

SPECIAL PURPOSE SIMULATION TEMPLATE FOR WORKFLOW ANALYSIS IN CONSTRUCTION

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ABSTRACT

Workflow analysis is an important component in the simulation of construction operations. It involves creating a specific number of work requests for a crew every time period, computing outputs such as work arrival rate for a downstream crew and plotting work in process (WIP). These outputs are not directly provided in many construction simulation software tools. Determining these outputs is generally considered a time consuming and tedious undertaking. Developing modeling constructs that automate the computation of these workflow outputs will be useful for construction modelers. This paper presents a special purpose simulation (SPS) template developed for workflow analysis. The SPS template consists of four modeling constructs that implement the workflow analysis functionalities mentioned above. The SPS template logic was verified using two simulation experiments. Use of this SPS template for analyzing different workflow based issues as well as to test the production management principles in construction is also highlighted.

1 INTRODUCTION AND BACKGROUND

Construction projects can be envisioned as a series of interconnected work processes. Work items flow from upstream processes to downstream processes during project completion. Of course, this concept is often employed in manufacturing settings, where the work piece flows through the workstations; to employ the concept in construction one must instead visualize the “workstations” as crews moving past the partially completed structure. In addition to managing a project using task-based management approaches such as project networks, construction managers use workflow to monitor and manage the project. This is especially true on repetitive construction projects such as high-rise construction and homebuilding. Production parameters such as the number of work requests released, the

number of work requests flowing through the processes, and work in process are considered useful in managing production. Determining these production parameters requires either custom coding by the modeler or post processing of the simulation trace which takes significant time. Discrete event simulation can be utilized to conduct the workflow analysis and produce the resultant production parameters.

2 USE OF SIMULATION FOR WORKFLOW ANALYSIS

Construction projects consist of a number of repetitive processes even though each project is unique (Abourizk et al 1992). This repetitive nature of construction enables the application of discrete event simulation (essentially process and resource based simulation) in construction. The application of simulation in construction was popularized first through the development of CYCLONE methodology (Halpin 1977). The CYCLONE methodology has been used to model and analyze numerous construction operations (Halpin and Riggs 1992). The CYCLONE modeling framework provided the foundation for construction simulation researchers to develop a number of construction simulation tools in the past 25 years. These include INSIGHT (Paulson 1978), MicroCYCLONE (Lluch and Halpin 1982), RESQUE (Chang and Carr 1986), UMCYCLONE (Ioannou 1990), COOPS (Liu and Ioannou 1992), CIPROS (Odeh et al 1992), STROBOSCOPE (Martinez and Ioannou 1994) and Symphony (Hajjar and Abourizk 1999). For a detailed review on the construction simulation literature, the reader can refer to Abourizk et al (1992), Sawhney and Abourizk (1993), Martinez and Ioannou (1999), Hajjar and Abourizk (2002) and Palaniappan et al (2006).

Although a number of software tools have been developed for construction simulation, the applications of most of them are limited to the academic/research community.

Most of the available simulation tools are based on General Purpose Simulation (GPS) concepts and provide abstract modeling constructs requiring significant knowledge of discrete event simulation. In order to address this issue the concept of Special purpose simulation (SPS) was introduced. SPS is defined by Abourizk and Hajjar (1998) as a domain-specific simulation tool that encapsulates domain knowledge into modeling elements that are used to build and simulate domain-specific models. The key concepts of SPS based tools include: domain specific modeling constructs that offer high degree of resemblance between simulation model representation and the real world construction objects, flexible visual modeling environment, producing outputs in a format that is native to the user, and modular hierarchical modeling (Hajjar et al 1998). Using the SPS concepts, three independent construction simulation tools were developed namely ‘AP2-Earth’ for the analysis of large earth moving projects (Hajjar and Abourizk 1997); ‘CRUISER’ for modeling aggregate production plants (Hajjar and Abourizk 1998); and ‘CSD’ for construction site dewatering (Hajjar et al 1998). Based on the experience gained through the development of these three tools, a framework capturing the common design patterns and the reusable code components required for developing a SPS tool was identified (Hajjar and Abourizk 2000). This framework resulted in a construction simulation tool development and utilization environment called ‘Symphony’. Symphony provides a number of SPS templates such as earth moving, aggregate production, construction site dewatering, tunneling, and tower crane (Hajjar and Abourizk 2002).

