INTEGRATION OF PREDETERMINED MOTION TIME SYSTEMS INTO SIMULATION MODELING OF MANUAL CONSTRUCTION OPERATIONS

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Abstract: Simulation modeling is a powerful tool widely used for designing construction processes and improving the efficiency of operations. However, there is often difficulty in estimating the duration of manual tasks for simulation purposes due to its dependence on the physical attributes of the worker performing the task. When designing a new process, there is usually a lack of sufficient data regarding the required duration for manual tasks, and in the case of evaluating and improving existing processes, there is no benchmark data for workers’ performance to enable comparison of the efficiency of the existing process. This study attempts to address this issue by exploring micro-motion-level simulation modeling in order to provide standard motion time required to perform a manual task for effective workplace design. The research method involves integrating a Predetermined Motion Time System (PMTS) into discrete event simulation, which provides the production planner with a standard task duration within which a worker must complete the task without delays or idling. As a case study, a manual task taking place in the production line of a construction steel fabrication company has been modeled using the developed automation tool in order to verify the feasibility of the proposed approach. The results show high correlation between the simulation model output and the actual time data from the jobsite and confirm the validity of the approach and its effectiveness in evaluating the productivity of the existing operations and providing detailed information for process improvement.

1 INTRODUCTION

Construction simulation is a powerful tool that enables analysis of different scenarios of the work process in order to optimize the use of available resources. Decision makers and production planners can highly benefit from simulation modeling in order to increase the productivity of construction operations. One of the most essential pieces of information required to create effective simulation models is time data. It is crucial to use accurate and realistic time information to represent the duration of the various tasks of a simulation model. Production planners usually use company historical data to calculate the duration of different activities. However, due to the uniqueness and complexity of manual tasks, it is difficult to record sufficient historical time data pertaining to manual tasks. Also, in the case of assessing and improving existing work processes, there is a lack of benchmark data for workers’ performance to enable comparison of the efficiency of the existing process. Estimating the duration of manual tasks is difficult due to the variety of factors affecting it and also its dependence on the physical attributes of the worker performing the task. Time studies can be conducted to obtain estimates of manual task durations but require a substantial amount of time. As a result, Predetermined Motion Time Systems (PMTS) have been developed that provide a standard task duration within which a worker must complete a task without
delays or idling. By taking advantage of PMTS, construction practitioners can use more reliable estimates of the duration of manual tasks, and thus develop more realistic and efficient simulation models. This study explores micro-motion level simulation modeling and integrates PMTS into discrete event simulation to automatically calculate the standard duration required to perform a task based on simple design data used as input.

1.1 Simphony Platform for Special Purpose Simulation

Simphony (Hajjar and AbouRizk 1999) is a simulation modeling platform that enables creating general and special purpose simulation tools. In this context, Special Purpose Simulation (SPS) is defined as (AbouRizk and Hajjar 1998):

[A] computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications, and reporting are completed in a format native to the domain itself.

Simulation theory, application domain, and object-oriented programming are the main components of creating a special purpose simulation tool (Ruwanpura et al. 2001). Simphony provides a structured approach to developing user-friendly SPS templates and offers a comprehensive set of services under its framework including a discrete event simulation engine, a trace manager, statistics collection, graphing, random number generation, and report generation (AbouRizk and Hajjar 1998). This study uses Simphony as a discrete event modeling platform in order to develop a special purpose simulation focusing on manual tasks at a motion level. The developed SPS is compatible with Simphony’s general purpose simulation which enables integrating elements representing manual activities into larger simulation models of the construction operations.

1.2 Predetermined Motion Time System (PMTS)

Various PMTSs have been developed based on studying large samples of diverse manual operations in order to provide a standard time required to perform a task. PMTSs are created based on the assumption that a universal and precise duration can be determined for each basic motion (e.g., moving a finger, grasping an object), and the time for a complete task can be calculated by adding the time values of each basic motion described in the task (Genaidy et al. 1989). The most widely used PMTSs include Methods-Time Measurement (MTM) (Maynard et al. 1948), Maynard Operation Sequence Technique (MOST) (Zandin 1980), and Modular Arrangement of Predetermined Time Standards (MODAPTS) (Heyde 1966). The MODAPTS method is used in this study since it has more potential applications than earlier PMTSs and is reported to be 25% faster to apply than the latest MTM (MODAPTS 2006). Another advantage of the MODAPTS method is that it describes tasks in human terms rather than mechanical, making it easier to understand (Aft 2000).

