Features, Practical Applications, and Validation of COSMOS Simulator: A Construction-Process Simulation Tool

Jirawat Damrianant
Department of Civil Engineering,
Faculty of Engineering, Thammasat School of Engineering,
Thammasat University,
Pathum Thani, Thailand
E-mail: djirawat@engr.tu.ac.th

Sakkaphant Meklersuewong
Department of Civil Engineering,
Faculty of Engineering, Thammasat School of Engineering,
Thammasat University,
Pathum Thani, Thailand
E-mail: sakkaphant@gmail.com

***Abstract*—Computer-based simulation software is essential for efficiently simulating complex processes. COSMOS Simulator is a program developed specifically for simulating models created using COSMOS methodology, a modified Petri Net designed for simulating construction-based operations. However, unlike some existing Petri Net-based simulators, which may require a deep understanding of Petri Net theory, COSMOS is designed to be intuitive and accessible to construction professionals. Although previous studies have used the COSMOS Simulator to simulate various construction processes and documented its accuracy, no published work directly describes the simulator itself. This article aims to provide a detailed description and illustration of the COSMOS Simulator's features, especially its ability to model and simulate specific construction behaviours. In addition, this article offers further summaries and discussions of previous studies on the software's practical applications and validation. The paper provides a resource for researchers and practitioners interested in leveraging COSMOS for their construction modelling and simulation needs.**

Keywords-COSMOS; Construction Process Simulation; Domain-Specific Modelling; Petri Nets; Practical Applications.

I. INTRODUCTION

Process modelling and simulation are valuable approaches for construction engineering. However, a suitable software tool is necessary to simulate complex construction operations. The need for construction simulation software has been driven by the increasing complexity of construction projects and the need for effective planning and resource management tools. To address this need, the authors previously presented a detailed description and comprehensive illustration of the Construction Oriented Simulation MOdelling System (COSMOS) Simulator's features at the Sixteenth International Conference on Advances in System Modelling and Simulation (SIMUL 2024) in Venice, Italy, and received the Best Paper Award [1]. The present paper significantly expands on that earlier work, further elaborating the simulator's distinctive capabilities, practical applications, and validations.

Before discussing COSMOS in more detail, it is helpful to briefly review the historical context of simulation software development in construction. This overview will illustrate the evolution of such software and highlight key challenges encountered in the past, providing necessary background that explains the rationale for COSMOS's development. A comprehensive review of this historical context was previously provided in [2] and is briefly summarised as follows.

Early systems like the Micro-Computerised CYCLic Operation NEtwork (MicroCYCLONE) and the Dynamic Interface for Simulation of Construction Operations (DISCO) laid the groundwork for the field. Still, their adoption was often limited by the specialised knowledge required to use them. The emergence of object-oriented programming and discrete-event simulation paradigms led to the development of more user-friendly and versatile tools like the Construction Operation Simulation Tool (COST) and the Construction Object Oriented Process Simulation (COOPS) system. As construction projects grew in complexity in the 2000s, simulation tools like Simphony and STROBOSCOPE were developed to offer customisable and user-friendly platforms for modelling specific construction operations. However, the inherent complexity of construction processes, with their intrinsic uncertainties and dynamic interactions, continued to pose challenges for simulation modelling. In addition, many previously developed tools remained difficult to use, requiring substantial technical knowledge of simulation methodologies for construction practitioners.

These challenges led to the development of COSMOS, a simulation methodology that extends traditional Petri net frameworks with construction-specific modelling elements. As detailed in this paper, the COSMOS Simulator significantly advances construction process modelling and simulation. The software can simulate models created using the COSMOS methodology [3], a modified Petri Net designed to facilitate simulation modelling of construction-based operations. The methodology introduces new nodes, arcs, and attributes to capture complex construction behaviours, improving the ease and realism of modelling for simulation and analysis. Reference [3] details how these extended elements interact to represent various construction scenarios, showcasing their flexibility in handling the complexities of construction. However, unlike some Petri Net-based simulators that may demand a deep understanding of Petri Net theory, COSMOS is crafted to be easily accessible for construction professionals.

This article addresses a gap in the existing literature by providing a direct and detailed description of the COSMOS Simulator's features and capabilities. While previous studies have utilised the simulator for various construction simulations (some in Thai) [4]-[12], and the software's accuracy has also been confirmed and reported in several articles (some in Thai) [6][8][9][11], a dedicated publication outlining its functionalities was lacking. This paper fills that void. The article offers a detailed description and illustration of the distinctive features of the COSMOS Simulator, notably its capability to model behaviours not typically accessible in other Petri Net simulators, such as [13]-[17]. These features include elements like Header, Follower, Buffer, Pipe, End Arc, and DPA, which can manage continuous processes and dynamically progressive activities commonly encountered in specific construction processes. In addition, this article offers further summaries and discussions of previous studies on the software's practical applications and validation. The COSMOS Simulator's user interface and key components will be described in Section II. Section III presents practical implementations of the simulator along with validation results that attest to its accuracy and applicability. A discussion, conclusion, and suggestions for future work will be provided at the end of the article in Sections IV and V.

II. Descriptions of User Interface and Key Components

This section will review COSMOS's user interface and explain the essential components of the COSMOS Simulator. Figure 1 displays the homepage of the COSMOS Simulator's user interface, which can be accessed by selecting "Model" in the "view mode selector" panel. It should be noted that the Model mode is pre-selected by default. The system interface comprises several key components: the Menu Bar, Simulation-Run Controller Panel, Simulation Control Bar Properties Palette, Modelling Element Panel, Model Drawing Area, Status Bar, and View Mode Selector. The following subsections will comprehensively describe each of these significant components of the COSMOS Simulator.

A. Menu Bar

The menu bar in Figure 1 is divided into three tabs: Files, Settings, and Help. Each tab contains commands for manipulating files and software settings, such as creating a new file, opening an existing file, saving files, and changing font and grid settings.

B. Simulation-Run Controller Panel

To operate the simulation, users interact with the buttons on the "simulation-run controller panel". This panel contains several buttons as follows;

"Continuous Run" initiates a continuous simulation with animation as transitions fire and tokens move.

"Flash Run" simulates without displaying any animation, only providing the simulation's results unless the user specifies that animation should be shown.

"Pause" temporarily halts the simulation.

"Reset" brings the simulation back to its initial state.

"Previous Step" steps the simulation backwards by one step.

"Previous Event" steps the simulation backwards by one event.

"Next Event" steps the simulation forward by one event.

"Next Step" steps the simulation forward by one step.

See Figure 2 for the locations of these buttons in the user interface.

It is important to note that running the simulation by a step or by an event differs in terms of how the animation displays tokens residing in the places between adjacent transitions. When simulating by an event, the animation does not show tokens temporarily residing in the places, whereas simulating by a step does display these tokens.

C. Simulation Control Bar

Before running a simulation, users can define a seed number in the "Seed" field of the "simulation control bar" (see Figure 1). The specified seed number is the initiator for generating a random number stream using the Linear Congruential Method. This stream is subsequently utilised to generate random samplings, including the firing duration, referred to as 'Service Time' within the COSMOS Simulator. Service time is sometimes stochastic; in such cases, the generated random numbers are used to determine the service time of the transitions each time they fire. These stochastic durations are governed by Probability Density Functions (PDF) specified by the users (see Figure 3). Additionally, the COSMOS Simulator utilises the stream to determine events for transition firings, whether they will fire or not. The determination is based on the probability ratios associated with transitions set by the users. These transition probabilities can be employed to resolve conflicts among transitions, should they arise.

The control bar offers additional functionalities. The Time Interval field allows users to specify the display frequency of the simulation run. For example, suppose the COSMOS simulation begins at time = 0, and the Time Interval is set to 5 minutes. In that case, the Simulator will visualise the run at 5, 10, 15, 20 minutes, and so on, showcasing the transition's firing and token movement animations at those time intervals. The simulation's speed can be adjusted using the Play Speed slider. Additionally, the Time Limit field allows users to define a specific time at which the simulation will be forced to terminate, even if its natural stopping conditions are not met.

