

Process Modelling in Civil Infrastructure Projects: A Review of Construction Simulation Methods

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Abstract –

It is known that process simulation is a feasible solution to deal with real-world complexities and problems. Civil infrastructure in particular, is a complex system that can benefit from process simulation. This paper provides a critical overview of different simulation modelling paradigms used in construction to achieve better system performance. Three simulation paradigms of agent based modelling, discrete events simulation, and system dynamics are reviewed and their different applications, specifically in civil infrastructure are discussed. The paper then discusses the hybrid paradigms of agent based modelling with system dynamics, and agent based modelling with discrete event simulation, and how hybrid approaches have better capabilities to model complex problems occurring in civil infrastructure. Such modelling approaches, therefore, will improve overall efficiency of construction production.

Keywords –

Construction project planning, Infrastructure sector; Integrated and combined models; productivity and efficiency; Supply chain management

1 Introduction

When prototyping or experimenting with a civil infrastructure system is expensive or impossible, modelling is the best way of solving real world problems, which gives the privilege of optimizing systems prior to implementation [1]. Modelling includes the abstraction process, which is mapping a problem from the real world to its model in the world of models, analyzing and optimizing the problem, then mapping it back to the real system [2]. There are three levels of abstraction, based on the range of problems that are efficiently addressed with simulation modelling, High

Abstraction “macro level”, Middle abstraction “meso level”, Low Abstraction “micro level”. Table 1 generates a better understanding of the abstraction level concept and different modelling schema used for each abstraction. Considering an example, macro level traffic and transportation models may not consider individual vehicles or packets. Supply chains are being modeled at very different abstraction levels and they could be placed anywhere in middle to high abstraction range. Problems at the top of Table 1 are typically approached in terms of aggregate values, global feedbacks, trends, etc. Individual elements such as people, parts, products, vehicles, animals, houses are never considered there. Thus, considering how different modelling approaches correspond to abstraction; System dynamics dealing with aggregates is located at the highest abstraction level. Discrete event modelling is used at low to middle abstraction. As for agent based modelling, this approach is being used across all abstraction levels [2, 3]. Agents may model objects of very diverse nature and scale: at the micro level agents may be pedestrians or cars or robots, at the middle level they can be customers, at the macro level they can be competing companies.

The purpose of this paper is to discuss different simulation paradigms in civil infrastructure by focusing on Agent Based Modelling (ABM), Discrete Events Simulation (DES), and System Dynamics (SD). Furthermore, different applications of these approaches along with related advantages/disadvantages are presented. After that, the paper discusses Hybrid paradigms and enhanced modelling performance that can be achieved when combining more than one paradigm. A focus will be on Hybrid ABM-SD, and Hybrid ABM-DES. The paper concludes that agent based modelling is not a substitution to the other modelling paradigms, but a useful add-on that can be combined with system dynamics and discrete event simulation to achieve better results.

Table 1. Paradigms corresponding to different abstraction levels, and applications related to different abstraction level

Abstraction Level	Applications of Simulation modeling (Some of)	Paradigms
High Abstraction/ Macro level/ Strategic Level/ Less details	<ul style="list-style-type: none"> • Market Place & Competition • Population Dynamics • Manpower & Personnel • Ecosystems • Health Economics 	ABM & SD
Medium Abstraction/ Meso level/ Tactical Level/ Medium details	<ul style="list-style-type: none"> • R&D project Management • Supply Chain • Waste Management • Transportation • Electrical Power Grid • Call Center • Emergency department 	ABM & DES
Low Abstraction/ Micro level/ Operational Level/ More details	<ul style="list-style-type: none"> • Pedestrian movement • Warehouses • Factory floor • Automotive Control System • Computer Hardware 	ABM & DES

2 Literature Review of Different Simulation Modelling

2.1 Agent Based Modelling (ABM)

ABM is a computer simulation technique that allows the examination of how system rules, and patterns emerge from the behaviours of individual agents [4]. There is no universally accepted definition for ABM, the primary reason is that researchers in literature are still arguing and discussing what kind of properties an object should have to earn to be called an “Agent” [2]. One of the widely accepted definitions provided by Wooldridge and Jennings, ‘A self-contained program capable of controlling its own decision-making and acting based on its perception of its environment, in pursuit of one or more objectives’ [5]. Nasirian, et al. [6] explain that Agent-based simulation is basically a model in which dynamic processes of agent interactions are simulated repeatedly over time as in SD, discrete event and other types of conventional simulations. An Agent Based simulation mostly consists of more than one agent interacting, that’s why it is often called a multi-agent system, MAS, [7]. Agent- based models, ABMs