MODAPTS was developed by Chris Heyde in 1966 (Stewart 2002) and is widely used in many industries, such as transportation, manufacturing, and health care, due to its simplicity and effectiveness. Designers, production planners, process engineers, and ergonomic analysts can evaluate and improve manual tasks using MODAPTS without the difficulties of recording and analyzing time data (Harputlu et al. 2012). The main concept behind MODAPTS is that all body motions can be expressed as multiples of a single finger movement and the time required to move a finger is called 1 MOD, which is equal to 0.129 second. MODAPTS enables users to describe a manual task as a sequence of motions, known as modules, and calculate an estimate of the standard time to perform the task as the sum of these modules. In order to use MODAPTS, a task has to be decomposed into basic motions defined by MODAPTS and for each basic motion a class and a numeric value (MOD value) has to be assigned. The final duration of the task will be the sum of the MOD values for the basic motions converted into seconds. MODAPTS classes are represented in MODAPTS codes with a capital letter and describe the motion type. Some frequently used MODAPTS classes include Movement, Get, Put, Walk, and Load Factor. As an example, M4G3 can represent the motion of moving the hand 12 inches with the whole arm to grasp a sheet of paper from a desk. For the purpose of this study, the MODAPTS method has been integrated into the simulation
modeling environment, enabling its use based on design data only, without requiring prior knowledge about MODAPTS and PMTS.

2 MICRO-MOTION LEVEL SIMULATION

Using the previously mentioned features of Simphony, the authors developed a micro-motion level special purpose simulation template, named MODAPTS.vb. In order to create a new SPS template, the modeling elements that will be used to create simulation models pertaining to the specific domain have to be first designed and then implemented. Designing these tasks requires thorough understanding of the targeted construction modeling domain (Hajjar et al. 2000). In the case of micro-motion level simulation, the modeling elements will need to represent motions associated with manual activities performed by a worker. In essence, one primary modeling element and six secondary elements were designed and implemented based on the MODAPTS method. The primary modeling element, named ManualTask, represents a manual task performed by a worker and requires some design data as input. Figure 1 shows these design inputs required. Based on the inputs, the simulation will calculate the required amount of time to perform the task based on the MODAPTS standard. As shown in Figure 1, the required set of inputs only includes simple design data (e.g., distance an object is carried, weight of the object, difficulty of grasping the object) that an operation designer or production planner will have at hand during design or redesign of a construction operation. As a result, this model will enable using a reliable standard duration for manual tasks without requiring prior knowledge about PMTS methods. Table 1 describes each attribute of the ManualTask element. This element can be used in any construction operation simulation model in conjunction with other elements of Simphony’s general template to represent a manual task (e.g., lifting, carrying, and placing an object).

Figure 1: Required inputs for the ManualTask modeling element
Six secondary elements have also been developed which encapsulate the lower level activities performed by a worker in order to complete a manual task. These elements include: Get, Move, Put, Walk, BendAndArise and SitAndStand. Figure 2 shows the ManualTask element and also the secondary elements inside the Simphony modeling environment. The secondary elements are designed based on the classes used by the MODAPTS standard. However, a designer not familiar with MODAPTS can also use these elements to model a detailed level motion of a worker. Some of these elements require an input (e.g., distance for the Walk element) and some can be used without any input from the designer (e.g., BendAndArise). The inputs required are the same as the ones used in the ManualTask element, but they are used as the attributes of the corresponding element. As an example, the PutCondition attribute of the Put element, which can be selected as GeneralLocation, WithTidiness, or ExactLocation, is the same as the EndPosition attribute of the ManualTask element.