D. Modelling Element Panel

The COSMOS modelling elements are located in the "modelling element panel", as shown in Figure 1. The panel contains various buttons representing different modelling element types, except for the top-left button, which serves as

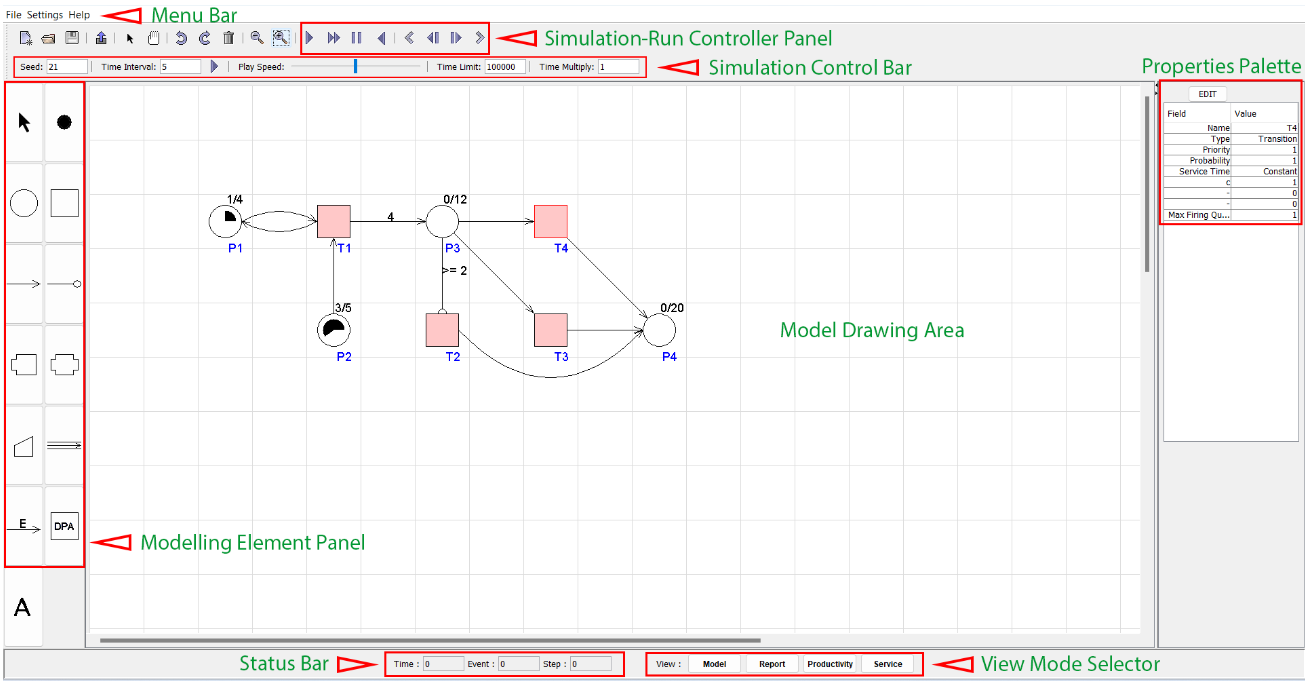

Figure 1. Homepage of the COSMOS Simulator's user interface.

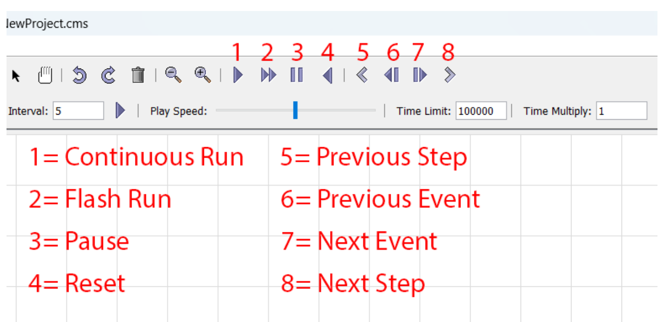

Figure 2. Simulation-Run Controller Panel

the selection mode. Clicking on any of these buttons allows users to enter the mode for placing the selected element type on the "model drawing area." The first four elements in the panel, located next to the selection mode, are the common Petri Nets elements: Token, Place, Transition, and Arc.

1) Place: A place element has two primary attributes: capacity and marking. Capacity refers to the maximum number of tokens that can be stored in a place at any given time, whereas marking indicates the current number of tokens present in the place. For instance, consider a Petri Net shown in Figure 1, where place P1 has a capacity of 4 tokens and currently contains one token. The current marking and capacity of the place are denoted by the numbers on the top-right corner as "1/4". A black area resembling a pie chart is used to visually represent the ratio between the marking and the capacity of the place.

2) Transition: Transitions in the COSMOS Simulator have several primary attributes that determine their behaviours during the simulation. These attributes include priority, probability, service time, and max firing queue. Figure 1 provides an example of a transition's properties palette (on the right-hand side of the figure), which displays its primary attributes. Priority and probability are used to resolve conflicts among transitions demanding tokens from the same place. Service time is the firing duration of the transition, which can be a constant value or a probability distribution. Users can change the firing duration type by clicking the "Edit" button in the properties palette. Figure 3 shows the properties editor for transition T1, which allows the user to specify the firing duration as a triangular distribution with minimum, mode, and maximum values of 5, 12, and 18 time units, respectively.

The term "max firing queue" refers to the maximum number of times a transition can fire simultaneously. This feature is handy for modelling certain construction behaviours. For example, when two loaders are working together to load three trucks, with each loader handling one truck at a time, there are instances when loading activities for two trucks occur simultaneously or overlap. The "max firing queue" feature can be used in this case.

Consider the initial state of a truck-loading model, as shown in Figure 4. Three trucks are located at P1, while two loaders are stationed at P2. By setting the maximum firing queue to 2, as shown in Figure 5, T1 can fire twice overlappingly. When firing, the number 2 displayed in the middle of T1 indicates that the transition handles two firings simultaneously. If the maximum firing queue were set to 1 (the default value), T1 could only fire once at a time. This scenario would not accurately reflect the real-world situation in which two loaders are available to handle the loading process simultaneously. Finally, the model in Figure 6 represents the circumstances when one truck is still being loaded while another truck has already finished loading. The number 1 displayed in the middle of T1 indicates that only one firing is being handled by T1 at this point in time.

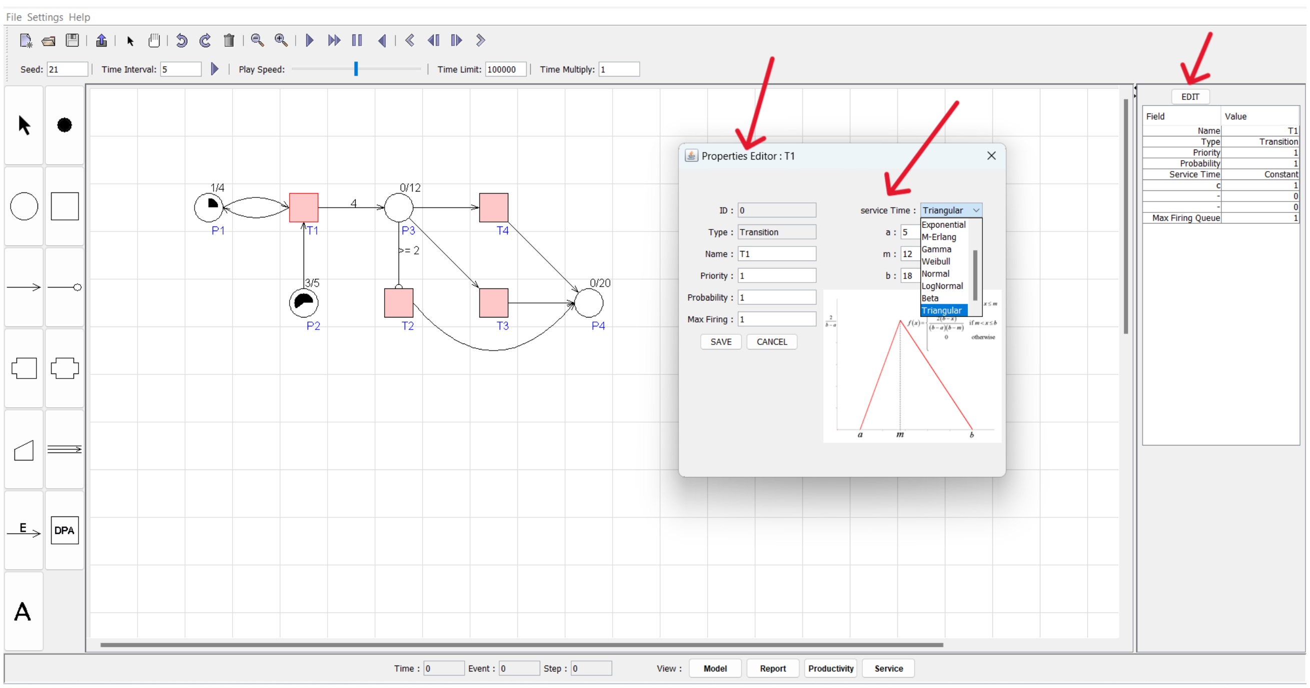

Figure 3. Properties Editor of Transition.

