GENERAL PURPOSE SIMULATION WITH STROBOSCOPE

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ABSTRACT

Stroboscope is a programming language designed for the simulation of processes common to construction engineering. These processes are very complex and involve many different types of resources. As a result, Stroboscope is also an efficient and effective general purpose simulation system. This paper presents an overview of Stroboscope and illustrates how it can be used to model a complex example taken from classic simulation literature.

1 OVERVIEW

Stroboscope (Martinez, Ioannou, and Carr, 1994) is an acronym for STate and ResOurse Based Simulation of COnstruction Processes. It is a programming language specifically designed to model construction operations. Stroboscope models are based on a network of interconnected modeling elements and on a series of programming statements that give the elements unique behavior and control the simulation.

The character of Stroboscope arises from its ability to dynamically access the state of the simulation and the properties of the resources involved in an operation. The state of the simulation refers to such things as the number of trucks waiting to be loaded; the current simulation time; the number of times an activity has occurred; and the last time a particular activity started. Access to the properties of resources means that operations can be sensitive to properties — such as size, weight, and cost — on an individual (the size of the specific loader used in an operation) or an aggregate basis (the sum of the weights of a set of steel shapes waiting to be erected).

Stroboscope modeling elements have attributes — defined through programming statements — that define how they behave throughout a simulation. Attributes represent such things as the duration or priority of an activity, the discipline of a queue, and the amount of resource that flows from one element to another. Most attributes can be specified with expressions and have default values that provide the expected behavior. Expressions are composed of constants; system maintained variables that access the state of the simulation and the properties of resources; user-defined variables; logical, arithmetic, and conditional operators; and scientific, statistical, and mathematical functions.

The attributes of Stroboscope modeling elements allow simulation models to consider uncertainty in any aspect (not just time), such as the quantities of resources produced or consumed (e.g., the volume of rock resulting from a dynamite blast). Attributes also allow models to dynamically select the routing of resources and the sequence of operations; to allocate resources to activities based on complex selection schemes; to combine resources and dynamically assign properties to the resulting compound resource; and to activate operations subject to complex startup conditions not directly related to resource availability (e.g., do not blast rock until all crews of all trades have left the vicinity, the wiring has been inspected, and there are less than 10 minutes left in the current shift).

2 EXAMPLE — AIRPLANE SERVICE CENTER

The Stroboscope simulation language is best illustrated with an example. For the purposes of this discussion we have selected an example that should be easily understood by a wide audience. It is an airplane service center, and is a paraphrasing of problem 2.32 in (Law and Kelton, 1991). Obviously, our intent is to illustrate the capabilities of the language, not the operations of an airplane service facility.

2.1 EXAMPLE DESCRIPTION

Planes of seven different types $i$ (see table 1) arrive at a service center for inspection and possible repair of their engines. The times between successive arrivals are exponentially distributed with means $\lambda_i$ days. The service
Table 1: Plane Types

<table>
<thead>
<tr>
<th>i</th>
<th>Type</th>
<th>a_i</th>
<th>b_i</th>
<th>A_i</th>
<th>B_i</th>
<th>p_i</th>
<th>r_i</th>
<th>c_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B707</td>
<td>4</td>
<td>8.1</td>
<td>0.7</td>
<td>2.1</td>
<td>0.30</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>B727</td>
<td>3</td>
<td>2.9</td>
<td>0.9</td>
<td>1.8</td>
<td>0.26</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>B737</td>
<td>2</td>
<td>3.6</td>
<td>0.8</td>
<td>1.6</td>
<td>0.18</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>B747</td>
<td>4</td>
<td>8.4</td>
<td>1.9</td>
<td>2.8</td>
<td>0.12</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>5</td>
<td>DC8</td>
<td>4</td>
<td>10.9</td>
<td>0.7</td>
<td>2.2</td>
<td>0.36</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>DC9</td>
<td>2</td>
<td>6.7</td>
<td>0.9</td>
<td>1.7</td>
<td>0.14</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>7</td>
<td>DC10</td>
<td>3</td>
<td>3.0</td>
<td>1.6</td>
<td>2.0</td>
<td>0.21</td>
<td>2.8</td>
<td>3.7</td>
</tr>
</tbody>
</table>

2.2 SOLUTION

Stroboscope models consist of a graphical network and a series of programming statements (the network is also defined via programming statements). This discussion will go through the network and the complete Stroboscope source code required to solve this problem.