The Move element represents the task of a worker moving his hand in order to grasp an object or put it down. The input for this task is the distance between the worker's fingers and the object. The Get element represents how a worker will grasp an object, which will either be touching an object (e.g., pressing a button), simple grasp (e.g., grasping a small tool without the need of visual feedback), or impeded grasp (e.g., grasping a particular bolt in a particular orientation from a container of bolts). The weight of the object should also be specified when using the Get element. The Put element deals with the condition of placing an object at a designated location and can be selected as placing an object in a general location (e.g., dropping a bolt into a bin), placing an object in a predetermined location and in a predetermined orientation, or placing an object at an exact location. The Walk element represents the task of a worker walking and requires the walking distance as input. The BendAndArise element represents the task of a worker bending to pick up an object and then arising and the SitAndStand element simply represents the task of a worker sitting and standing, while other tasks might occur in between. The secondary elements have been developed to give the designer or production planner more flexibility during redesign of the operations. The designer can focus on one of the lower level motions and change its attributes to investigate the impact on the simulation results. Furthermore, in cases when only one of these manual

<table>
<thead>
<tr>
<th>Input</th>
<th>Attributes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>-</td>
<td>The distance that the worker walks carrying an object.</td>
</tr>
<tr>
<td>EndPosition</td>
<td>GeneralLocation</td>
<td>Placing an object at a general location without attention to its exact position.</td>
</tr>
<tr>
<td></td>
<td>WithTidiness</td>
<td>Placing an object at a predetermined location using visual feedback.</td>
</tr>
<tr>
<td></td>
<td>ExactLocation</td>
<td>Placing an object at an exact location with increased attention.</td>
</tr>
<tr>
<td>RetrievalEnd / RetrievalStart</td>
<td>OneInch</td>
<td>Moving a finger less than 1 inch.</td>
</tr>
<tr>
<td></td>
<td>TwoInches</td>
<td>Moving a hand 2 inches or less.</td>
</tr>
<tr>
<td></td>
<td>SixInches</td>
<td>Moving a hand about 6 inches.</td>
</tr>
<tr>
<td></td>
<td>TwelveInches</td>
<td>Moving a hand about 12 inches by moving the arm.</td>
</tr>
<tr>
<td></td>
<td>EighteenInches</td>
<td>Moving a hand about 18 inches by moving the shoulder.</td>
</tr>
<tr>
<td></td>
<td>ThirtyInches</td>
<td>Moving the hand about 30 inches by moving the trunk.</td>
</tr>
<tr>
<td>StartGrasp</td>
<td>SimpleGrasp</td>
<td>Grasping an object without the need of visual feedback.</td>
</tr>
<tr>
<td></td>
<td>ImpededGrasp</td>
<td>Grasping an object that is difficult to grasp.</td>
</tr>
<tr>
<td>Weight</td>
<td>-</td>
<td>The weight of the object that is being handled.</td>
</tr>
</tbody>
</table>

Table 1: Description of attributes of the ManualTask element
activities (e.g., a worker walking without carrying an object) takes place between other non-manual activities, the appropriate secondary element has to be used instead of the primary element.

Figure 2: Modeling elements of the MODAPTS.vb SPS template

3 CASE STUDY

As a case study, the developed SPS template has been used to model manual activities taking place in a fabrication shop of a steel fabrication and construction service provider in Edmonton, Canada. The main base of operations of the company is a 70,000 m² facility comprising six fabrication shops and various manual tasks are performed by workers at these shops in two ten-hour shifts every day. Using micro-motion level simulation is essential for effective modeling of the construction operations at such a facility. The general sequence of operations at the shop is shown in Figure 3. In particular, the manual task of moving drilled steel plates from the drilling equipment and placing them in the designated bins is modeled as an example to illustrate the functionality of the elements in the MODAPTS.vb template. The sequence of motions consists of the worker picking up a drilled plate from the drilling station and walking a few meters to place it in a bin. The average weight of the plates is approximately 20 kilograms and the average size is 40 cm x 40 cm x 5 cm. In order to collect the required data, the task has been observed at the steel fabrication facility and the duration for the worker to perform the task has been recorded using a stopwatch. Also, for each iteration of the task, the weight of the plate that the worker handled, the distance that he walked carrying the plate, and the conditions of grasping (e.g., difficulty of grasping the plate) and placing (e.g., precision of the final location of the plate) the plate was also recorded. This data was collected for 18 instances of the task, with each cycle starting when the worker moved his hands to grasp the plate, until when he placed the plate at the designated bin.
The sequence of the manual tasks in the plate drilling workstation includes the worker collecting the plate from the drilling machine when the drilling is finished, carrying the plate to the designated bin, and placing the plate inside the bin. This whole task can be modeled using the ManualTask element. Figure 4 describes what each of the input attributes of the element represent in this manual activity.

