Chapter 7
System Verification and System Validation

7.1 Introduction

One of the difficulties for Integrated System development is trying to determine whether a virtual system is an accurate representation of the actual system being simulated; that is, whether the system is valid and credible.

This chapter describes a practical discussion of how to test the accuracy and reliability of the Integrated System. The accuracy of the system is determines through system verification and system validation. The topics in this chapter are as follows: 1) system verification, 2) verification method, 3) system validation, 4) validation method, 5) results of system verification, and 6) results of system validation.

7.2 System Verification

In order to verify the accuracy of the system development, points of time and the action of the 3D models of construction activities generated by MAX Scripts programming are tested. All points of time must generate the correct action of construction activities (See Table 7.1).

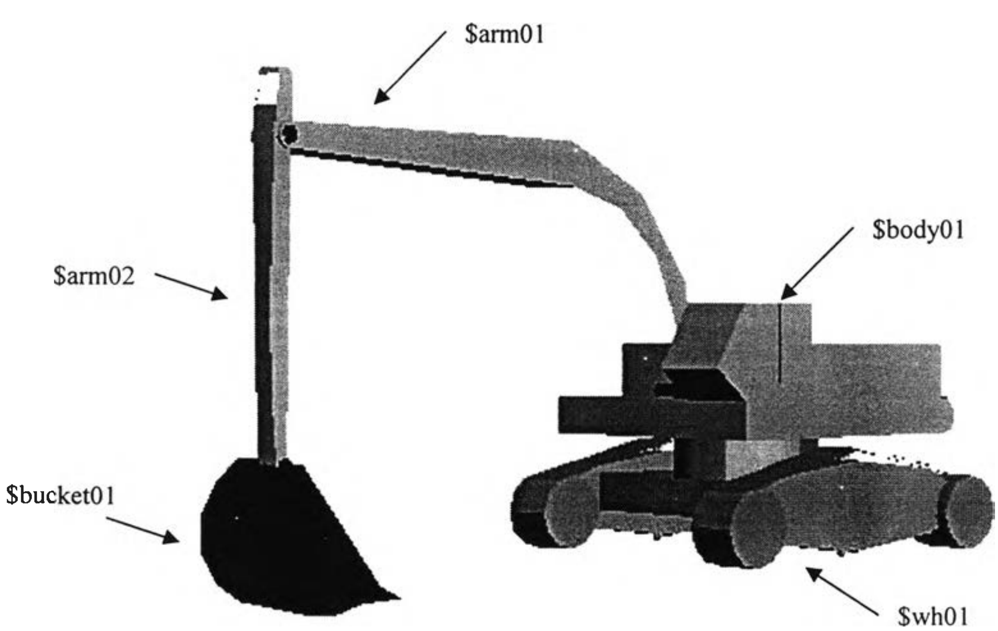

Figure 7.1: Names of excavator's components employed to verify the Integrated System

```
--------------------------------------------------------------------------------
--Source codes of earth excavation by one excavator: created by Noppadon J.
--------------------------------------------------------------------------------
hole = 3 --cu.m
buc = 1 -- cu.m
ncy = hole/buc
-----------------------
p1 = ncy-1
s= 1000f
-----------------------
t1 = 10f
t2 = 10f
t3 = 10f
t4 = 10f
t5 = 10f
t6 = 10f
t7 = 10f
t8 = 10f
t9 =  10f
t10 = 10f
t11 = 10f
t12 = 10f
t14 = 10f
t15 = 10f
-------------------------------------------------------
c = t1+t2+t3+t4+t5+t6+t7+t8+t9+t10+t11+t12+t14+ (2*t15)
n = c*p1
-------------------------------------------------------
ni = s+n -- end = start + sub total time
-------------------------------------------------------
d1=0
tr1=5
d2=d1+tr1
-------------------------------------------------------
for j = 1 to 5 do
(
for i in s to ni by c do
(
cy1= t1+i
cy2= cy1+t2
cy3= cy2+t3
cy4= cy3+t4
cy5= cy4+t5
cy6= cy5+t6
cy7= cy6+t6
cy8 = cy7+t7
cy9 = cy8+t8
cy10 = cy9+t9
cy11 = cy10+t10
cy12 = cy11+t11
cy14 = cy12+t12
cy15 = cy14+t14
cy16 = cy15+t15
------------------------------------------------------------------------------
n1= random 5f 10f
n2= random 50f 100f
-------------------------

m1 = cy16+n1
m2 = m1+n2
------------------------------------------------------------------------------
-- continue programming in next page
```