2.2.1 THE NETWORK

Figure 1 shows the network for this model. At an abstract level, the Combis (rectangles with cut-offs in the top-left corner), Normals (rectangles), and Queues (large circles with a slash in the bottom right corner) shown in this figure are similar in appearance and function to CYCLONE modeling elements (Halpin and Riggs 1992, Ioannou 1989); the Forks (smaller circles with an inscribed triangle) resemble COOPS Routers (Liu 1991, Ioannou and Liu 1992). The Links connecting elements are named, by convention, with 2 letters that abbreviate the type of resource that flows through them followed by a number. In this model PL stands for plane, AS for arrival scheduler, and SF for service facility.

Resources move from node to node in the direction of the Link arrows. Queues are storage locations for
inactive resources. Combs and Normals are classes of activities that require and take hold of resources for a certain amount of time. Combs activate themselves when enough resources are available in the Queues that precede them; upon activation they remove from their preceding Queues the resources needed to support the activity they represent. Normal activities start when activated by any of their preceding nodes and receive the resources released by the ending activity. A Fork is a probabilistic or decision-making node that selects which one of its successors to activate and route resources to.

Figure 1 shows planes going through a cycle. Initially a plane is in the PlaneWorld Queue until it is removed by the InterArrival Combi, which later releases the plane to the PlaneWait Queue. The plane remains in the PlaneWait Queue until the CheckInPl Combi removes it and immediately releases it to the Inspect Normal. After inspection, the PassInspection Fork decides probabilistically whether to activate the Repair Normal (inspection failed) or the IsPlDone Fork. If the IsPlDone Fork is activated it decides non-probabilistically whether to activate the Inspect Normal again (inspect another engine in the same plane) or the CheckOutPl Normal (plane is done and leaves the service facility). The Inspect Normal then releases the plane to whichever of the three possible successors: Repair via PL5-PassInspectionPL6, CheckOutPl via PL5-PassInspection-PL8-IsPlDone-PL10, or another instance of Inspect via PL5-PassInspection-PL8-IsPlDone-PL9. If the Repair Normal is activated, it takes hold of the plane for repairs and then releases it to a new instance of Inspect where the same engine is re-inspected. A plane may go through several Inspect- Repair cycles before it goes to service another engine or leaves the facility. Eventually all the plane’s engines will be serviced and the CheckOutPl Normal will be activated. Upon activation, CheckOutPl will immediately release the plane to the world of operating planes, the PlaneWorld Queue.

Arrival schedulers are fictitious resources used to control the inter-arrival of the different types of planes. Only one arrival scheduler resource exists for each of the seven plane types. An arrival scheduler starts out in the ArvlSchdlrs Queue until it is removed by the InterArrival Combi. Later, the InterArrival Combi releases the arrival scheduler back to the ArvlSchdlrs Queue, where the cycle starts again.

A service facility is initially in the ServiceFac Queue until the CheckInPl Combi removes it. The service facility is then implicitly attached to a plane until the plane to which it is attached enters the CheckOutPl Normal. CheckOutPl then explicitly releases the service facility to the ServiceFac Queue, where the cycle starts again.

The Combs control inter-arrivals and plane check-ins. The InterArrival Combi requires both an arrival scheduler and a plane for it to start. While the number of arrival schedulers is exactly seven, the number of planes in the world is possibly enormous. Because of this, the number of simultaneous instances of InterArrival is limited to the number of arrival schedulers. Once all available arrival schedulers are involved in instances of InterArrival, further instances of InterArrival can not occur because the ArvlSchdlrs Queue is empty. As denoted by the superscripts in links AS1 and PL1, the InterArrival Combi first removes an arrival scheduler and then a plane. By looking at the properties of the arrival scheduler, it can decide which type of plane to remove from the PlaneWorld Queue. When an instance of InterArrival ends, the arrival scheduler returns to the ArvlSchdlrs Queue. This allows a new instance of InterArrival to take place — another plane of the appropriate type is removed from PlaneWorld.