![Diagram of the sequence of operations at the steel fabrication production line](image)

**Figure 3: Sequence of operations at the steel fabrication production line**

**Figure 4: Description of attributes for the plate handling task**

- What is the distance that the worker walks with plate in meters?
- How does the worker place the plate in the bin at destination?
- What is the distance between the worker's hand and the plate when he intends to pick up the plate from the drilling machine?
- What is the distance between the worker's hand and the plate when he places the plate in the bin?
- How hard is it to grasp the plate?
- How much does the plate weigh?
The same task can also be created using the secondary elements. Figure 6 shows the model using the secondary elements and a description of what activity each element represents. It should be noted that the plate handling task is modeled in Figure 5 as the only task for demonstration purposes and it will be used as part of larger construction operation simulation models in construction process design.

Table 2 shows the inputs for 10 instances of the plate handling task and the result of running the simulation model. For each task, the actual time that it took the worker to perform the task at the jobsite is also shown. The MODAPTS code and duration for each task is also calculated in order to compare it to the duration reported by the simulation time. The manual MODAPTS time is calculated for each task by summing the digits (MODs) of the MODAPTS code and multiplying it by 0.129 (1 MOD = 0.129 sec). As shown in the table, the simulation duration is consistent with the MODAPTS duration calculated manually.

Table 2: Input and results for the plate handling task

<table>
<thead>
<tr>
<th>Task</th>
<th>Weight (kg)</th>
<th>Distance (m)</th>
<th>Start Grasp</th>
<th>End Position</th>
<th>Retrieval Start (inch)</th>
<th>Retrieval End (inch)</th>
<th>Actual Time (sec)</th>
<th>Simulation Time (sec)</th>
<th>MODAPTS Code</th>
<th>Manual MODAPTS (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>6.5</td>
<td>Simple</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>8.2</td>
<td>7.224</td>
<td>M2G1L1W50 M2P0</td>
<td>7.224 (56x0.129)</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>1</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Thirty</td>
<td>Thirty</td>
<td>5.1</td>
<td>3.87</td>
<td>M7G3L3W8M7P2</td>
<td>3.870 (30x0.129)</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6</td>
<td>Impeded</td>
<td>General Location</td>
<td>Six</td>
<td>Two</td>
<td>7.3</td>
<td>7.482</td>
<td>M3G3L3W47 M2P0</td>
<td>7.482 (58x0.129)</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>6</td>
<td>Simple</td>
<td>General Location</td>
<td>Six</td>
<td>Thirty</td>
<td>7.5</td>
<td>7.869</td>
<td>M3G1L3W47 M7P0</td>
<td>7.869 (61x0.129)</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>5.5</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Six</td>
<td>Thirty</td>
<td>8.4</td>
<td>7.869</td>
<td>M3G3L3W43 M7P2</td>
<td>7.869 (61.129)</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>6</td>
<td>Impeded</td>
<td>With Tidiness</td>
<td>Six</td>
<td>Thirty</td>
<td>8.1</td>
<td>8.385</td>
<td>M3G3L3W47 M7P2</td>
<td>8.385 (65x0.129)</td>
</tr>
</tbody>
</table>

Worker moves his hand to pick up the plate after drilling is done.

Worker grasps the plate from the drilling machine.

Worker walks towards the bins with the plate in hand.