or MASs, consist of a set of agents characterized by attributes, and interact with each other through the definition of pre-set rules in a given environment [8]. Agents produce output behaviour according to their interaction with each other and their environment and also by following their rules. Many scholars have tried to introduce properties for agents in ABM, [9] defines three properties for agents to be: Cooperative, Learning and Autonomous, and that every agent should possess two of three at least [10]. Pro- and re-activeness, spatial awareness, ability to learn, social ability, “intellect”, etc. as described in [7] are some of the many properties of ABM. Aside from the different properties that define Agents, an important feature that distinguishes Agent Based Models from SD or DE is that they are essentially decentralized [2]; there is no such place in AB model where the dynamics of the system could be defined. Instead, the modeler defines behaviour at individual level, and the global behaviour emerges as a result of the many individuals interacting, each following its own behaviour rule, living together in some environment and communicating with each other and with the

environment [2]. The complexity of the ABM system arises from the interactions between different agents [11]. The main objective of the ABM simulation is to track the interactions of the agents in their artificial environment and understand processes through which global patterns emerge [12]. The number of applications to which ABM can be applied are endless due to its distributed and flexible computational power [13]. ABM is a suitable tool to describe the behaviour of complex systems as it serves a ‘bottom-up’ approach to seize the interactions between individual agents, recognizes each entity as heterogeneous rather than identical, and allows the agents to dynamically evolve and adapt [4]. Extremely complex behaviours can arise from repetitive and competitive interactions between agents enabled to be accounted by the computational power of computers [14]. And thus, ABM is progressively seen in more natural science and engineering purposes, though specific construction applications are more limited. Most recently, Son, et al. [15] have reviewed the use of ABM in construction research and noted its ability to deal with emergent behaviour in complex systems and the advantage that ABM might have over more reductionist approaches. Sawhney, et al. [16] reviewed the use of ABM in answering questions within complex construction systems. They conclude that by combining ABM with more traditional discrete event approaches, these systems can consider human factors that impact the construction site. The traditional approach adopted in studying and understanding construction models has been defined as a “central control” approach, in which the construction plan and schedule are created in advance based on defined resource and constraints [16].

2.2 Discrete Events Simulation (DES)

Discrete Events modelling origins back to 1960s by Geoffrey Gordon, who developed the existing idea of GPSS and brought about its IBM implementations [17]. Entities in DE are passive objects that represent people, parts, documents, they can be delayed, processed, seized and release resources, split, combined, etc. [18], defined the DE methodology as “the modelling of a system as it evolves over time by a representation in which the state variables change only at a countable number of points in time”. Pidd [19], defined DE simulation as “An instant of time at which a significant state change occurs in the system”. Simulation entities can be defined as the elements of the system being modeled and individually identified and processed [20]. Moreover, flow entities and resource entities need to be distinguished in simulation [21]. Flow entities, are usually referred to as (customer entity or temporary entity) and pass through a sequence of activities in a process, and interact with the

resource entities (server entities or permanent entities). In contrast with resource entities, flow entities are identical to one another, in a sense that no physical attributes are required to define and distinguish them [22]. A flow entity only carries a time cell to track their arrival times, waiting times, and departure times at activities. The “transaction-flow world view” often provides the basis for discrete-event simulation. In this simulation view, a system is visualized as consisting of discrete units of traffic that move/flow from point to point in the system while competing with each other for the use of scarce resources. The units of traffic are sometimes called Transactions, giving rise to the phrase “transaction flow” [23].” Plentiful systems fit the previous description, which include many manufacturing, material handling, transportation, health care, civil, natural resource, communication, defense, and information processing systems, and queuing systems in general. A discrete-event simulation is one in which the state of a model changes at only a discrete, but possibly random, set of simulated time points. Two or more traffic units often have to be manipulated at one and the same time point. Such “simultaneous” movement of traffic at a time point is achieved by manipulating units of traffic serially at that time point. This often leads to logical complexities in discrete-event simulation because it raises questions about the order in which two or more units of traffic are to be manipulated at one time point. Discrete-event simulation has been recognized as a very useful technique to be taught to tertiary engineering students for the quantitative analysis of operations and processes that take place during the life cycle of a constructed facility [24, 25]. Construction planning is the most crucial, knowledge-intensive, ill-structured, and challenging phase in the project development cycle due to the complicated, interactive, and dynamic nature of construction processes [26, 27]. DES provides support to construction planning by predicting the future state of a real construction system following the creation of a computer model of the real system based on real life statistics and operations [28]. Simulation models for typical construction systems have been delivered as electronic realistic prototypes for engineers to experiment on, which eventually will lead to productive, efficient, and economical field operations.