3) Token and Arc: Tokens and arcs in the COSMOS Simulator serve the same function as those in common Petri Nets. In the current version of the simulator, all tokens and arcs are black and do not have any additional attributes or colours.

4) Condition Arc: Condition arcs in the COSMOS Simulator share similarities with inhibitor arcs found in modified Petri Nets, although substantial disparities exist between them. While the weight on a typical inhibitor arc is fixed at "equals zero," a condition arc possesses the flexibility to adopt any integer value as its weight, thereby enabling the expression of conditions in either equality or inequality formats. For instance, a condition arc's weight can be designated as "greater than or equal to 4." Additional instances illustrating the practical applications of condition arcs can be found in references [6][10] or a brief model delineated in Figure 7.

The model depicted in Figure 7 entails the transportation of 8 pieces of precast elements from a casting plant to a construction site. A loader situated at the plant facilitates the loading of precast elements onto a truck for transportation while also managing the unfinished precast elements within the plant. Nonetheless, the primary emphasis of this operation lies in the transportation of the eight precast elements. Consequently, the simulation of the process necessitates termination upon the completion of transporting the eight elements to the construction site and the subsequent return of the truck to the plant. In this model, a condition arc with a weight of ">= 1" (greater than or equal to one) is employed to govern the cessation of the process.

These features of condition arcs are handy for modellers who require control over specific logic or conditions in their construction process models. The features allow modellers to make their models more concise.

5) Header, Follower, Buffer, Pipe, and End Arc: Specific construction activities can only begin after their respective preceding activities have operated for a designated period. However, the completion of preceding activities is not mandatory before commencing the succeeding ones. When two or more activities share this interdependent relationship, they are classified as overlapping activities. To manage such overlapping activities, the COSMOS Simulator utilises five modelling elements: Header, Follower, Buffer, Pipe, and End Arc. Figure 8 displays the symbols of the five elements in the "modelling element panel" of the COSMOS Simulator.

A header is a unique transition type representing the first activity in a series of overlapping activities. Like a normal transition, it can be enabled and fired (shot). The primary function of a header is to convert discrete units of work into continuous units, represented as a percentage. When a header shoots, it sends portions of the work through pipes and a buffer to the next activity in the series.

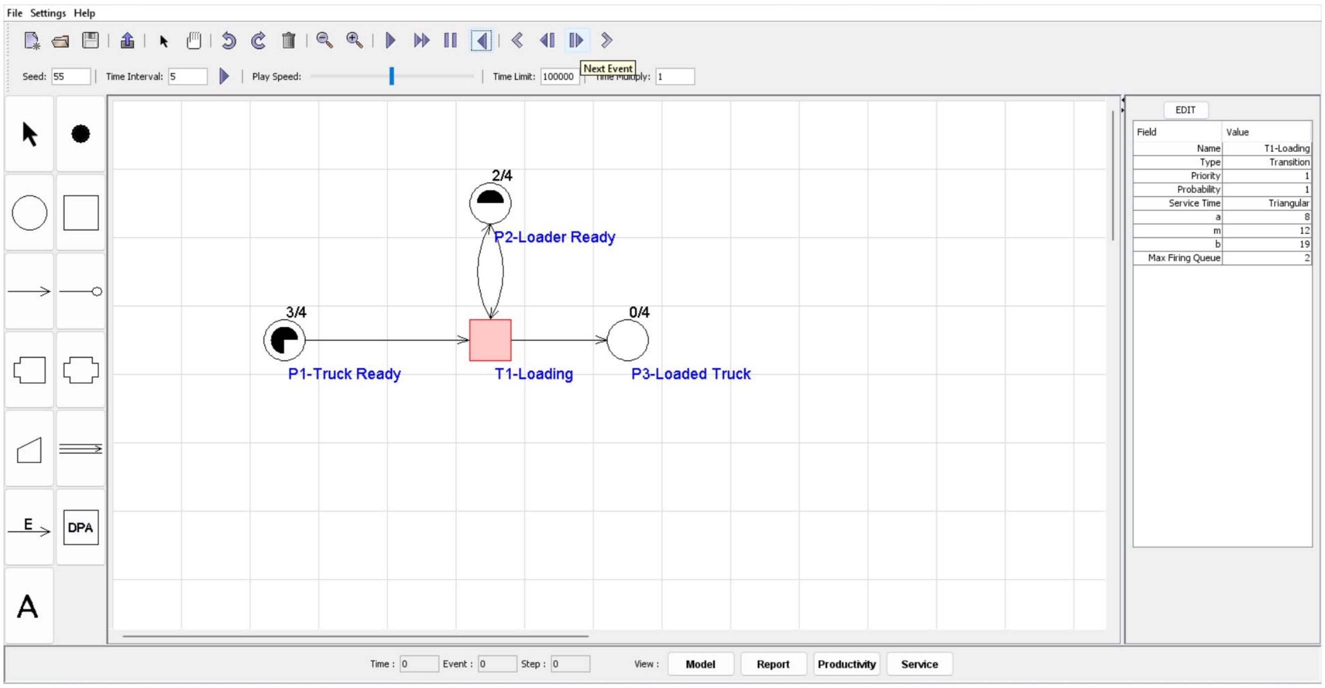

Figure 4. Model illustrating “Max Firing Queue” feature (State 1).

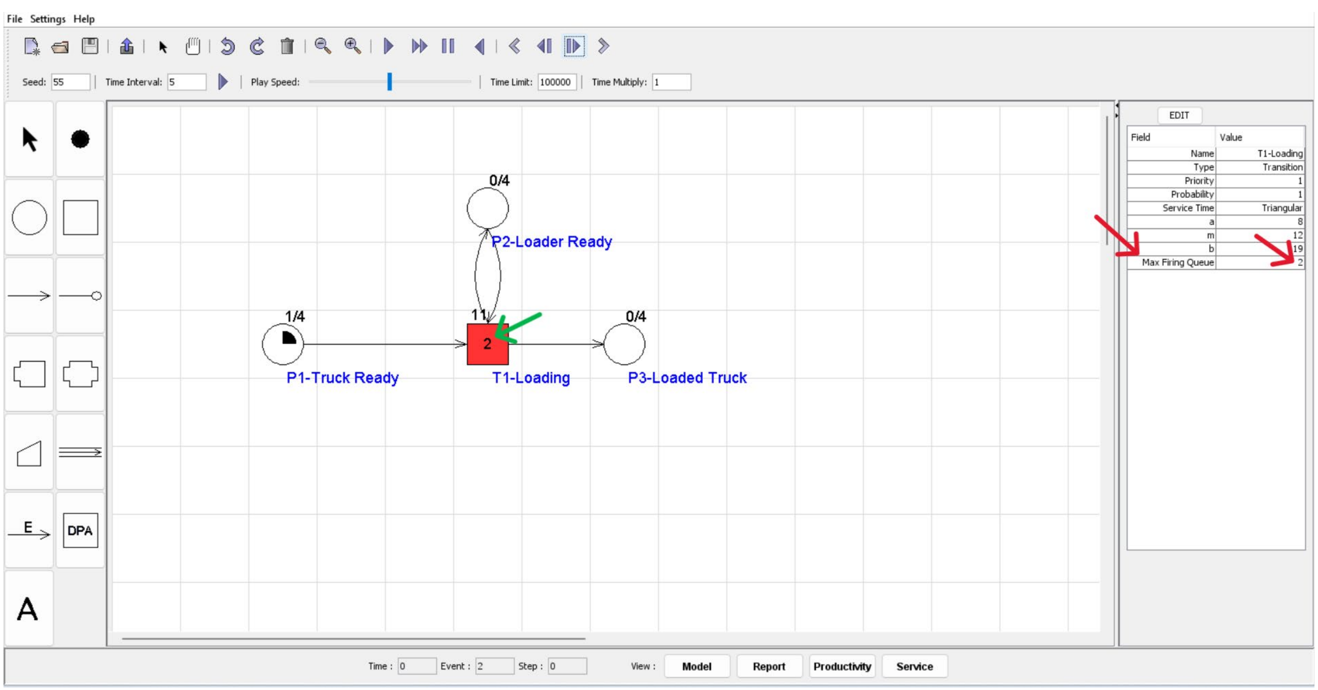

Figure 5. Model illustrating “Max Firing Queue” feature (State 2).