Worker moves his hand to place the plate inside the bin.

One cycle of the task is done.

Worker places the plate inside the bin.

Figure 5: Plate handling model using secondary elements
<table>
<thead>
<tr>
<th>Task</th>
<th>Weight (kg)</th>
<th>Distance (m)</th>
<th>Start Grasp</th>
<th>End Position</th>
<th>Retrieval Start (inch)</th>
<th>Retrieval End (inch)</th>
<th>Actual Time (sec)</th>
<th>Simulation Time (sec)</th>
<th>MODAPTS Code</th>
<th>Manual MODAPTS (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>10</td>
<td>5</td>
<td>Impeded</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>6.7</td>
<td>6.321</td>
<td>M2G3L3W39 M2P0</td>
<td>6.321 (49x0.129)</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6</td>
<td>Simple</td>
<td>General Location</td>
<td>Two</td>
<td>Two</td>
<td>8.2</td>
<td>7.095</td>
<td>M2G1L3W47 M2P0</td>
<td>7.095 (55x0.129)</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
<td>5</td>
<td>Impeded</td>
<td>With Tidness</td>
<td>Six</td>
<td>Twelve</td>
<td>6.7</td>
<td>6.966</td>
<td>M3G3L3W39 M4P2</td>
<td>6.966 (54x0.129)</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>4.5</td>
<td>Impeded</td>
<td>With Tidness</td>
<td>Six</td>
<td>Twelve</td>
<td>6.2</td>
<td>6.45</td>
<td>M3G3L3W35 M4P2</td>
<td>6.450 (50x0.129)</td>
</tr>
</tbody>
</table>

Figure 6 depicts the actual time versus the MODAPTS time resulting from the simulation model, visualizing the correlation between the actual time from data collection and the result of the simulation. Each point represents an iteration of the task. A correlation analysis has been performed between the actual time and the simulation time for 18 instances of the plate drilling task and a Pearson product-moment correlation coefficient of 0.96 has been calculated which indicates a very strong relationship.

![Pearson correlation coefficient = 0.96](image)

Figure 6: Correlation between actual time and MODAPTS simulation time

The results of the case study indicate that the proposed approach provides construction managers and production planners with a reliable estimate for the duration of manual tasks based on the MODAPTS system. The developed SPS template can be used to estimate the actual time of non-existing manual tasks based on MODAPTS using the correlation between the simulation time and the actual time from the jobsite. This correlation can be used as a benchmark for worker's performance to evaluate the efficiency of the ongoing operations and implement improvements.

The developed simulation template, in its current form, can be used to improve the efficiency of manual tasks of construction operations. In future work, the authors will also study incorporating ergonomic analysis into simulation modeling using the developed template, in order to provide the designer with an initial insight into the ergonomic risks associate with the operation design. The model will be linked to motion data by using the secondary elements and automated ergonomic evaluation will be performed to evaluate each manual activity based on standard ergonomic analysis tools.

## 4 CONCLUSION

Despite the wide use of simulation modeling for analyzing the efficiency of construction operations, there is a lack of automated methods to model manual tasks involved in construction processes. As these manual tasks have a considerable impact on the productivity of the operations, having reliable estimates...
of the duration of different types of manual construction activities can provide designers and production planners with more accurate production analysis results. The special purpose simulation tool developed in this study provides standard motion time data required for performing manual tasks based on the MODAPTS method inside a simulation modeling environment. One primary element and six secondary elements have been developed to model different types of manual construction activities. These elements can be used in conjunction with the elements of Simphony’s general template to model the manual motions of any construction process simulation model. This study can assist practitioners in modeling construction manual activities based on MODAPTS, without requiring prior knowledge about PMTS methods, and can assist researchers to further explore the impact of manual activities on construction operation efficiency. The correlation between simulation time and actual time can be used to evaluate the efficiency of the ongoing operations by providing a benchmark for production performance.

References


MODAPTS. 2006. MODAPTS© Modular Arrangement of Predetermined Time Standards. International MODAPTS Association, Woodbridge, VA, USA.