Similarly, the CheckInPl Combi creates the queuing effect in the PlaneWait Queue. Because only n service facilities exist, planes that enter the PlaneWait Queue may not find a service facility available in the ServiceFac Queue — the CheckInPl Combi will not remove the plane. It is not until the CheckOutPl Normal releases a service facility to the ServiceFac Queue, that CheckInPl will start and remove a waiting plane from the PlaneWait Queue. Note that the CheckInPl Combi also controls queuing in the the ServiceFac Queue — a service facility is not removed (and CheckInPl will not start) if there is no plane to check-in.

2.2.2 SIMULATION MODEL SOURCE CODE

The network provides a high level representation of the operation. More specific details of the model are shown only in the source listing. The discussion that follows will go through the entire source-code listing for this model.

Stroboscope statements end in a semicolon. They can span several lines with arguments separated by white-space. Arguments that include white space must be enclosed in single quotations; text arguments must be enclosed in double quotations. In this paper, source code lines are shown using a fixed-pitched font; object names that have been defined explicitly for this model and are not part of the Stroboscope language are shown in italics (Stroboscope keywords and plain numbers are not).

2.2.2.1 DECISION VARIABLES

Variables that store model parameters are placed at the beginning of the source file so that they can be found
and changed easily when performing experiments with the model:

VARIABLE WideBodyFirst 1;
VARIABLE nServiceFacilities 11;
VARIABLE DaysToSimulate 3650;

WideBodyFirst is a flag used to specify the queuing discipline. It is set to zero to indicate strict FIFO, and to a non-zero value to indicate wide body - FIFO. nServiceFacilities holds the number of service stations in the service center. DaysToSimulate holds the number of days for which the simulation will run.

2.2.2.2 RESOURCE TYPES

The resource types used in this model need to be defined (arrival scheduler, plane, and service facility). Both 'arrival scheduler' and 'plane' are characterized resource types (i.e., they represent non-bulk resources that have properties attached to them). The resource type 'service facility' is generic (i.e., it represents bulk amounts of property-less resources). These three types are defined below:

/*/********** AS = ArvSchnlr **********/
CHARTYPE ArvSchnlr i a;
/***********************************************************************/
SUBTYPE ArvSchnlr ASB707 1 8.1;
SUBTYPE ArvSchnlr ASB727 2 2.9;
SUBTYPE ArvSchnlr ASB737 3 3.6;
SUBTYPE ArvSchnlr ASB747 4 8.4;
SUBTYPE ArvSchnlr ASDC8 5 10.9;
SUBTYPE ArvSchnlr ASDC9 6 6.7;
SUBTYPE ArvSchnlr ASDC10 7 3.0;

ArvSchnlr is the actual type name used for the arrival scheduler resource type. Resources of type arrival scheduler have properties that indicate the type of plane i, and the mean inter arrival time in days a. ASB707, ASB727 ... ASDC10 are subtypes of ArvSchnlr that have specific values assigned to the i and a properties.

/*/********** PL = Plane **********/
CHARTYPE Plane i nEng c WB
A B p r;
 /***********************************************************************/
SUBTYPE Plane B707 1 4 2.1 0
 0.7 2.1 30 2.1;
 SUBTYPE Plane B727 2 3 1.7 0
 0.9 1.8 26 1.7;

Resources of type Plane have properties that indicate the type of plane i, the number of engines in the plane nEng; the daily downtime cost c; a flag to indicate their classification as regular (0) or Wide Body (1) WB; parameters for the duration of the inspection of one of its engines A, and B; probability of failing the first inspection p, and a parameter for the duration of the repair of one of its engines r. B707, B727 ... DC10 are subtypes of Plane that have specific values assigned to their properties.

Resources of type Plane additionally have the following read/write properties:

SAVEPROP Plane EngsToGo;
SAVEPROP Plane Repaired;
SAVEPROP Plane RepStartTm;

EngsToGo keeps track of how many engines in a plane are pending inspection/repair. Repaired is a flag that indicates if the current engine has been repaired already. RepStartTm stores the simulation time at which a plane checks-in.