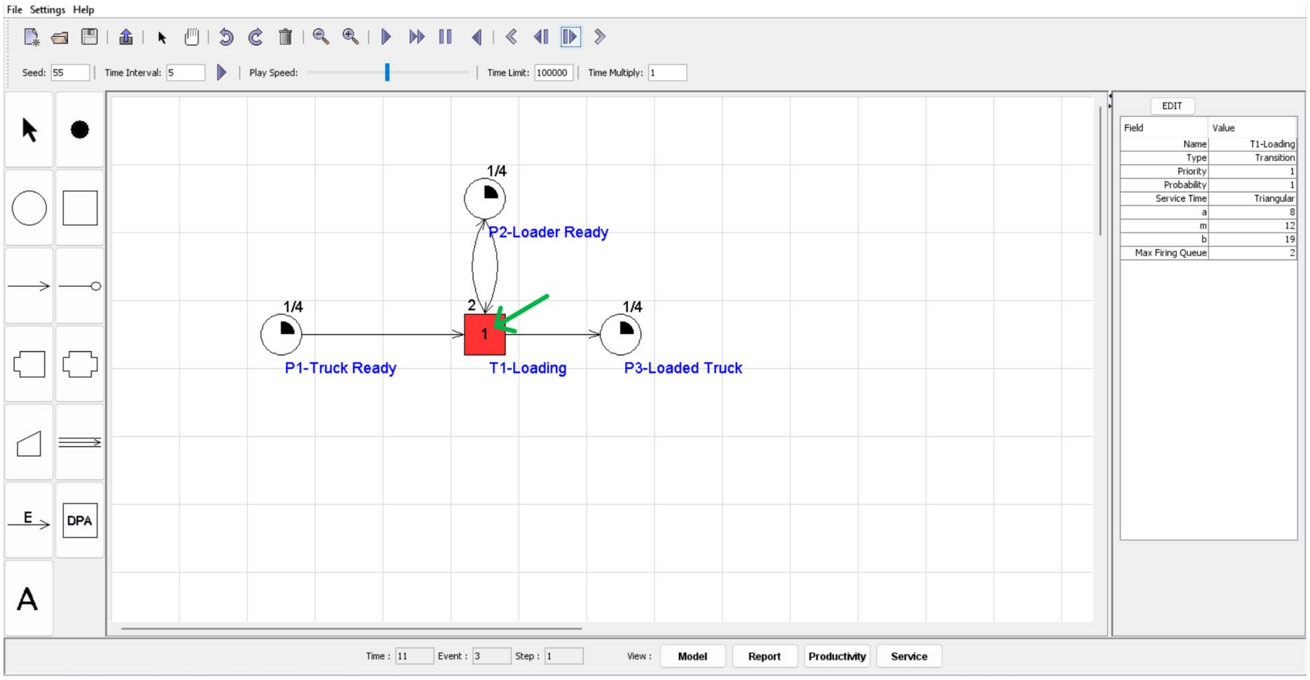

Figure 6. Model illustrating “Max Firing Queue” feature (State 3)

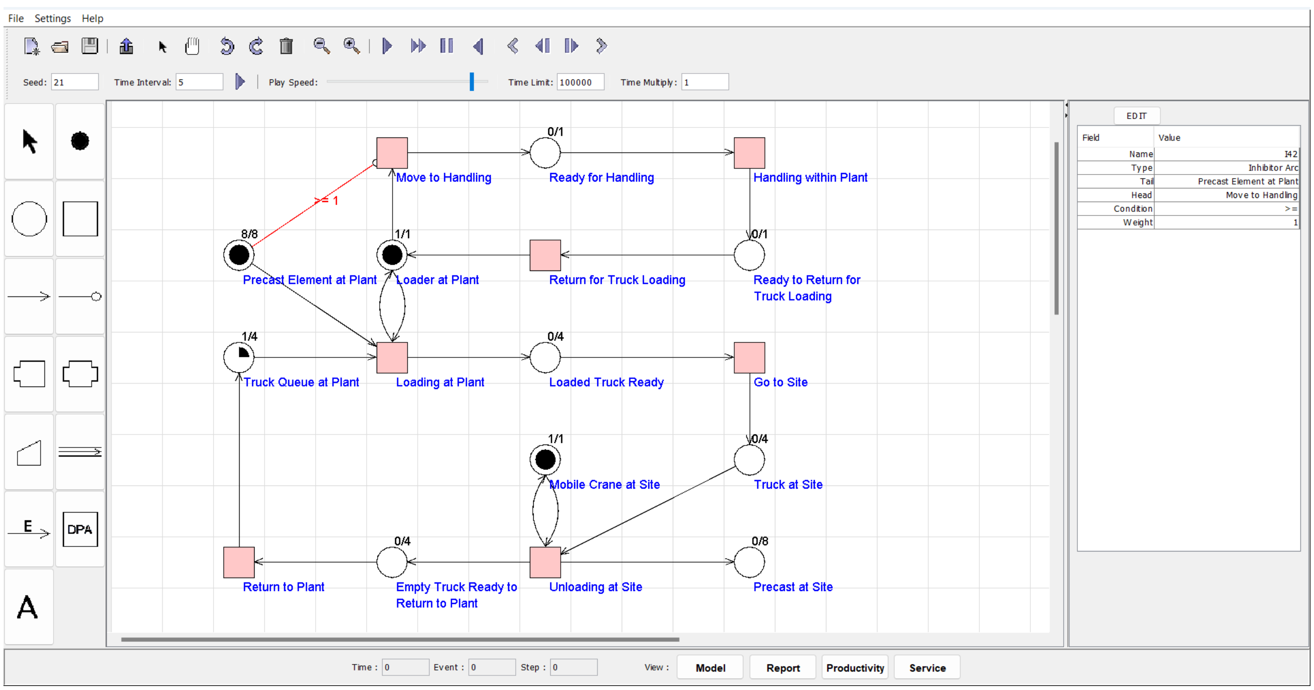

Figure 7. Model illustrating a sample application of "Condition Arc".

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Additional details regarding the shooting mechanism and the functionality of headers can be found in [4].

A follower can be regarded as a particular type of transition, similar to a header. However, followers represent subsequent activities instead of representing the first activity in a series of overlapping activities. Like headers, followers release portions of continuous work through shootings. The quantity of work released from each shooting of a follower is equal to the shooting percentage specified in the header of the series. The shooting criteria for a follower are the same as those for a normal transition, with the additional condition that the released quantity of work from the preceding element (either a header or another follower) must be available in the input buffer of the follower. Further details on the functionality of followers can be found in [4].

A buffer is a special type of place where portions of the quantity of work released from headers or followers are stored. Buffers are connected to headers or followers via pipes. It's important to note that tokens cannot reside in buffers, and buffers have an unlimited capacity.

A pipe is a particular type of arc used to represent the flow of work released from headers or followers. In other words, pipes are used to send portions of work resulting from shootings of headers or followers. Pipes can only connect headers or followers to buffers and buffers to followers.

The COSMOS Simulator utilises an "end arc" to conclude overlapping series when the shooting percentage of the final follower reaches 100%. Once this threshold is met, the end arc sends a token or tokens to the connected outgoing place, with the number of tokens depending on the weight of the arc. This mechanism effectively terminates the series and ensures proper execution of the simulation.

Reference [11] demonstrates the use of the five elements (header, follower, buffer, pipe, and end arc) in a sample application to simulate overlapping activities in a concreting and waste-handling operation. The COSMOS model of the operation is shown in Figure 9.

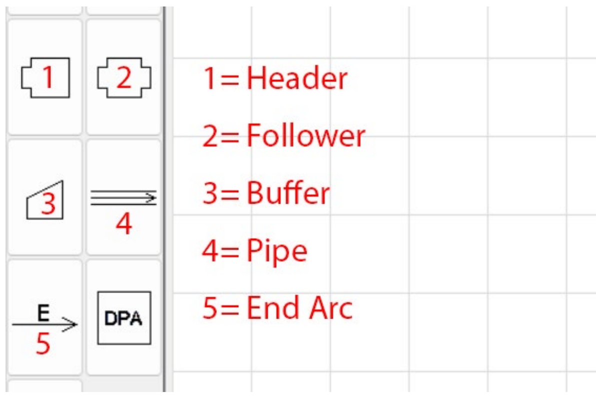

Figure 8. Header, Follower, Buffer, Pipe, and End Arc in Modelling Element Panel of the COSMOS Simulator.