The GPS based tools do not provide features that allow rapid workflow analysis of simulated processes. To address this issue the authors have extended the concept of special purpose template to include these analysis features. This work presents the details of a special purpose simulation template developed for modeling and analysis of workflow in construction. The specific objectives of this work are:

- study the characteristics of workflow analysis in construction
- identify a list of special purpose modeling constructs
- design and implement the modeling constructs
- verify the logical correctness of modeling constructs through simulation experiments and demonstrate its usefulness for workflow analysis in construction simulation

3 MODELING WORKFLOW

Construction projects can be modeled as a series of work processes linked to each other in a dependent network, with some processes running serially and some running concurrently. This approach is used in a number of practi-

cal and theoretical abstractions, including simulation modeling and scheduling, for example. In this world-view, work flows from one process to the next, typically as completed work ready for the next process to augment. The potential deleterious effects of the inter-linkages between processes (sometimes called “handoffs”) have been highlighted by past studies (Ballard and Howell 1994, Howell et al 1993, Tommelein et al 1999, Walsh et al 2007, Sawhney et al. 2007). The focus of workflow modeling is to capture these effects and allow managers to visualize impact of their decisions on the workflow. This focus is also sometimes referred to as production management view of the construction process.

Figure 1 shows a process map with a portion of a project’s interlinked work processes. A mechanism by which work is released into the project is provided in the beginning of this process map. Work items can be released into the system at a uniform or non-uniform rate. A number of processes interlinked to each other via buffers or quality control inspections are also included in the process map. Work released to the upstream processes is completed and is sent to downstream work processes. At any given time the system can have a number of work requests that are being processed. Processes are sometimes supplied with resources such as crews where needed. Rework resulting from failed quality control inspections is also provided in the process map. To model, simulate, and analyze the workflow in a generic process described above, a SPS template was created.

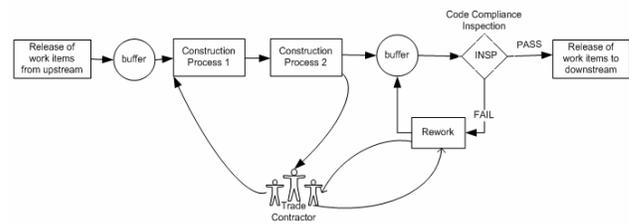


Figure 1: Characteristics of workflow analysis

3.1 SPS Modeling Constructs

To model a generic construction process and capture the workflow characteristics shown in Figure 1, an SPS template was created. Four modeling constructs identified for the SPS template are described as follows:

3.1.1 Generating a Set of Work Items Per Time Period

This refers to the generation of a specific number of work items or requests per time period (such as a week) to a work process. The number of work items generated per time period can be uniform or variable based on the production goals of the general contractor or owner for example number of bays released on a floor of a high-rise building. Time between arrivals of any two sets of work items is

usually constant in this case and it is equal to the number of days in a week. A modeling construct named 'Starts' was designed to implement this functionality. The input parameters for this modeling element are number of weeks, number of work items to create every week, number of days in a week or time between arrivals of work items between two weeks. The processing logic of this modeling element is to release a specific number of work items every week based on the given input. This is different from the functionality of the CREATE node in the conventional discrete event simulation where input variables are number of entities to create, time at which first entity is created, time between the arrival of any two entities.