/*/********** SF = ServFac **********/
GENTYPE ServFac;

ServFac is the actual type name used for the service facility resource type.

2.2.2.3 NETWORK DEFINITION

The network shown graphically in figure 1 is defined in the source file as follows:

/*/********** Queues ***********/
QUEUE ArvSchnlr ArvSchnlr;
QUEUE PlaneWorld Plane;
QUEUE PlanesWait Plane;
QUEUE ServiceFac ServiceFac;
Combis

combi InterArrival;
combi CheckInPl;

Normals

normal Inspect;
normal Repair;
normal CheckOutPl;

Forks

fork PassInsp Plane;
fork IsPlDone Plane;

AS Cycle

link AS1 ArvlSchdlrs InterArrival;
link AS2 InterArrival ArvlSchdlrs;

PL Cycle

link PL1 PlaneWorld InterArrival;
link PL2 InterArrival PlanesWait;
link PL3 PlanesWait CheckInPl;
link PL4 CheckInPl Inspect Plane;
link PL5 Inspect PassInsp;
link PL6 PassInsp Repair;
link PL7 Repair Inspect Plane;
link PL8 PassInsp IsPlDone;
link PL9 IsPlDone Inspect;
link PL10 IsPlDone CheckOutPl;
link PL11 CheckOutPl PlaneWorld;

SF Cycle

link SF1 ServiceFac CheckInPl;
link SF2 CheckOutPl ServiceFac;

The preceding statements that define the graphical network can be inferred directly and unambiguously from figure 1. This section of a Stroboscope model is highly amenable to interactive graphics preprocessing tools.

2.2.2.4 Modeling Element Attributes

Elements in the network have attributes that define the way they behave. Attributes have default values that make the network element to which they apply behave the natural or expected way. In the next part of the source file, attributes of modeling elements that are different from the default are set:

drawwhere PL1
   i=InterArrival.ArvlSchdlr.i;

ordinarily, a Combi starts by removing the first available resource from each one of the Queues that precede it. The statement above specifies that the plane to be removed by the InterArrival Combi from the PlaneWorld Queue through Link PL1 must be such that its i property is the same as the i property of the arrival scheduler already acquired. Note that Link AS1 is defined before Link PL1 in the network definition; this is indicated in the network drawing with the superscripts on the Link labels.

duration InterArrival
   "Exponential[
      InterArrival.ArvlSchdlr.a];"

Unless otherwise specified, an activity (Combi or Normal) has no duration. This statement indicates that the duration of an instance of the InterArrival Combi is sampled from an exponential distribution with mean equal to the a property of the arrival scheduler acquired.

Discipline PlanesWait
   WideBodyFirst=-WB:1;
   /i.e., IF(WideBodyFirst,-WB,1)

The default queuing discipline for Queues is FIFO. The above statement sets the discipline for Queue PlanesWait to give priority to wide-body planes if the WideBodyFirst variable is true (i.e., not zero). Otherwise the discipline remains FIFO. When resources tie in their values of WB, the FIFO rule takes effect. Similarly, in the case in which WideBodyFirst is false, the constant sub-expression '1' is the same for all resources and thus a strict FIFO rule takes effect again.

collector WaitCost;
ondraw PL3 WaitCost
   (SimTime-TimeIn)*c;

WaitCost is a statistics collector that keeps track of costs incurred while planes are waiting. When the CheckInPl Combi draws a plane from the PlanesWait Queue, the cost incurred (the time spent in queue multiplied by the daily cost of the plane c) is added to the set of samples collected by WaitCost (SimTime is a system maintained variable that represents the current simulation time and TimeIn is a read-only property defined and updated by the system).

onrelease PL4 EngsToGo nEng;
onrelease PL4 Repaired 0;
onrelease PL4 RepStartTm SimTime;

When CheckInPl releases a plane through Link PL4, the EngsToGo, Repaired, and RepStartTm properties of the plane are initialized. Originally all the engines in the
plane are pending service (EngsToGo=xEng) and the current engine has not been repaired (Repairede=0). The plane is checked into the facility at the simulation time at which it flows through Link PL4 (RepStartTM = SimTime).

