it provides information on when, by whom and by when the work must be carried out, but also enables monitoring of the projects' progress. Moreover, it is often used for contractual matters, for example as a basis for claiming liquidated damages in case of delays.

To develop these schedules, most construction management programs teach students the critical path method (CPM). CPM was developed in the 1950s [1], [2] and has been widely accepted due to its applications in planning, scheduling, and control [3]. Scholars found that by the early 2000's, CPM was used to produce 80% of all construction schedules [4]. It is the most common scheduling approach in the United States [5] and the United Kingdom [6] for planning and controlling construction projects [7]. In a survey of Engineering News Record Top 400 Contractors, 98.5% of the participating companies used CPM in their projects [8]

However, scholars increasingly note the limitations of CPM for production management in construction. Today, schedules are developed without considering the resources systematically while scheduling. Afterwards, a resource levelling process is performed to prevent an over-allocation of resources. The new distribution in turn affects the previous schedule, which must then be adjusted again, making the process of creating a reliable schedule an iterative task. Furthermore, CPM often does not take advantage of digital technologies such as Building Information Modelling. For example, 4D BIM does not automatically generate the sequence of production but instead acts as a visualization or check of the proposed CPM sequences. The four most relevant limitations can be summarized as 1) initial reliance on assumption of unlimited resources, 2) no consideration of spatial or location-based constraints, 3) lack of automation, and 4) lack of dynamic change process (i.e. changes require many laborious steps). Due to space limitations, we refer readers to Dallasega et al. [3] for a comprehensive summary of CPM limitations.

One emerging alternative to CPM is the Tri-Constraint Method (TCM) [9], [10]. In TCM, precedence, resource availability and spatial constraints are operationalized into the following formal scheduling constraints: precedence, discrete resource capacity and disjunctive constraints. This allows TCM to systematically consider precedence, resource and spatial constraints when scheduling activities. As a result, scheduling no longer requires an iterative process to consider resources. By combining the mechanisms that resolve the constraints with mechanisms that vary the feasible sequences of activities, TCM is able to loop through a predefined algorithm and create multiple feasible schedules. In doing so, it allows the selection of the most optimal of all feasible schedules for a given project [9]. The systematic consideration of resources right from the start makes the scheduling process more structured and transparent and facilitates automation. With powerful computers, numerous reliable schedules can now be created and compared in less time.

One application to apply the TCM is already on the market. ALICE, a cloud-based scheduling software, uses TCM for the generation of schedules. When uploading a BIM model, the software automatically determines the precedence relationship between the elements. Then, each element can be assigned a recipe that describes the sequence of activities to create the element. Each activity can then be assigned resources (labor, material, equipment) and productivity rates or durations. The software then automatically generates multiple schedules that can be compared and analyzed. By parameterizing using production rates and the BIM model, changes to schedules or resources can be quickly incorporated into a new schedule.

However, a corresponding change in how construction management (CM) programs teach construction scheduling has not followed. CM classes can be reluctant to integrate these new approaches into their curricula for various reasons. First, new methods such as TCM and new software such as ALICE may have only recently attracted the interest of industry and the academic world lacks broad expertise in these areas [11]. There may be fear of teaching a new method that might not ultimately be successful. Finally, and most importantly, CM programs often are not able to make room for new content in existing curricula because they already have a tight timetable and also do not have sufficient time and resources to create a new curriculum [12].

It is important that CM programs do not fall behind industry implementations. CM curricula has an important role to play in researching these new methods and technologies, demonstrating their applicability and their benefits for industry, and thus supporting and motivating industry to apply new methods. University education is also a good starting point to provide students, future employees of the industry, academic foundations and technical knowledge about different innovative approaches that may support or shape their future careers. Software companies can offer guides, tutorials, training materials and seminars on how to use their tools that are tailored for companies. However, these cannot be directly integrated into existing university curricula, as they focus on the practical application of their tools in the industry and can remain a “black box” to practitioners. There is need for teaching of the fundamental principles and theoretical knowledge behind such algorithms, alongside some practical introduction to software applications.