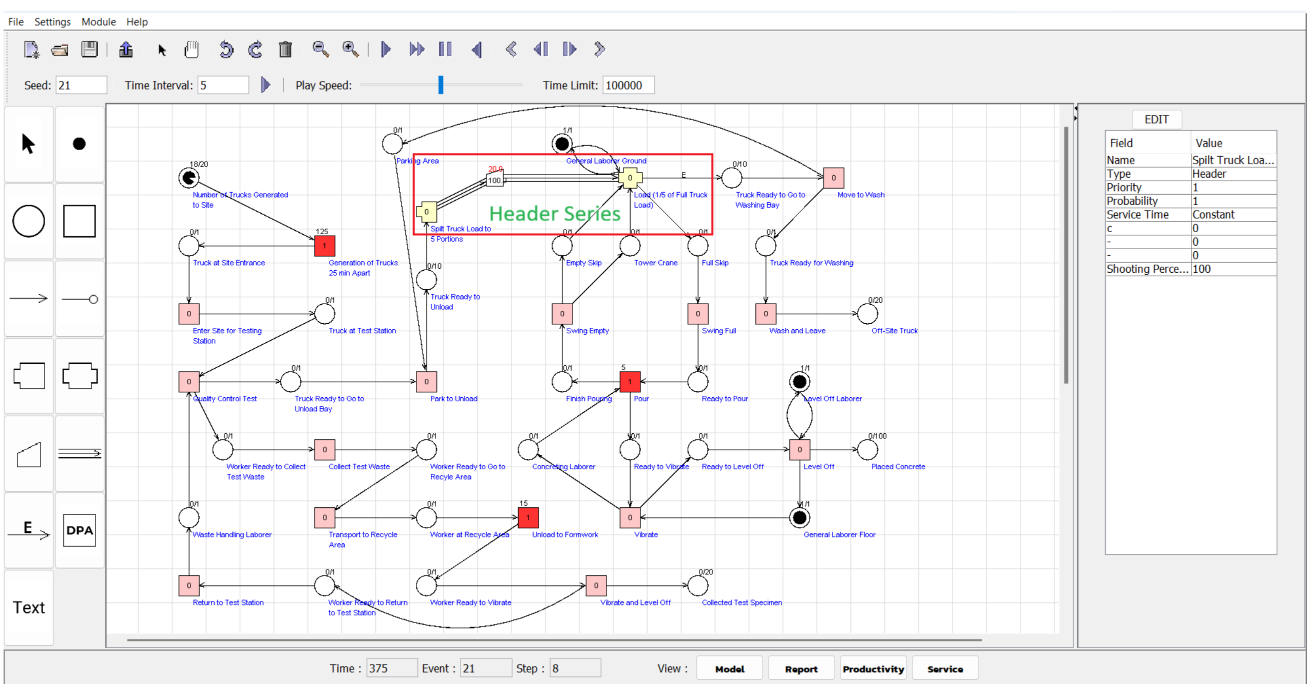

Figure 9. COSMOS model with Header, Buffer, Follower, Pipes, and End Arc.

6) Dynamically Progressive Activity (DPA): Dynamically Progressive Activity (DPA) is defined in COSMOS as an activity whose duration varies due to the increase in the amount of work for each iteration. DPAs commonly occur in linear construction processes such as road construction and drainage pipe installation. For example, in reinforced-concrete road construction, the "moving to placing spot" activity will have a longer duration as the length of the road being constructed increases with each iteration of the placement. This is because the starting point of the placement area remains stationary while the placing spots get further away for each round of the placement. As a result, the distances between the beginning of the placement zone and the placing spots increase, thereby increasing the duration of the "moving to placing spot" activity performed by ready-mixed concrete trucks.

If a DPA's working rate and amount of work are known, its activity duration can be calculated. For instance, in reinforced-concrete road construction, suppose a concrete truck moves between the starting point of the placement area and a placing spot at an average speed of 10 km/hr or 166.67 m/min (this represents the working rate), and the distance between the beginning of the placement zone and the placing spot is 100 m (this represents the amount of work). In this case, the duration required for the truck in the "moving to placing spot" activity will be 0.6 minutes, indicating that, on average, the truck can cover a distance of 100 m within 0.6 minutes. Therefore, for distances of 200 m, 300 m, and 400 m, the truck will require 1.2, 1.8, and 2.4 minutes, respectively, to complete the activity.

After determining the duration of a DPA, users can input this information into the corresponding activity within the COSMOS Simulator. Subsequently, the simulator will calculate the duration of each iteration of the DPA by incrementally advancing the amount of work completed and using these values to simulate the process.

Figure 10 presents a concrete-road placement model, representing an operation similar to the abovementioned process. The model showcases the implementation of the DPA concept. Notably, a DPA element in the COSMOS Simulator is a unique type of transition that features a dynamically progressive firing duration. In the figure, the elements labelled "DPA1-Truck proceeds from the starting point of the placement area to the placing spot" and "DPA2-Truck returns to the starting location of the placement area" represent DPAs. When DPA1 fires for the first time, its firing duration will be zero since a truck can discharge concrete immediately upon reaching the starting point of the placement area without needing to move further forward. In the subsequent three iterations, the firing durations will be 0.6 minutes, 1.2 minutes, and 1.8 minutes as the placing points for the truck will be located 100 meters, 200 meters, and 300 meters away, respectively, from the beginning of the placement zone.

These modelling features collectively enable users to construct detailed and realistic simulations of construction processes.

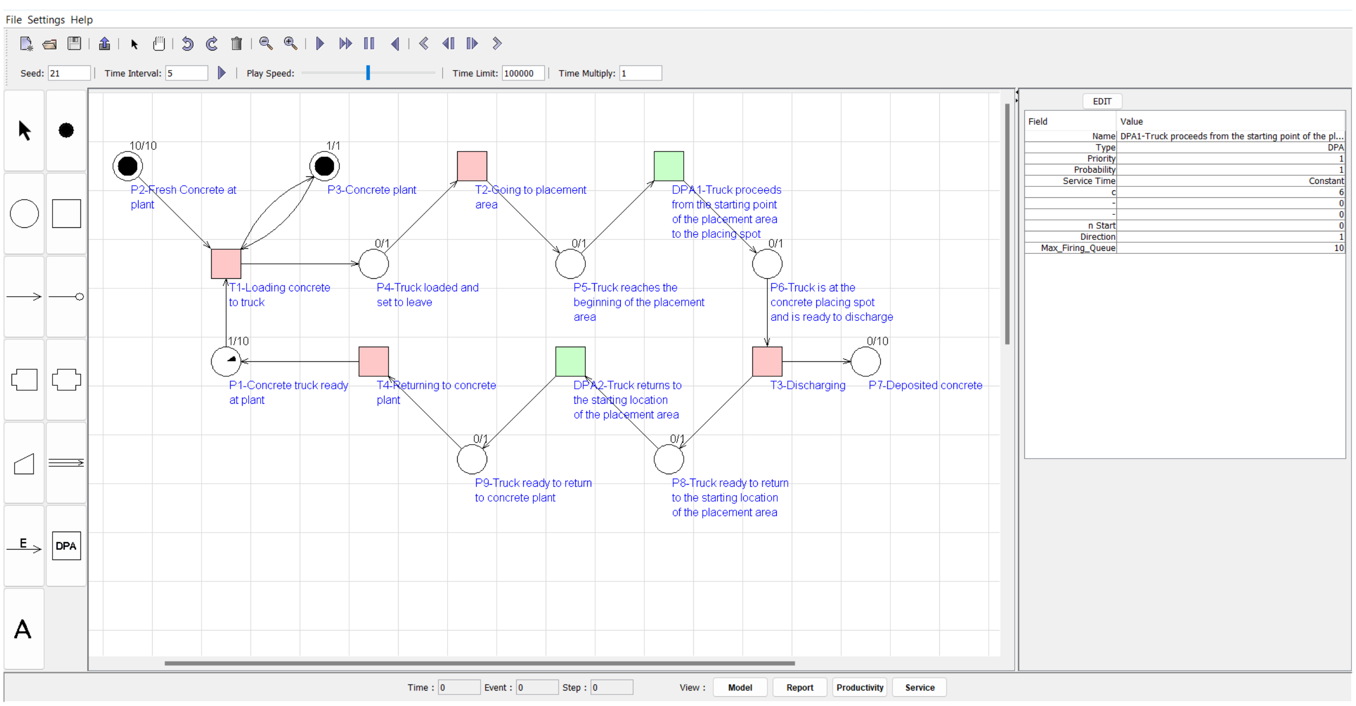

Figure 10. Dynamically Progressive Activities (DPAs) in a concrete-road placement model.