VARIABLE RepairFactor

1+Inspect.Plane.Repaired;

The time required to inspect an engine and the probability that the engine requires repair are reduced by a factor of 2 if the engine has already been repaired. RepairFactor is an auxiliary variable that is re-computed every time it is used. Its value is either 1 or 2, depending on the value of the Repaired property of the Plane currently in the Inspect Normal.

DURATION Inspect


The duration of an engine inspection is uniformly distributed between the A and B properties of the Plane to which it belongs. If the engine has been previously repaired, the time is reduced by 50%.

STRENGTH PL9

Inspect.Plane.p/RepairFactor;

STRENGTH PL8

100-Inspect.Plane.p/RepairFactor;

The probability that a Fork activates a particular successor depends on the strength of the Link that goes from the Fork to the successor. The strength of a post Fork Link is converted to a probability through division by the sum of the strengths of all the Links that originate from the Fork. The probability that the PassInsP Fork activates the Repair Normal is given by the p property of the Plane held by the Inspect Normal. If the engine has been previously repaired, the probability is reduced by 50%.

ONRELEASE PL5 EngsToGo

EngsToGo !Repair.InContext;

ONRELEASE PL5 Repaired

!Repair.InContext ?Repaired; / i.e., !x means IF(x<>0,0,1)

When the Inspect Normal releases a plane through Link PL5, Stroboscope updates the EngsToGo and Repaired plane properties. EngsToGo is decremented and the Repaired flag is cleared if the engine passes the inspection !Repair.InContext returns 0 if Repair is the node selected and activated by the PassInsP Fork at the end of the Inspect Normal, otherwise it returns 1.

DURATION Repair

'Erlang[2,Repair.Plane.r/ (Repair.Plane.Repaired+1)];

The duration of the Repair Normal follows a 2-Erlang distribution with mean equal to the r property of the acquired Plane. If the plane has been repaired, the mean is reduced by 50%.

ONRELEASE PL7 Repaired 1;

When repairs on an engine conclude, the Repaired flag for the plane is turned on.

STRENGTH PL9

Inspect.Plane.EngsToGo=!1;

STRENGTH PL10

Inspect.Plane.EngsToGo==!1;

When the PassInsP Fork activates the IsPlDone Fork, IsPlDone decides whether to activate the Inspect Normal (go to the next engine in the same plane) or the CheckOutPl Normal (all engines have been serviced). The Boolean expressions that define the strengths of Links PL9 and PL10 force the probabilities to be 1 for one Link and 0 for the other. The Strength of PL10 is 1 when all engines have been serviced (EngsToGo is 1 but will be decremented to 0 when the plane is released through Link PL5).

RELEASEAMT SF2 1;

When the CheckOutPl Normal finishes, it releases the corresponding service facility through Link SF2 (the service facility had been removed by the CheckInPl Combi and was implicitly carried along with a plane).

COLLECTOR ServiceCost;

ONRELEASE PL11 ServiceCost

(SimTime-RepStartTM) *c;

ServiceCost is a statistics collector that keeps track of costs incurred while planes are serviced. When the CheckOutPl Normal releases a plane to the PlanesWorld Queue, the cost incurred (the time spent between check-in and check-out multiplied by the daily cost of the plane c) is added to the set of samples collected by ServiceCost.

At this point the behavior of the model is completely defined.
2.2.2.5 QUEUE INITIALIZATION

The model’s resources are created from the defined types and placed in the appropriate Queues:

INIT ArvlSchdlrs 1 ASB707;
INIT ArvlSchdlrs 1 ASB727;
INIT ArvlSchdlrs 1 ASB737;
INIT ArvlSchdlrs 1 ASB747;
INIT ArvlSchdlrs 1 ASC8;
INIT ArvlSchdlrs 1 ASDC9;
INIT ArvlSchdlrs 1 ASDC10;

One Arrival Scheduler of each type is created and placed in the ArvlSchdlrs Queue.

INIT PlaneWorld 60 B707;
INIT PlaneWorld 60 B727;
INIT PlaneWorld 60 B737;
INIT PlaneWorld 60 B747;
INIT PlaneWorld 60 DC8;
INIT PlaneWorld 60 DC9;
INIT PlaneWorld 60 DC10;

A sufficiently large number of planes of each type are created and placed in the PlaneWorld Queue.