Based on the above, this paper proposes a 5-week curriculum for teaching the TCM within an existing CM course on construction scheduling. We created and implemented a 5-week curriculum that teaches the fundamentals and limitations of the CPM, the theoretical foundations of the TCM, and an introduction to the software ALICE for further exploration of how such theoretical foundations can be operationalized in practice. The objective of this paper is to share the basic learning objectives and course structure of the proposed curriculum, along with preliminary feedback from the first implementation of the curriculum in Autumn 2020. The long-term goal of this work is to share the curriculum for use and adaptation from the broader CM educational community. All course lessons, teaching notes, exercises and presentation templates are freely available online [13].

2 Departure and Approach

The Tri-Constraint Method (TCM) is a new generative planning method that is specially adapted to the conditions of BIM-based construction planning. It is applied in the form of an automated event simulator, using three fundamental constraints in the execution of a construction project to determine the sequence of activities and their start and end dates [9]. These constraints are mechanisms that prevent the execution of an activity at a given time [9]. The basic unit of work within the TCM are referred to as operations. An operation describes the work of a crew on a component of an element [9]. The three fundamental construction constraints of TCM are:

- Precedence constraints - relationships used to define logical links between activities, analogous to the traditional planning approach. They are not dependent on the current moment or current constraints and can be displayed using a graphical representation such as a network diagram [9]. An example of such a precedence constraint is the condition that foundations must be built before the overlying columns can be placed. If this restriction is violated during planning, physically unfeasible schedules will be created.

- Discrete resource capacity constraints - depend on the current point in time. They take into account the availability of discrete resources and therefore cannot be represented in a network diagram [9]. Discrete means in this case that these resources can be available in integer quantities greater than or equal to 1 [9]. Examples of such resources can be workers, tools or materials. If this restriction is violated during planning, resources may be over-allocated and operations may not take place as planned.
- Disjunctive spatial constraints - prevent operations from taking place at the same time and place. Disjunctive means that either one option or another option is chosen, but never both at the same time. To take this restriction into account in planning, TCM considers the available space as a unary resource. It therefore takes values between 0 (entire space occupied) and 1 (entire space not occupied) [9]. This restriction is therefore also dependent on the current time and cannot be represented using a network diagram. Examples are two otherwise independent activities taking place in the same place. If this restriction is violated, their workspaces will overlap. On the construction site, this could reduce the productivity and increase the probability of onsite accidents.

Based on these constraints, the actual schedule of the project is generated using a generative algorithm that can generate millions of scheduling sequences. This is based on the event simulator of Waugh, where operations are moved from a TODO list, via a CANDO and a DOING list to a DONE list by iterating over time. Due to space limitations, readers are referred to the work of Morkos [9] and Waugh [14] for detailed description and further discussion about the automated/generative scheduling algorithm.

To the knowledge of the authors and in conversation with ALICE technologies, the TCM is currently only taught at two universities – ETH Zurich and Stanford University. The first author had previously attempted to teach the TCM in 2018 and 2019 courses at ETH Zurich. Feedback was that these specific lessons were interesting and showed promise, but the unstructured nature of the assignments was difficult and hard to implement. Furthermore, the lead author wanted to go deeper into the theoretical exploration of how the TCM works instead of only practical applications. Due to practical constraints, the course only had a limited period of time to teach the TCM. Any proposed curriculum needed to be streamlined so that it could be effectively taught in a 5-week timeline. Furthermore, the course should engage with latest trends in pedagogy including the use of a flipped classroom for active and problem-based learning.

The overall approach to this work can be summarized as the development of a scalable project-based curriculum for CM courses that teaches the theory behind TCM and highlights its advantages over traditional planning methods. The aim is to ensure that a long-term learning effect is achieved among students. In addition to this theoretical perspective, the application in practice shall also be addressed. This is important in order to enable them to apply TCM in their upcoming professional life with the appropriate tools such as the ALICE software and thus to plan projects more successfully. The curriculum should be embedded in an existing management course in order to introduce students to the TCM method and its application with ALICE within a few weeks.