2.3 System Dynamics (SD)

Developed in the early 1950s by an electrical engineer, Jay W. Forrester, defined System Dynamics as “the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise” [27]. Since then, definitions and applications

of System Dynamics have been widely studied both in literature and in practical life. Mathematically, a System Dynamics model is a system of differential equations [2]; it is a methodology to understand a specific, predefined- problem or complex problems that include changes over time through multiple feedback loops. System Dynamics uses feedback loops, stocks and flows to model the behavior of complex systems over time [29]. In real world, stocks are a representation of different processes such as, people, money, knowledge, material, etc. Also, real world processes interactions are represented by the flows between the different stocks, and the information that determines the values of the flows [2]. Specifically, feedback loops are closed chains of cause and effect links in which information about the result of actions is fed back to generate further action [30]. To describe the System Dynamics behavior accurately, it should be highlighted that the system is rising from two fundamental types of feedback loops; Negative loops showing goal-seeking behavior and represented with minus sign, and positive feedback loops, represented as plus sign, having the tendency to strengthen their input, leading to exponential growth or decay [31]. A positive feedback loop generates evolution or progression, not equilibrium as in a negative feedback loop [32]. System Dynamics abstracts from single events and entities and takes a comprehensive view concentrating on policies. To method an SD problem, one has to describe the system behavior as a number of interacting feedback loops, balancing or reinforcing. Once the feedback loop are structured and identified, they are translated to what is called stock-flow diagrams to enable simulations [31]. It is important to highlight that large-scale construction projects are extremely complex, highly dynamic, have multiple feedbacks and nonlinear relationships, and require both hard and soft data [31]. That explains why System Dynamics can fulfill certain modelling requirements, especially for large-scale construction models. In general, the strength of SD lies in its ability to account for nonlinearity in dynamics, feedbacks and time delays [14], and thus, System Dynamics has been a widely successful tool applied to issues ranging from social, industrial and environmental to project management systems [33]. In construction management, System Dynamics is a widely used modelling tool; however, SD developments in the construction field focus on the characteristics of the traditional construction, or separate sub-systems [30]. A first simple SD model for general project management is developed by [32]. This model then modified for managing different project phases.

3 Analysis of Different Hybrid Paradigms

3.1 Hybrid ABM-SD Simulation

SD and ABM are two simulation methods used to investigate nonlinear social and socio-economic systems [29]. SD has difficulties in many situations and ABM might help to cope with these problems [34]. However, this does not mean that SD is a poorer methodology than ABM, most likely the field of SD is more mature than ABM, which is still in its infancy [35]. Schieritz and Milling [7] presented a comparison between ABM and SD characteristics and found some similarities between the two models. Both of them have the same aim, which is to search for principles underlying the dynamics of complex systems [11]. Lorenz and Jost [36] argued that combining two methodologies helps to be closer to reality as they can synchronize best-fit methods of different methodologies. Schieritz and Milling [7] showed that combining SD and ABM offers the strength of the two methodologies. Adding to that, they believe this combination reduces complexity of the model from the beginning. A hybrid paradigm approach has the advantage of allowing complex problems to be represented more naturally, which improve efficiency and enhance better communication with the simulation project developers [37]. Hybrid simulation involves the use of multiple simulation paradigms, and is becoming an increasingly common approach to modelling modern, complex systems [38]. ABM and SD are among the most important simulation methods available [34]. The idea of creating hybrid models consisting of ABM and SD has been started in the late 1990s. An integration of the two concepts can be successful when it allows for the combination of properties that are otherwise proprietary to a single concept [7]. To fruitfully design a hybrid ABM-SD model; firstly, the framework for this hybrid simulation has to be proposed. This aids construction modelers to combine ABM and SD to benefit the strengths of the two methodologies [29]. It is necessary to define whether a single simulation method or a hybrid ABM-SD simulation approach is needed to model the problem from the beginning, as every simulation method has limited capabilities. The selection of the simulation method relies on the problem type. One should determine the problem can be simulated by one of the ABM or SD, or a hybrid simulation approach is needed [29]. The next step is to define the modelling hierarchy “a top-bottom as in SD, or Bottom –up as in ABM”. Prior to defining the hierarchy, an important note should be highlighted; despite the growing interest in hybrid simulation, little guidance exists for modelers regarding the nature and variety of hybrid models [38]. They proposed three types of hybrid ABM-SD simulation classification including Integrated, Interfaced and Sequential. The