3.1.2 Computing the Number of Work Items Per Time Period at Any Downstream Step

The analysis of workflow variability is an important part of the production management approach. Variability in the workflow between any two processes can be analyzed by computing the number of work items before or after any process step per time period from an upstream process to a downstream process. In general, even for a linear process, a poor process performance on the upstream results in a highly variable workflow to the downstream process. On the other hand, an ideal performance on the upstream may generate uniform work flow to downstream processes each week. This functionality was implemented using a modeling construct named 'NOS' (Number of starts). This modeling construct can be placed between any two construction processes so that all work items that complete a construction process in the upstream passes through this element before reaching the downstream process. The processing logic is to compute the number of work items released per week to the downstream process.

3.1.3 Work in Process (WIP)

Work in process (WIP) refers to the number of work items that are in progress in a construction process. WIP for a process can be estimated by computing the number of work items that are in progress each week during the simulation period. The number of work items in this calculation refers to both work items that undergo construction and rework process and the work items that wait for the resource. WIP plots can be used to study workflow issues such as the performance of a process or to identify bottleneck associated with a process, and also to calculate inventory holding costs. A modeling construct named 'WIP' was designed to implement this functionality.

WIP for a construction process can be computed as the difference between cumulative number of inputs to the process and the cumulative number of outputs from that process each week. The input parameters to the 'WIP' modeling element are two 'NOS' modeling constructs. The 'NOS' modeling element placed before the process is used

to compute the number of inputs per week to the process. The number of outputs per week from the process is computed using the 'NOS' element placed after the process. At the end of the simulation, the 'WIP' modeling construct accesses the input and the output data from the two NOS elements, computes cumulative inputs and cumulative outputs and finds the WIP.

3.1.4 Number of Work Items Waiting for a Resource

To design an effective process flow configuration for a system, workflow analysis is performed and potential bottlenecks in any processes of a project are identified. Examples of bottlenecks include long cycle time or waiting time for work items due to limited crew availability or inefficiencies in the processes such as reworks, or a mismatch in process capacity between adjacent activities. Most of the discrete event simulation tools only provide a one point estimate such as average number of entities waiting in the queue or the average waiting time of entities. In addition to these outputs, plotting the number of entities in the queue at specific time intervals during the simulation period will enable a modeler to get better understanding of the system performance. This functionality was implemented using a modeling construct named 'PQL' (print queue length). This modeling element provides the number of work items that wait for a resource in a queue at specific time intervals during the simulation period. The input to this modeling element is a queue or waiting file in the simulation model. The processing logic of this modeling construct is to access the queue at specific time intervals and stores the number of entities that are waiting for resource.

4 TEMPLATE IMPLEMENTATION

The SPS template for construction workflow analysis was implemented using the construction simulation environment called 'Symphony.NET' (Abourizk and Mohamed 2000). The implementation of the template consists of three steps. The first step is to define the template and the modeling elements. A new template and the list of modeling elements within that template can be defined using the template manager. The second step involves assigning two types of images to each modeling element namely bitmap ('.bmp') and icon ('.ico') files. Bitmap images define the way the modeling element is shown in the simulation model. Icon files define the way each modeling element will appear in the template menu that is shown in the left navigation portion of Symphony.NET menu. The third step is to implement the logic of each modeling element by writing code for various event handlers that are available within Symphony.NET. The logic of each modeling element is defined using several event handlers such as 'OnCreate', 'OnGraphicsInitialize', 'OnSimulationInitialize', 'OnSimulationInitializeRun', 'OnSimulationProcessEvent', 'OnSimulationPostRun', and 'OnListBoxInitialize'.

The snapshot of the Simphony platform with the code window and various event handlers is shown in Figure 2. For additional details on the template development, the reader can refer to Hajjar and Abourizk (1999).