3 Proposed Curriculum

The developed curriculum has a total length of five lecture weeks with two lectures of 45 minutes each per week. On the one hand, this ensures that, from the perspective of the lecturers, there is sufficient time for teaching the contents. On the other hand, there is enough time for a spaced repetition of individual topics, and to review the topics in the context of assignments. Since the curriculum is closed in itself and only lasts about one third of the usual 14 weeks of lectures during a semester, it can easily be integrated into already existing courses at other universities.

The flipped classroom approach is used for the individual lessons. Therefore, each topic is introduced and deepened over three sessions: Pre-Class Homework, Lecture, Post-Class Homework. In the first Pre-Class Homework session, the new content is delivered through papers and videos. Afterwards, obligatory multiple choice and text questions ensure that the students have done their homework and come to the lecture with the basic understanding of the topic. The acquired knowledge is then deepened in class by repeating and discussing the new content and by doing in-class activities. Following the lecture, students work in groups on the Post-Class Assignments, where they are asked to solve more complex problems. The repetition of each new topic three times over a two-week period through different approaches is designed to ensure a long-term learning effect.

3.1 Lecture Plan and Learning Objectives

Table 1 gives an overview of the contents of the five lessons. These are divided into two blocks: Lectures 1 and 2 serve to impart theoretical knowledge. In the first lecture, the traditional planning method will be presented and in the second lecture TCM will be introduced. Lectures 3 to 5 focus on the practical application of TCM with ALICE. In these, both interactive demonstrations of ALICE by the teaching staff are given and the students work independently with the software. For the In-class activities, a simpler LEO 1 model is used to demonstrate features of ALICE and for the Post-class activities, a more complex LEO 2 model is used to show a more extensive and more relevant use of the software later in practice (see Figure 1).

Table 1. Summary of course structure and learning objectives.

No.	Lecture Title	Learning Objectives
1	Traditional Project Scheduling	• Understand the theory behind traditional scheduling • Apply traditional scheduling to a simple example • Describe the limitations of traditional scheduling
2	Tri-constraint Method	• Differentiate between planning and scheduling • Comprehend the effects of the 3 constraints on scheduling • Understand and apply the scheduling algorithm of TCM • Analyze benefits and drawbacks of TCM
3	Introduction to ALICE	• Implement basic features of ALICE (Plans, Models, Supports, Recipes, etc.) • Identify the association between ALICE and CPM • Create independently a non-resource-constrained schedule using ALICE
4	Modelling Constraints in ALICE	• Develop an ALICE model with consideration of the tri-constraints • Understand factors that influence the creation of schedules with TCM • Create feasible schedules with realistic activity durations. • Analyze and compare multiple schedules using ALICE
5	Optimization in ALICE	• Learn how to influence schedules and optimize them for a specific goal • Describe the advantages of parameterization and automation of scheduling using a tool such as ALICE.

In Lesson 1 (Traditional Project Scheduling), the objective is for students to understand and independently apply traditional planning methods in combination with CPM. This helps to ensure that all students have the same level of knowledge about planning methods currently used in practice, while independent application enables them to recognize and discuss the limitations of these methods.

In Lesson 2 (Tri Constraint Method), the students are introduced to the TCM without any advanced visualization technology (e.g. no BIM interface). Students are introduced to the influence of the three fundamental constraints on the schedule, the significance of the distinction between planning and scheduling, and the exact mechanisms of the scheduling algorithm. The advantages of TCM compared to the traditional methods are discussed.

In Lesson 3 (Introduction to ALICE), the students are introduced to the ALICE software. Here the students should learn the basics of the ALICE software, before the consideration of resources or the optimization of schedules is dealt with. The objective is therefore to explain how ALICE works and to enable students to enter required inputs themselves in order to create a basic schedule. The students are asked to build a simple schedule using the recipe function in the LEO I BIM. To achieve this simplification, this first schedule is based on priority relationships only (similar to how the CPM works) with no consideration of resources.