INIT ServiceFac nServiceFacilities;

The appropriate number of service facilities are made available by setting the initial content of the ServiceFac Queue.

2.2.2.6 SIMULATING & PRINTING RESULTS

Finally, the source file contains instructions that perform the simulation and display the results:

SIMULATE UNTIL SimTime>=DaysToSimulate;

The simulation will run until the value of SimTime becomes at least as large as the number of days to simulate.

PRINT StdOutput "FIFO=0, WB/FIFO=1" : $0.0f
!!WideBodyFirst;";

PRINT StdOutput "FIFO=1, WB/FIFO=1" : $0.0f
!!WideBodyFirst;";

PRINT StdOutput "Av. downtime cost : $0.2f $/day
(WaitCost.SumVal+ ServiceCost.SumVal)/SimTime*10000;";

PRINT StdOutput "Av. delay in Queue : $0.2f days
PlanesWait.AveDur;";

PRINT StdOutput "Av. planes in Queue : $0.2f
PlanesWait.AveCount;";

REPORT StdOutput;

Print to standard output the queuing discipline, number of service facilities, average daily downtime cost, average delay in queue, and average number of planes in queue. The last statement prints a report that shows detailed statistics about the modeling elements and the resources involved in the simulation.

2.3 RESULTS

The output from a run of this model (the detailed statistics report is omitted due to space considerations) is as follows:

(FIFO=0, WB/FIFO=1) : 0
Service facilities : 11
Av. downtime cost : 323985 $/day
Av. delay in Queue : 2.59 days
Av. planes in Queue : 3.73

For each Queue, the detailed report presents the current content, lifetime content, average waiting time, and average, standard deviation, minimum and maximum queue length.

For each Activity, the detailed report presents the number of currently active instances; the lifetime number of instances; the time at which the first and last instances started; the average, standard deviation, minimum and maximum duration of the instances; and the average, standard deviation, minimum and maximum times between successive instantiations.

For all possible combinations of Subtypes and network nodes, the detailed report presents the average number of entries, average total time spent, and average, standard deviation, minimum and maximum visit time.

For each collector, the detailed report presents the number of samples and the average, standard deviation, minimum and maximum of the values collected.
3 IMPLEMENTATION

Stroboscope is implemented in two forms: a command-line compiler and an MS Windows integrated development environment (editor-debugger-compiler). Both are native MS Windows NT 32-bit programs developed in C++. The command-line compiler can run under DOS using the TNT DOS-extender. The integrated development environment can run under MS Windows 3.1, if the Win32s subsystem is installed.

4 CONCLUSION

The example presented in this paper illustrates Stroboscope’s power as a general-purpose simulation system. Complex and realistic problems such as the example presented can be modeled, analyzed and optimized quite easily.

REFERENCES


AUTHOR BIOGRAPHIES

JULIO C. MARTINEZ is a Horace H. Rackham Pre-Doctoral Fellow and a Doctoral Candidate in Civil Engineering at the University of Michigan. He designed and implemented the Stroboscope simulation language as partial fulfillment of the requirements for the degree of Doctor of Philosophy (Civil Engineering) at the University of Michigan. He received a Civil Engineer’s degree from Universidad Catolica Madre y Maestra (Dominican Republic) in 1986, an M.S. degree in Civil Engineering from the University of Nebraska in 1987, and an M.S.E. degree in Construction Engineering and Management from the University of Michigan in 1993. His research interests are in computer applications to Construction Engineering and Management.

PHOTIOS G. IOANNOU is an Associate Professor in the Department of Civil and Environmental Engineering at the University of Michigan. He received a Diploma in Civil Engineering from the National Technical University, Athens, Greece, in 1979; and he received a SMCE and PhD from MIT in 1981 and 1984 respectively. He is currently serving as Chairman of the Computing in Construction Committee of the American Society of Civil Engineers. He co-developed the UM-CYCLONE construction process simulation system with R. I. Carr, supervised the design and development of COOPS by L. Y. Liu, and is currently serving as chairman of J. C. Martinez’s PhD Dissertation committee. His research interests are primarily focused on the areas of construction decision support systems and construction process modeling.