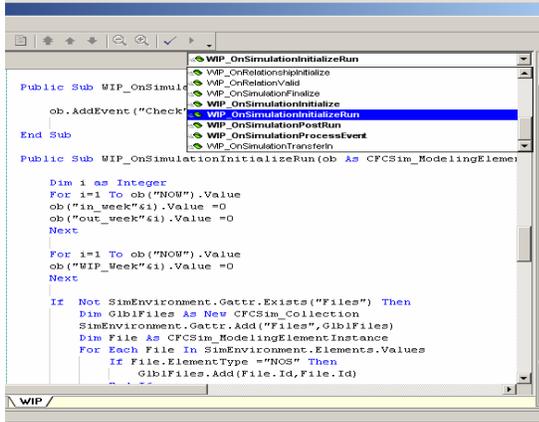


Figure 2: Simphony Code Window for Event Handlers

The construction simulation object library available within Simphony.NET was utilized to develop the SPS template. This library simplifies the template development process through several built-in classes and functions for modeling many simulation related services. This allows the SPS template developer to focus more on the domain specific logic implementation. To obtain further details, the reader can refer to the Simphony.NET FAQ and the developer’s reference available at the URL: <irc.construction.ualberta.ca/html/research/software/simphony.net.html>. Manuals for various SPS templates developed in Simphony are available in <irc.construction.ualberta.ca/html/research/software/simphony_legacy.html> (URLs accessed on 15th March 2007). The four modeling constructs identified for workflow analysis are presented in Table 1.

Table 1: Workflow analysis SPS template modeling constructs

| Modeling Construct | Bitmap Image |
|--------------------|--------------|
| Starts | |
| NOS | |
| WIP | |
| PQL | |

‘Starts’ Modeling Construct: ‘Starts’ simulates the generation of specific number of work items each week based on the input given by the user. This modeling element was implemented by adapting the functionality of CREATE node that is part of the COMMON template available within Simphony.NET platform. Figure 3 shows a snapshot that provides the graphical user interface (GUI) details of the ‘Starts’ node. The time between arrivals or generations of any two sets of work items is constant and is equal to 7 days. Variables ‘Quantity1’ through ‘Quantity5’ represent the number of work items that will be generated in weeks ‘week 1’ through ‘week 5’ respectively. The GUI will be dynamically updated to include additional ‘Quantity’ variables when the user changes the value of number of weeks (‘NoOfWeeks’). These variables are defined in the ‘OnCreate’ event handler. The logic for generating a specific number of work items each week is implemented using the event handler ‘OnSimulationProcessEvent’.

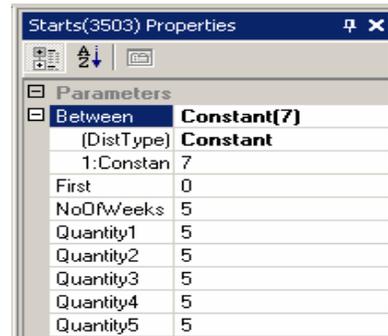


Figure 3: Starts Modeling Construct

‘NOS’ Modeling Construct: ‘NOS’ modeling element computes the number of work items that are released each week to a downstream process. This modeling element was implemented by adapting the functionality of COUNTER node that is part of the CYCLONE template available within Simphony.NET platform. Figure 4 shows a snapshot that provides the graphical user interface (GUI) details of the ‘NOS’ node. The variables ‘week1’ through ‘week9’ represent the number of work items that are released to the downstream process from week 1 to week 9 respectively. For example, in this case, 5 work items were released in weeks 4, 5, 6, 7 and 8. These variables are defined in the ‘OnCreate’ event handler. The logic for counting the number of work items released each week is implemented in the ‘OnSimulationProcessEvent’ event handler. The results of the NOS node shown in the GUI are written as text output file with the file name same as the name of the NOS node (‘NOS_4094.txt’ in this case). The GUI of NOS node can be instantly modified by the user to collect workflow data for any number of weeks, for example 100 weeks, by changing the value of a hidden variable ‘NOW’ from 9 to 100.