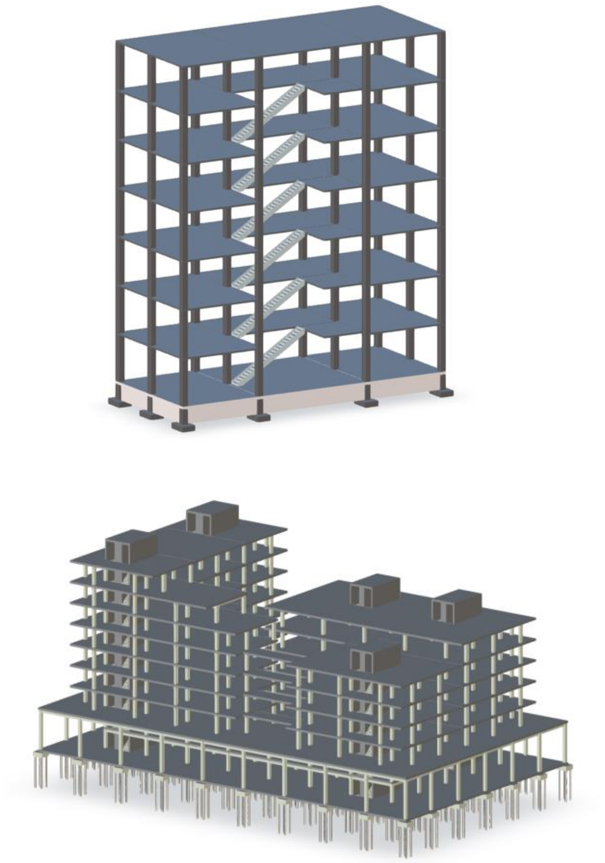

Figure 1. The LEO 1 (above) and LEO 2 (below) models used in the curriculum.

In Lesson 4 (Modelling Constraints in ALICE), students begin to explore more advanced possibilities to create schedules using ALICE software. Specifically, resource constraints are introduced when creating schedules with ALICE. Furthermore, students learn how to specify the duration of single activities parametrically using productivity rates and other element properties (e.g. volume, lateral surface) in ALICE. As a result, the students created a more constrained (and likely longer) schedule for the LEO 1 model according to TCM during this lecture. The reasons for the longer scheduling time are discussed with the class.

In Lesson 5 (Optimization in ALICE), the students begin to explore factors that have large influence on schedule duration. By adjusting the input parameters in ALICE, the students begin to develop intuition on how to optimize schedules in terms of duration, costs or use of resources. Especially the larger Post-Class model LEO II enables a thorough exploration of how optimization changes the overall schedule outputs.

4 Implementation and Assessment

Once the proposed curriculum was designed, the authors sought pre-implementation feedback to assess the quality of the curriculum. For pre-implementation assessment, the authors presented the curriculum in a video conference with three employees of ALICE Technologies Inc., including Dr. Rene Morkos the inventor of TCM and founder of the company. During the discussion, the general structure of the curriculum and the most important lecture contents were presented. The feedback positively emphasized that first a theoretical introduction should be given and then the software should be used first (M. Faloughi, personal communication, May 20, 2020). It had been a recurring problem with the ALICE training that some users had not internalized the theory behind TCM. With regard to the theoretical contents, almost everything important is included in the curriculum and the quantity is appropriate for the planned 5 weeks (R. Morkos, personal communication, May 20, 2020). One key feedback was that the limitation of sequencing with traditional methods should be dealt with more clearly (R. Morkos, personal communication, May 20, 2020). This was then included in the full course implementation.