integrated class incorporates feedbacks between ABM and SD representing a continuous process. It means within the Interfaced class may be run in parallel where their outputs are combined as required to represent the desired output as a function of time. In the Sequential class, ABM or SD has to be run first and its output will then be fed to the next. And thus, to determine the hierarchy of the model, for the integrated class of hybrid simulation, SD and ABM can be in a higher or lower level in comparison to each other [38]. However, the SD model is in a higher level in comparison to ABM for the sequential class of hybrid simulation. The next step is to define Information flow path, which the created information passes from one model to another, SD to ABM or vice versa. Nasirzadeh, et al. [29] suggested that the defined path of information flow can be determined based on the purpose of modelling. For example, there is a mutual IFP between SD and ABM models for the integrated class of simulation. The following step is to determine the simulation type based on the modelling purpose. In the case that there is not any connection between ABM and SD models, an interfaced class will be selected. However, if there is an interaction between the two, an integrated or sequential class would be selected. In the case that the interaction is mutual, an integrated class is used. When this interaction is not mutual, a sequential class is used. The last step is to define the Interface variable; which is to determine what should be exchanged between SD and ABM. The variables whose values are changed or influenced by variables of the other model and the variables which influence the values of variables of other models during hybrid simulation are named as 'interface variables'. The interface variables pass data from one model to another in the integrated and sequential classes of hybrid simulation and act as a gate for the transition of data between the two models. So that, SD and ABM exchange data through running time of the hybrid model.

3.2 Hybrid DES-ABM Simulation Modelling

DES is widely accepted in the construction simulation literature as the default approach for modelling construction. Humans, machineries and organizations are modeled in ABM and activities and project environment modeled using DES. The agents' decisions are dependent on the variables in the DES simulation. DES is very established in construction simulation and can be easily adapted to allow interaction with an ABM model. The hybrid framework consists of discrete event simulation as the core, but heterogeneous, interactive and intelligent (able to make decisions) agents replace traditional entities and resources [37]. Many DES models can become more representative of the real

world if entities are agents with the ability to adapt to changes in the model. Instead of using the simulation approaches individually, a hybrid DES-ABM simulation proposes framework to integrate unlimited behavioral activities, such as considerations in safety behavioral into construction activity planning. [37]. With further investigation into the relationships of the two modeling paradigms, in DES model, individual entities already exist; those entities can naturally become agents. The DES entities are however described as passive objects and the rules that drive the system are concentrated in the flowchart blocks. Hybrid DES-ABM is described as the process from the entity's viewpoint, thus decentralize "some of" the rules. Goh, et al. [37] describes the hybrid model in a simple manner as; the first component of the hybrid model is an ABM-DES model that analyzes a system in an individual level [39]. This component therefore produces data for the existing base case system, as well as, for systems to test strategic planning scenarios. The second component is the intelligent DES workflow-based that takes as inputs the incident data that is generated from the base case and scenarios. The DES model then combines the time-based input data, and compares the KPIs between the simulated scenarios [39].

4 Conclusion

Prior work has utilised different simulation approaches to model civil infrastructure processes [40, 41]. This paper reviews such simulation approaches. Some simulation techniques such as ABM allow the examination of how systems behave, and patterns emerge from the behaviours of individual agents. ABM is a suitable tool to describe the behaviour of complex systems as it serves a 'bottom-up' approach to seize the interactions between individual agents, recognizes each entity as heterogeneous rather than identical, and allows the agents to dynamically evolve and adapt. Researchers have reported on ABM's ability to deal with developing behaviour in complex construction systems and the advantage that ABM have over other approaches.

DES on the other hand, provides entities that are passive objects and represent people, parts, and documents. Entities can be delayed, processed, seized and released, split, and combined. DES provides support to construction planning by predicting the future state of a real construction system following the creation of a computer model based on statistics and operations. Applications of System Dynamics have been widely studied both in literature and in practical life. The strength of SD lies in its ability to account for nonlinearity in dynamics, feedback and time delays. Thus, SD has been a widely successful tool applied to large scale and complex construction projects. To sum

up, Table 2 shows advantages and disadvantages of using individual modelling paradigms.

Table 2. Comparison of Advantages and Disadvantages between the individual modeling approaches, DES, ABM, and SD

	DES	ABM	SD
Advantages	Easier to create a DES model	Absence of existing elements to be used, provides more flexibility to the modelers to model any scenario in any way they like Understanding the model logic is quite easier as the state-charts do not require simulation modelling knowledge to be understood	Ability to account for nonlinearity in dynamics, feedbacks and time delays
Disadvantages	Output elements had to be added to the model to improve the model performance Understanding the model logic can be difficult	Models are harder to create because no existing and built-in blocks can be used	Difficult in heterogeneous environments As the structure of the system tends to be fixed in SD, it is impossible to use it to study systems which tend to evolve through time

Moreover, the paper focuses on the hybrid modelling paradigms and resultant enhanced applications that can be achieved. The paper findings confirm that better modelling performance can be achieved using hybrid paradigms. A hybrid approach has the advantage of allowing complex problems to be represented more naturally, which improves efficiency and enhances modelling robustness. Hybrid simulation involves the use of multiple simulation paradigms, and is becoming an increasingly common approach to model modern and complex systems.

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