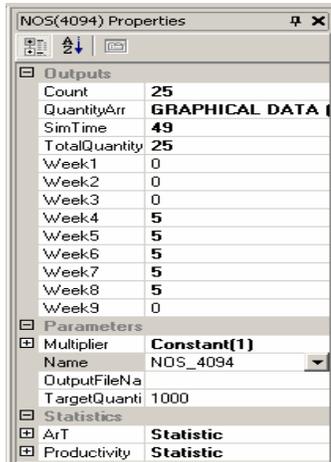


Figure 4: NOS Modeling Construct

‘WIP’ Modeling Construct: ‘WIP’ modeling element computes the number of work items that are in progress for a process or a set of processes bounded by any two points specified by the user. The ‘WIP’ modeling element is implemented as a stand alone modeling element similar to the ‘waiting file’ or ‘resource declaration’ available in the COMMON template. Figure 5 shows a snapshot providing the GUI details of the WIP node. The variables ‘WIP_Week1’ through ‘WIP_Week9’ show the work in process from week 1 to week 9 respectively. For example, in this case, the WIP for week1, week2 and week3 are 5, 10, and 15 respectively. These variables are defined in the ‘OnCreate’ handler. The logic for computing WIP is implemented in the ‘OnSimulationPostRun’ event handler. The WIP results shown in the GUI are written as text output file with the file name same as the name of the WIP node (‘WIP_4097.txt’ in this case). In the GUI shown in Figure 5, WIP data is collected for 9 weeks. This can be extended to any number of weeks by changing the value of the hidden variable ‘NOW’, for example from 9 to 100.

WIP modeling element consists of two input parameters namely ‘From_This_NOS’ and ‘To_This_NOS’. These two input parameters define the start and the end point for WIP computation. The user can select any NOS node that is present in the simulation model as a potential input for these two input parameters. As shown in Figure 5, the NOS nodes ‘NOS_4091’ and ‘NOS_4094’ are selected as the start point and the end point respectively. The cumulative inputs and the cumulative outputs for every week are calculated using the data obtained from ‘NOS_4091’ and ‘NOS_4094’ respectively. WIP is computed as the difference between cumulative inputs and the cumulative outputs for each week. The implementation of WIP modeling element has three key steps namely populating the list of NOS nodes as input to the user, obtain the reference of the selected NOS object and get the workflow data from the selected NOS node using the reference. Sample code for these three key steps is presented in Figure 6.

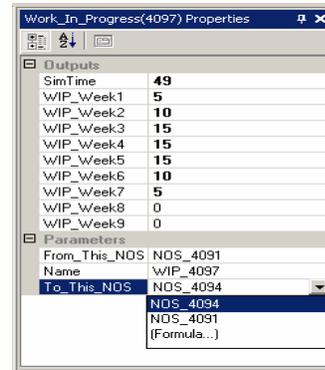


Figure 5: WIP Modeling Construct

```
Dim list As New ArrayList
Dim File As CFCSim_ModelingElementInstance
if attr.name = "From_This_NOS" then
For Each File In SimEnvironment.Elements.Values
If File.ElementType = "NOS" Then
list.Add(File("Name").Value)
End If
Next
End if
```

(a) Populate the list of NOS modeling constructs

```
Dim FileItem As CFCSim_CollectionItem
Dim ID As Integer
ob("FileObs").Reference=Nothing
For Each FileItem In SimEnvironment.Gattr("Files").Values
ID = System.Convert.ToInt32(FileItem.Item)
If SimEnvironment.Elements(ID)("Name").Value = ob("From_This_NOS").Value Then
ob("FileObs").Reference =
SimEnvironment.Elements(ID)
ob("Id_From_NOS").Value = ID
Exit For
End If
Next
```

(b) Obtain the reference of the NOS construct

```
Dim FileObStart As CFCSim_ModelingElementInstance
FileObStart = ob("FileObs").Reference
Dim i as Integer
For i=1 To ob("NOW").Value
ob("in_week"&i).Value =
FileObStart.Attr("Week"&i).Value
Next
```

(c) Obtain the workflow data from NOS construct

Figure 6: Sample Code for WIP Modeling Construct

‘PQL’ modeling construct: The GUI details of the ‘PQL’ node is shown in Figure 7. The input to this node is any waiting file present in the simulation model. In a typical simulation model various process steps use resources. A work item arriving at this process step looks for the resource and is processed only when a resource is available. If the resource is busy the work item waits for the resource. This waiting work item is typically stored in an internal waiting file. The PQL element accesses this waiting file to provide the PQL output needed by the modeler. The output is a text file that presents the number of entities waiting in the queue at specific time intervals during the simulation.