The authors implemented the curriculum as part of the larger course Lean, Integrated and Digital Project Delivery at ETH Zurich in Autumn Semester of 2020. This is a 4-credit course (corresponds to 120 hours of workload for the total course) for graduate students that introduces students to newly emerging trends in the construction industry, such as Lean Principles, BIM, parametric scheduling and Integrated Project Delivery. Due to COVID-19 restrictions, the first lesson was presented in person while the following four lessons were presented via Zoom.

During implementation, the teaching team collected student feedback in order to conduct a post-assessment of retained learning. Three surveys were conducted before, during, and after teaching the curriculum to assess learning. Data from these surveys are currently under statistical analysis with the expectation they will be included in a future full-length journal paper. To further assess the student experience in learning the curriculum, the teaching team reviewed qualitative feedback obtained from the yearly course evaluation. These are summarized below:

- “The organization surrounding ALICE and the TCM was done pretty good”
- “For some tasks with ALICE more time would be nice during the lecture to better understand the tasks. It was sometimes a little of a rush”
- “The frequent guest presentations bring this course very close to the industry which I thought was also very good as most other courses in civil

engineering are too theoretical to really be able to see it in the perspective of the industry itself. For example, I really liked the use of ALICE as this is a software that is also used on construction sites and not just a tool used to instruct students."

- "I think explaining ALICE and the short exercises in class was really great and should be unchanged."

In addition, the general experience for students in the course was positive. For example, the evaluation question "how satisfied were you in general with the course unit?" received an average response of 4.7 (n = 28), where 5.0 is the highest possible score and represents that a student is "very satisfied" with the course. However, the curriculum for TCM only represented 5 out of 13 lectures in the overall course, so it is not possible to say if TCM is a primary cause of the strong student evaluations.

5 Discussion and Conclusion

Reflecting on the first implementation of the proposed curriculum, the following limitations were noted. The curriculum places high demands on the teacher to incorporate a flipped classroom approach into their teaching. Additionally, the hiring of teaching assistants will be necessary to support the classroom activities. The teaching staff has to prepare for the implementation of the curriculum, such as contacting ALICE, preparing the models, arranging the groups for group work, adapting the documents etc. Additional time and effort are required as ALICE is a software that is constantly evolving. Furthermore, the curriculum demands a collaboration with ALICE, so if a collaboration for any reason is not possible anymore, the curriculum cannot be successfully implemented without major modifications. However, ALICE Technologies Inc. has expressed a willingness to partner with universities in order to facilitate students learning about their generative construction scheduling approach.

A further structural limitation of the curriculum is that it is very precisely structured, as a lot of content has to be taught in a very short time span. As a result, students do not have much freedom to explore the application on their own. If the number of students is small and the necessary resources (time and teaching assistants) are available, it is recommended not to use the prepared models for each lesson, but to provide the students with an unprocessed model that they can work on throughout the curriculum.

Beside the mentioned limitations and possible implication difficulties, we expect that this curriculum will motivate CM programs to include TCM into their courses and foster the spread of TCM and/or other novel scheduling methods. This in turn can enable students as future project managers to question the traditional scheduling method and seek more efficient approaches. Future planned research will include a statistical analysis of pre- and post- learning retention regarding the TCM and automated or generative scheduling techniques.

Overall, the proposed curriculum can give the students a solid knowledge of the theory behind TCM and its automated application with ALICE. In addition, the flipped classroom approach allows an efficient use of the lecture and enables to dive deeper into the topic and reflect critically on the acquired knowledge. This is enhanced by the basic structure of the curriculum that additionally encourages students to make connections between the taught topics. Further, by teaching each new topic over a period of three weeks and thus ensuring spaced repetition, there is potential for the achievement of a long-term learning effect; however, more research is needed to confirm this. With the above-mentioned aspects, we believe this curriculum enables a high-quality teaching of a novel scheduling approach. Future research will quantitatively assess student learning from this first implementation.

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The curriculum has been designed to be shared with other CM course instructors. All course lessons, teaching notes, exercises, grading templates, and presentation templates are freely available online at https://www.research-collection.ethz.ch/handle/20.500.11850/482232 [13].

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