While the COSMOS methodology is based on an extended Petri Net framework, its implementation in the COSMOS Simulator intentionally abstracts away much of the theoretical and mathematical complexity commonly associated with Petri Nets. Users are not required to understand formal definitions such as marking functions or matrix-based calculations, although a basic understanding of how tokens move and how transitions fire remains necessary to develop valid models. Importantly, users do not need to interact directly with abstract Petri Net syntax. Instead, COSMOS offers domain-specific visual blocks—such as headers, followers, buffers, pipes, and dynamically progressive activities—that closely represent real construction operations. As long as users can identify construction activities and define logical relationships between them (e.g., precedence, concurrency, or dependencies), they can effectively create simulation models. This design lowers the entry barrier for construction professionals, ensuring practical usability while retaining the analytical power of a Petri Net-based system.

III. Practical Applications and Validation of COSMOS Simulator

The COSMOS Simulator has been used to simulate various construction processes, and its accuracy has been demonstrated. This section will provide further summaries and discussion of previous studies on the software's practical applications and validation. These aspects will further reinforce confidence in the accuracy and reliability of the COSMOS software and system, which is crucial for its widespread adoption. Greater utilisation of the software will, in turn, facilitate continuous improvements and advancements in the COSMOS Simulator, enhancing its capability not only in construction process simulation but also in modelling other process-driven operations. Six cases from "Energy Reduction" to "Concreting and Waste-Handling Operation" will be discussed in this section.

A. Energy Reduction

The COSMOS Simulator was applied in the study to analyse and optimise the utilisation of heavy equipment fleets in an asphaltic-concrete road construction project in Ratchaburi, Thailand [5]. The research aimed to minimise energy consumption by identifying inefficiencies in the construction process and improving resource allocation. The study involved modelling and simulating the construction operations using the COSMOS system, which is based on Petri Nets.

The analysis covered seven key construction procedures, including clearing, levelling, excavation, embankment construction, base preparation, prime coating, and pavement finishing. Data on activity durations, equipment usage, and energy consumption were collected from an actual construction site. The simulation identified significant idle and waiting times within the equipment fleet, which contributed to excessive fuel consumption. Specifically, the original arrangement of one truck, one water truck, and one asphalt truck resulted in a total process duration of 5,653 minutes, with substantial waiting times for key equipment.

Process improvements were implemented by increasing the number of trucks and asphalt trucks from one to three while keeping the number of water trucks constant. The revised simulation showed a substantial reduction in process duration to 2,969 minutes and significantly decreased idle times. As a result, energy consumption was reduced by 26.8%, lowering diesel fuel usage from 523 litres to 383 litres.

These findings demonstrate the effectiveness of the COSMOS Simulator in optimising construction operations through systematic modelling and simulation. The study highlights the potential of process adjustments in achieving energy efficiency in road construction projects. However, the research was limited to a specific project scope and construction setting, and further studies could explore the broader applicability of the approach to different project types and conditions.

B. Optimisation of Supply Trains in Tunnel Boring Operation

The COSMOS Simulator was employed in this study to optimise the operation of supply trains in tunnel boring using tunnel boring machines (TBMs) [6]. The research focused on the Beung-Nongbon drainage tunnel project in Bangkok, Thailand, which required an efficient muck evacuation system due to the unusual tunnel length of 5.5 km without an intermediate vertical shaft. The challenge was to determine the optimal number of supply trains needed to synchronise with the TBM's excavation process.

A COSMOS (Petri Net-based) model of the tunnelling operation was developed and simulated using the COSMOS system (see Figures 11 and 12). The model accounted for key activities, including muck evacuation, tunnel segment transportation, and rail relocation. The results revealed that the number of supply trains required varied based on the tunnel length. For example, the optimal number of supply trains was found to be two for tunnels up to 0.9 km, three for 0.9–2.7 km, four for 2.7–4.5 km, and five for 4.5–5.5 km. The study also determined the optimal placement of double track points to avoid bottlenecks, suggesting their positioning at 1.8, 3.6, and 4.5 km for tunnels longer than 4.5 km.

A critical finding was that deadlock situations could occur if supply trains were not strategically positioned at double-track points. The simulation also established that the maximum permissible single-track length (Track T) between the last double track point and the TBM should not exceed 0.9 km, ensuring continuous TBM operation with minimal delays. The maximum allowable distance between adjacent double track points was found to be 2.3 km to maintain optimal productivity. The study confirmed that the highest achievable tunnelling rate was 27.8 rings per day, aligning with historical data from similar projects.

These findings demonstrate the effectiveness of the COSMOS Simulator in optimising TBM operations by improving synchronisation between excavation and muck evacuation processes. However, the study's limitations include the assumption of ideal conditions without equipment breakdowns or unforeseen operational delays. Future research could incorporate these uncertainties to refine the optimisation approach further.

C. *Resource Management for Concrete Placing Operation*

The COSMOS Simulator was applied in this study to analyse and optimise the resource management of a concrete-placing operation in a gas separation plant construction project in Rayong Province, Thailand [7]. The research focused on reducing the duration of concrete placement by improving the coordination of ready-mixed concrete trucks, crane operations, and other logistical factors.

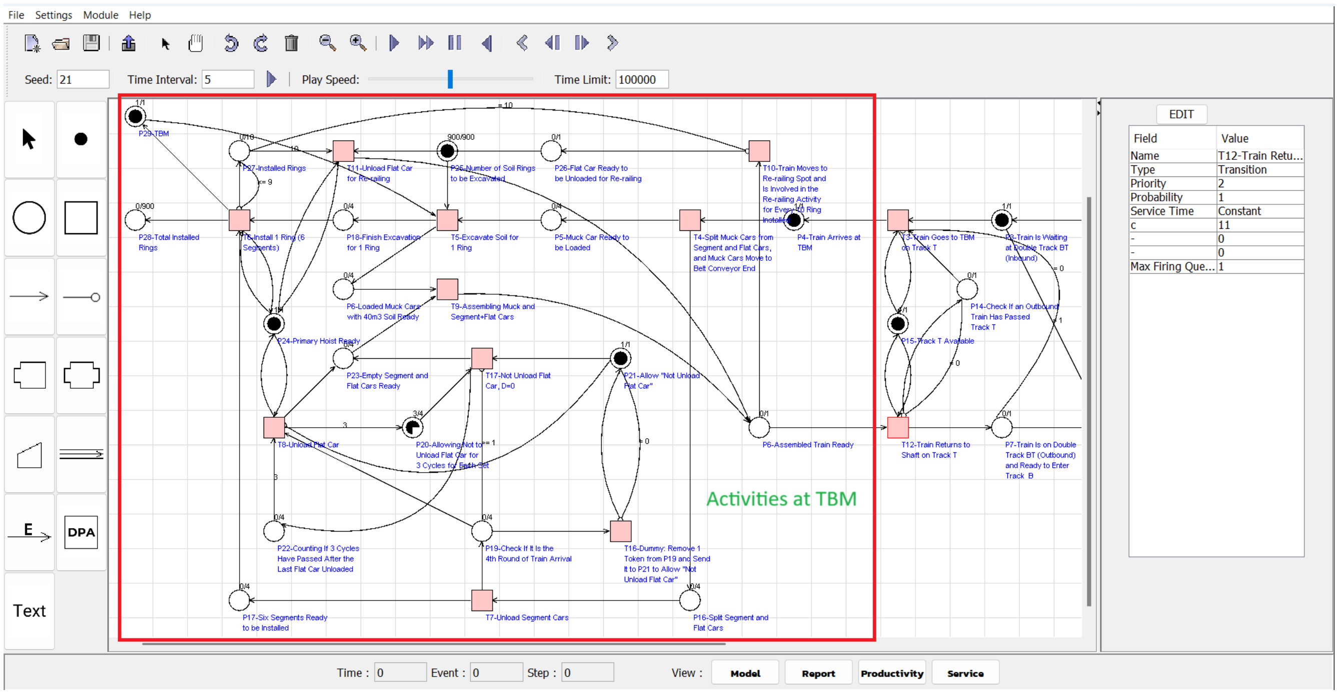

Figure 11. Partial COSMOS model represents activities at TBM in a tunnel construction operation [6].