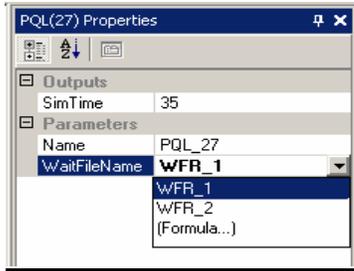


Figure 7: PQL Modeling Construct

A modeler interested in conducting a workflow analysis experiment can use this workflow analysis template in conjunction with other modeling elements to create a model of their construction process. By using the four modeling constructs they can study the workflow and other production parameters.

5 VERIFICATION OF THE WORKFLOW ANALYSIS TEMPLATE LOGIC

The workflow analysis SPS template was tested using two simple experiments. These experiments capture the key features of workflow analysis using examples from construction scenarios.

5.1 Experiment-1

The simulation model in this experiment consists of one Starts node, two NOS nodes, a service process and a WIP node. The duration for the service process is 21 days. Five work items are released every week from week 1 to week 5 using the Starts node. The snapshot of the simulation model developed in Symphony.NET is shown in Figure 8. The simulation results are presented in Table 2. It was found that the results generated by the SPS template are same as that of the manual method. This verifies the logical correctness of the modeling constructs in the workflow analysis SPS template implementation. Figure 9 shows the WIP plot for this experiment. The cumulative starts and cumulative finishes plot is shown in Figure 10.

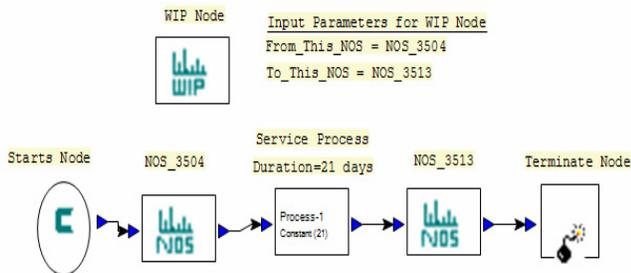


Figure 8: Simulation Model for Experiment-1

Table 2: Simulation Results (Experiment-1)

| Week | Number of work items released | | Cumulative | | WIP |
|------|-------------------------------|----------|------------|--------|-----|
| | NOS_3504 | NOS_3513 | Input | Output | |
| 1 | 5 | - | 5 | - | 5 |
| 2 | 5 | - | 10 | - | 10 |
| 3 | 5 | - | 15 | - | 15 |
| 4 | 5 | 5 | 20 | 5 | 15 |
| 5 | 5 | 5 | 25 | 10 | 15 |
| 6 | - | 5 | - | 15 | 10 |
| 7 | - | 5 | - | 20 | 5 |
| 8 | - | 5 | - | 25 | - |
| 9 | - | - | - | - | - |