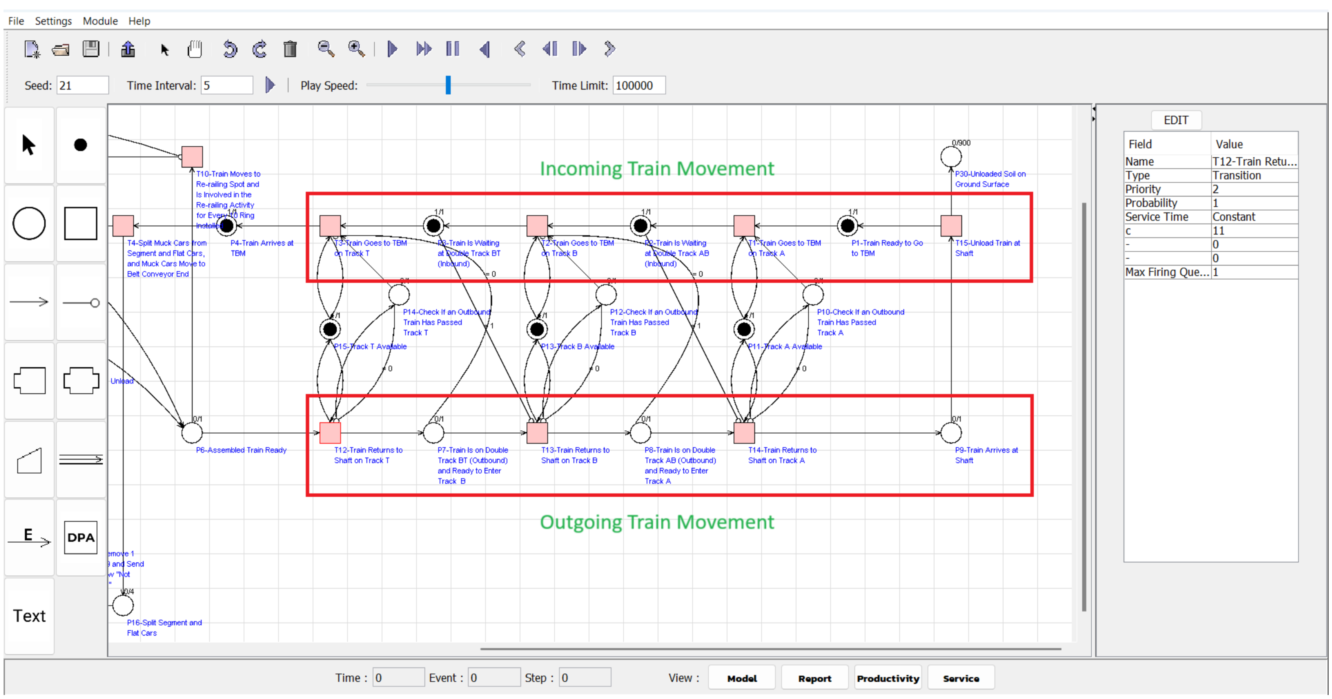

Figure 12. Partial COSMOS model illustrates the movement of supply trains in a tunnel construction operation [6].

A COSMOS-based simulation model was developed to represent the real-world construction process. The study collected empirical data over five months to identify patterns in truck arrival times, concrete placement durations, and crane availability. Various scenarios were simulated, adjusting the number of trucks and daily concrete placement volumes. The results indicated that using three concrete trucks and placing 50 cubic meters of concrete per day provided the optimal balance between efficiency and resource utilisation. Implementing this strategy in the second phase of the project resulted in a noticeable improvement in construction progress compared to the first phase, where no simulation-based planning was used. The optimised approach reduced project delays and eliminated unnecessary truck waiting times, which had previously led to inefficiencies.

The study demonstrates the effectiveness of the COSMOS Simulator in optimising construction scheduling and resource allocation through systematic modelling and simulation. However, limitations include the exclusion of unpredictable external factors such as weather conditions and equipment breakdowns. Future studies could incorporate stochastic modelling to account for these uncertainties and enhance the robustness of the simulation approach.

D. Comparison between COSMOS Simulator and Arena

The COSMOS Simulator has been verified and applied in various construction process simulations, with a comparative analysis conducted against the widely used Arena simulation software [8]. Two key case studies were employed to validate COSMOS's accuracy and applicability: (1) concrete placement using a concrete pump and (2) earthmoving operations in tunnel excavation.

The first case study examined the concrete placement process for an eight-story building, where ready-mix concrete was transported by trucks and pumped through pipes to the designated floors. The model accounted for potential operational disruptions, such as pipe blockages and relocations. Simulation results from COSMOS and Arena showed strong consistency in key performance metrics, including the concrete pouring rate and waiting times at the mixing plant and pump. While minor variations were observed due to stochastic process durations, statistical hypothesis testing confirmed no significant differences between the two software outputs.

The second case study focused on tunnel excavation, specifically the earthmoving operations involving a tunnel boring machine (TBM) and supply trains operating on a single-track system with designated passing stations. The COSMOS model successfully replicated the process flow, including train scheduling, material transport, and resource allocation. The total process duration from both COSMOS and Arena simulations matched precisely at 46,690 minutes, further validating COSMOS's reliability.

These verifications demonstrate that the COSMOS Simulator can produce accurate results comparable to Arena, reinforcing its credibility as a tool for construction process simulation. Moreover, the study highlights the suitability of COSMOS for modeling construction workflows due to its Petri Net-based methodology, which aligns well with the logic of construction scheduling techniques such as the Critical Path Method (CPM). This feature enhances model interpretability for construction professionals, distinguishing COSMOS from manufacturing-based simulation tools like Arena

Overall, the findings confirm COSMOS's robustness in simulating complex construction operations, making it a viable alternative to established simulation software for process analysis and optimisation in the construction industry.

E. Auger Horizontal Earth-Boring Process: Comparison with MicroCYCLONE

The COSMOS Simulator was evaluated against MicroCYCLONE in modelling an Auger Horizontal Earth-Boring (HEB) process [11]. The case study involved the installation of 100 linear feet of casing using an auger boring machine, with activities including track placement, auger installation, casing attachment, and soil removal. Both deterministic and stochastic simulations were performed to compare the total operation duration.

The deterministic results showed an identical process completion time of 1,107 minutes for both simulators, confirming COSMOS's ability to replicate MicroCYCLONE's output. In stochastic simulations, 40 independent runs were conducted, yielding mean process durations of 1,092 minutes for MicroCYCLONE and 1,096 minutes for COSMOS. A statistical hypothesis test confirmed that the differences were not significant, verifying that COSMOS produces statistically equivalent results to MicroCYCLONE. This validation demonstrates COSMOS's capability to model cyclic construction processes accurately while leveraging Petri Net-based representations that facilitate process visualisation. The COSMOS model of the operation is given in Figure 13.

F. Concreting and Waste-Handling Operation: Comparison with PROMODEL

A second verification in [11] compared the COSMOS Simulator with PROMODEL and SDESA in modeling a concreting and waste-handling operation. The case study involved a tower crane-based concrete pouring process, incorporating skip cycles, slump testing, and waste handling. The COSMOS model shown in Figure 14 effectively captured the flow of materials, truck arrivals, and resource allocations using Petri Net constructs.

The results were analysed in terms of resource utilisation rates. COSMOS exhibited only a 0.6% deviation from PROMODEL, demonstrating a high degree of consistency. When compared to SDESA, COSMOS showed a slightly larger deviation of 3.4%, but this was within acceptable margins given the stochastic nature of the process. An alternative COSMOS model incorporating a more advanced resource allocation technique (using headers, buffers, and end arcs) (see Figure 9) further reduced the deviation from PROMODEL to just 0.1%. This suggests that COSMOS not only provides accurate results but also offers enhanced flexibility for modeling complex resource interactions.