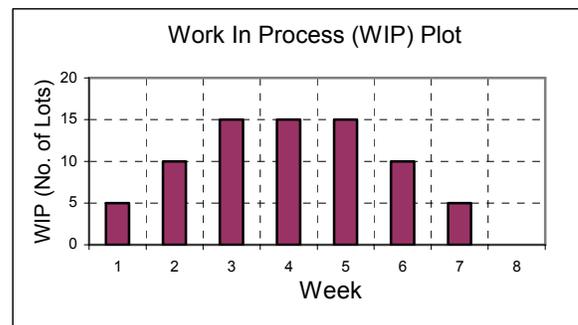


Figure 9: WIP Plot for Experiment-1

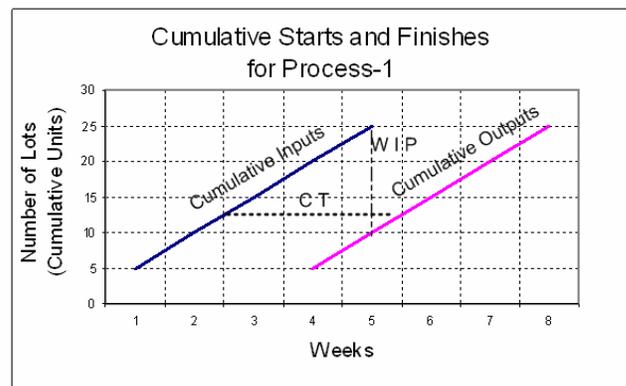


Figure 10: Cumulative Starts and Finishes (Experiment-1)

5.2 Experiment-2

This section discusses workflow analysis using a case study from the production home building. Production home building involves repetitive construction of multiple but similar houses. Multiple specialty trade contractors coordinate to complete the construction of each lot. Managing the workflow among these trade contractors is essential for the successful completion of each lot (Bashford et al 2003). Figure 11 shows the workflow characteristics of a typical production home building operation. The workflow

of a downstream trade contractor depends on the successful transfer of control from the preceding trade. Each trade gets a specific number of starts (lots) per week from the upstream process. If the trade crew is available, then the lot undergoes construction work immediately or else it waits till crew is available. Once the crew completes the construction work, the lot undergoes code compliance inspection process performed by the city building inspector. If the lot passes the inspection, it is released to the next trade; otherwise it undergoes a rework process by the same trade. It can be noted that the trade contractor crew is shared across multiple sub-divisions for performing both construction and rework. The lot undergoes rework and re-inspections repeatedly until it passes the inspection. The workflow between any two trade contractors is influenced by three key factors: the number of work starts per week by the upstream trade contractor, crew availability; and the inspection pass rate. In addition to the conventional simulation outputs such as cycle time, waiting time and crew utilization rate, workflow analysis in production home building requires the computation of the number of lots released per week to the downstream and the WIP of a process.

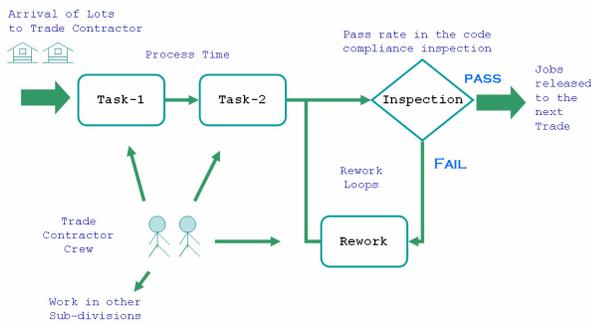


Figure 11: Production Home Building Operations

This experiment captures the key concepts of production home building workflow and demonstrates the analysis of workflow variability in a construction process with rework loops. The simulation model (shown in Figure 12) has one construction process with duration 3 days and a rework process with duration 2 days. It is assumed that the crew size is one. There is 25% probability of passing the first inspection and 80% pass rate in the successive re-inspections. The lot undergoes re-inspections repeatedly till it passes the inspection. Specific numbers of lots are released to the trade every week using the Starts node. In this model, the number of lots released from week 1 to week 11 is 2, 2, 2, 3, 2, 2, 3, 2, 2, 3, and 2 respectively. The number of lots finished by the trade every week is observed using the NOS node. This represents the workflow or the job arrival rate to the downstream trade contractor. Workflows for two scenarios were tested. The first inspection pass rate was 25% and 100% in the first and second scenarios respectively. The workflow computed using NOS node for

scenarios 1 and 2 are shown in Figure 13 and Figure 14 respectively (CT - cycle time and WIP - Work in Process). From the figures, it can be noted that the CT and WIP reduces significantly when the upstream pass rate improves from 25% to 100%. The workflows for the two scenarios were computed manually using the simulation trace and it was verified that the results generated by NOS node is same as the results based on manual calculations.

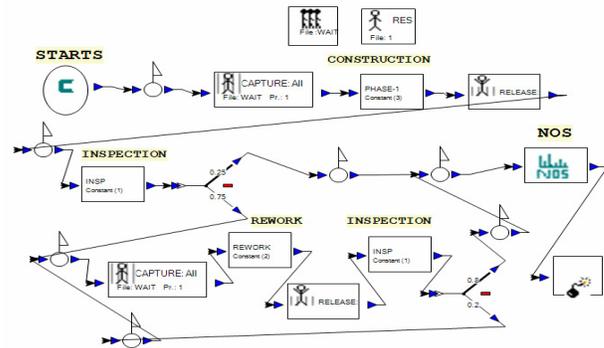


Figure 12: Simulation Model for Experiment-2

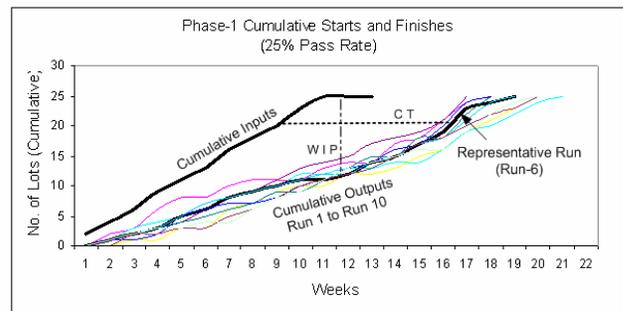


Figure 13: Downstream Workflow (Scenario 1)

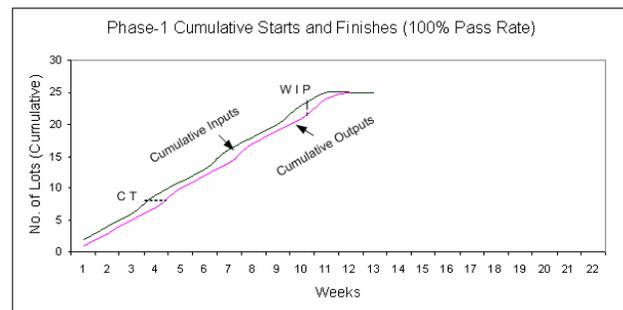


Figure 14: Downstream Workflow (Scenario 2)

CONCLUSIONS

Workflow analysis involves generation of a specific number of work orders every week, computing outputs such as work arrival rate for a downstream process and work in process. These outputs are not directly provided in most

construction simulation software tools that are currently available. Determining these outputs requires either custom coding by the modeler or post processing of the simulation trace which takes significant time. Automating the computation of these outputs will enable modelers to focus more on evaluating different scenarios rather than on post processing simulation output. This paper presented an SPS template developed for workflow analysis. Four SPS functionalities were identified based on the analysis of workflow characteristics including: a) generating a set of work items every week; b) computing the number of work items released every week to downstream; c) work in process; and d) plotting the number of work items waiting for resource at specific time intervals. Using these functionalities, an SPS workflow analysis template was designed and implemented using the construction simulation object library provided within Symphony. Two simulation experiments were conducted to verify the template. The use of this SPS template will significantly reduce the time spent by a modeler on calculating various outputs related to workflow analysis. This template helps in adopting a production management view for managing construction operations. In addition to looking at a task based network of activities for a construction project it is beneficial to study the flow of work for various disciplines on a construction project. For example with the help of the template the construction manager can study the impact of work release on various downstream trade contractors. Additionally the impact of various resource deployment strategies on WIP can be rapidly studied and an optimal course of action selected.

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