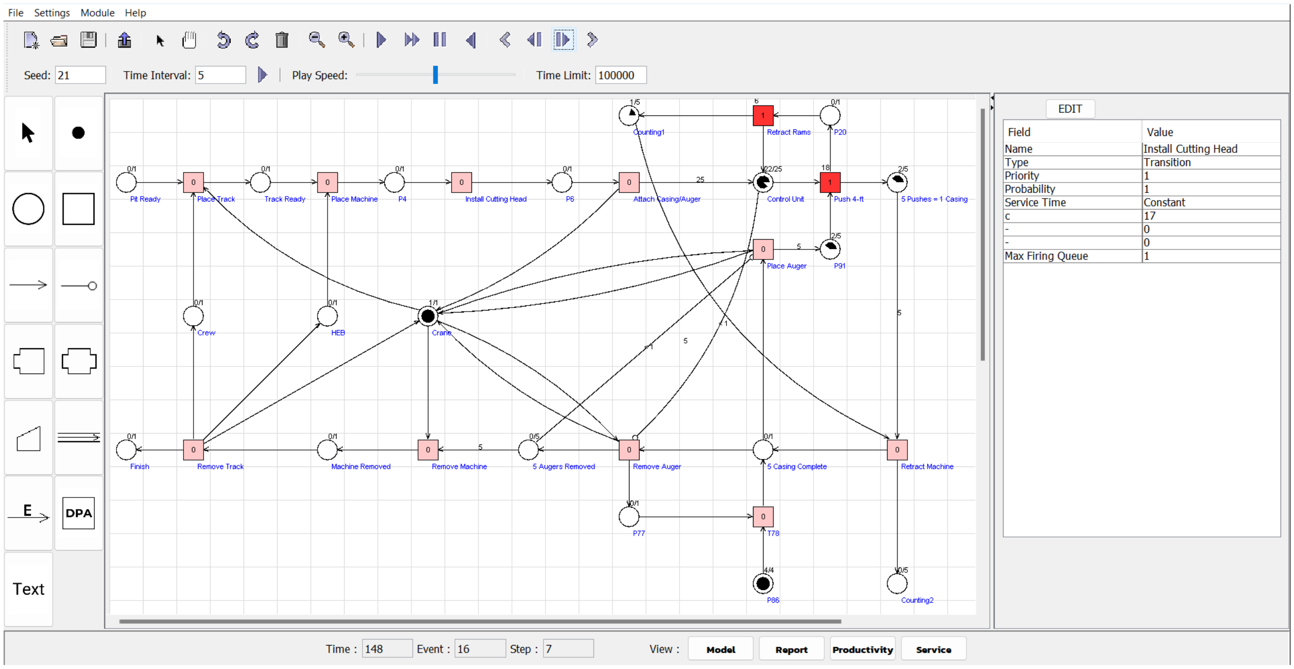

Figure 13. COSMOS Model for an auger horizontal earth-boring process [11].

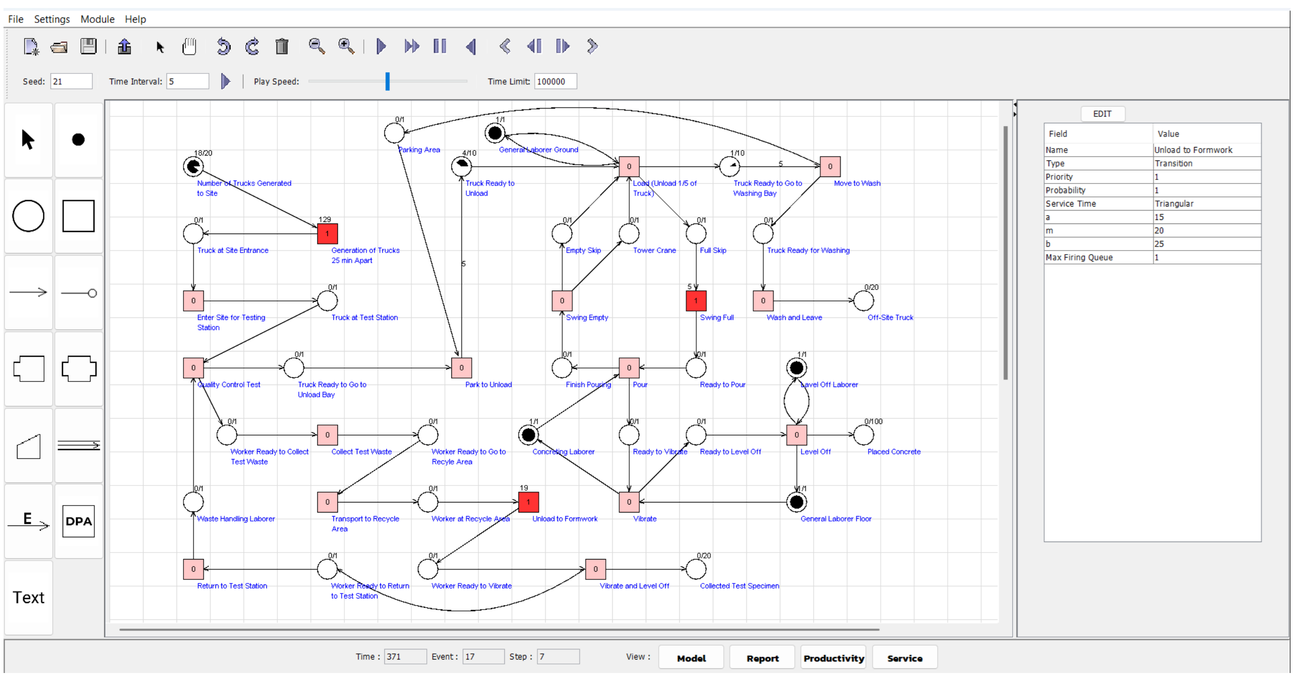

Figure 14. COSMOS model (Petri Nets-based model) of a concreting and waste-handling operation [11].

These verifications confirm that COSMOS can effectively replicate results from both domain-specific (MicroCYCLONE) and general-purpose (PROMODEL) simulation tools while providing construction engineers with an intuitive and domain-relevant modelling approach. The findings reinforce COSMOS's viability as a robust construction-process simulation tool, ensuring accuracy while enhancing process transparency and interpretability.

IV. Discussion

Unlike some existing simulators, which often require users to understand abstract Petri Net constructs or mathematical formalisms, the COSMOS Simulator was developed with a strong emphasis on usability and domain alignment. Its visual modelling components—such as headers, followers, buffer, pipe and dynamically progressive activities—reflect how construction professionals naturally conceptualise their operations. This domain-specific design lowers the learning curve and enables practitioners with a limited background in simulation theory to develop models that still leverage the expressive power of Petri Net-based logic.

In terms of modelling capability, COSMOS enables the representation of complex construction behaviours that are often difficult to express using traditional tools. These include overlapping activities, dynamically progressive operations, flexible precedence logic, and resource allocation constraints. While COSMOS delivers results comparable in accuracy to established simulators, its practical value lies in making such capabilities accessible and directly applicable to construction workflows. This combination of analytical strength and usability differentiates COSMOS as a simulation tool purpose-built for real-world construction process analysis and design.

While COSMOS represents a significant step forward, it is essential to acknowledge its limitations and potential areas for future development. The simulator's primary focus on discrete-event simulation may limit its applicability to continuous processes or systems with complex interactions. Additionally, although COSMOS can simulate dynamic processes, its current version may have limitations in incorporating real-time data from construction sites, which is crucial for achieving a true digital representation of construction processes. Future research and development efforts can focus on expanding COSMOS's capabilities in these areas, further enhancing its value and impact in the construction industry.

The current version of the COSMOS Simulator is available online [18].

V. Conclusion and Future Work

This paper provided a comprehensive description and illustration of the distinctive features of the COSMOS Simulator, a computer program designed to simulate construction processes effectively. COSMOS accounts for real-world construction behaviours such as:

- Concurrent execution of similar activities through "max firing queue" settings.
- Overlapping or interleaved activities facilitated by headers, followers, buffers, pipes, and end arcs.
- Simulation of Dynamically Progressive Activities (DPAs), where duration varies based on workload, commonly seen in tasks like asphalt paving.

Notably, these modelling elements and features—headers, followers, buffers, pipes, end arcs, and DPAs—are unique to COSMOS, enabling the simulation of specific behaviours found in construction, and they are not available in other simulation tools.

Apart from normal arcs, COSMOS also has condition arcs similar to inhibitor arcs in modified Petri Nets but allow more flexibility. They can have any integer weight, enabling the expression of equality or inequality conditions.

The COSMOS Simulator has been validated through various practical applications, demonstrating its accuracy and reliability in simulating construction processes. Its ability to model complex workflows, optimise resource utilisation, and produce results comparable to established simulation tools highlights its potential for broader adoption in the construction industry. However, further research is needed to explore the needs and gather feedback from diverse users. This information will be crucial in enhancing the COSMOS system to make it even more effective in simulating construction processes.

This paper offered a resource for researchers and practitioners interested in leveraging COSMOS for their construction modelling and simulation needs.

Despite its emphasis on functionality for construction practitioners, the COSMOS Simulator and its associated methodology can be used to model and simulate any discrete event process.

Future research and development efforts will focus on expanding COSMOS's capabilities to incorporate real-time data from construction sites. Additionally, it would be beneficial to broaden its functionality to simulate construction processes with even more complex interactions. Enhancing the modelling logic with appropriate control statements will enable users to have finer control over the behaviours of the COSMOS models and support an even wider range of use cases relevant to complex construction scenarios.

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