Figure 7.2: Source code used to verify earth excavation by one excavator

```
AnimationRange = Interval 0 m2
set animate on
    set time i
    rotate $body01 0 z_axis
set animate on
    set time cy1
    rotate $body01 90 z_axis
set animate on
    set time cy2
    rotate $arm01 0 x_axis
set animate on
    set time cy3
    rotate $arm01 30 x_axis
set animate on
    set time cy4
    rotate $bugket01 0 x_axis
set animate on
    set time cy5
    rotate $bugket01 60 x_axis
set animate on
    set time cy6
    rotate $arm02 0 x_axis
set animate on
    set time cy7
    rotate $arm02 20 x_axis
set animate on
    set time cy8
    rotate $arm01 0 x_axis
set animate on
    set time cy9
    rotate $arm01 -30 x_axis
set animate on
    set time cy10
    rotate $body01 0 z_axis
set animate on
    set time cy11
    rotate $body01 -90 z_axis
set animate on
    set time cy12
    rotate $arm02 0 y_axis
set animate on
    set time cy14
    rotate $arm02 20 y_axis
set animate on
    set time cy15
    rotate $bugket01 0 y_axis
set animate on
    set time cy16
    rotate $bugket01 60 y_axis
)

a = bezier_position ()
$wh01.position.controller = a
k = addNewKey a m1
k.value = [d1,20,0]
k.outTangentType = #linear
k = addNewKey a m2
k.value = [d2,20,0]
k.inTangentType = #linear
k.outTangentType = #step
s=m2
ni=m2+n
d1=d1+tr1
d2=d2+tr1
)
--end of programming
```

Figure 7.3: Source code used to verify earth excavation by one excavator (*continued*)

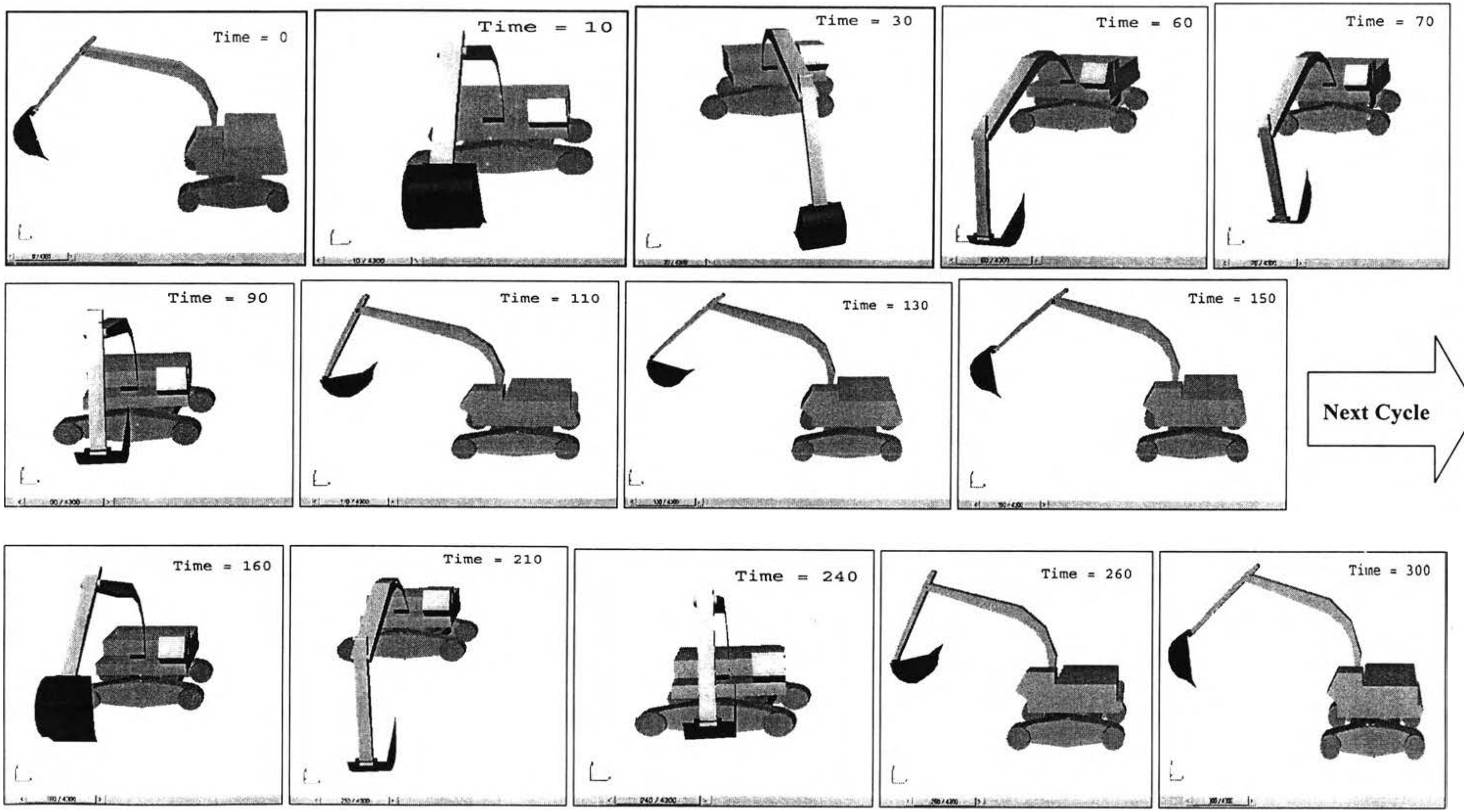

Figure 7.4: 3D model of excavators captured at different simulation times for verifying the time of earth excavation

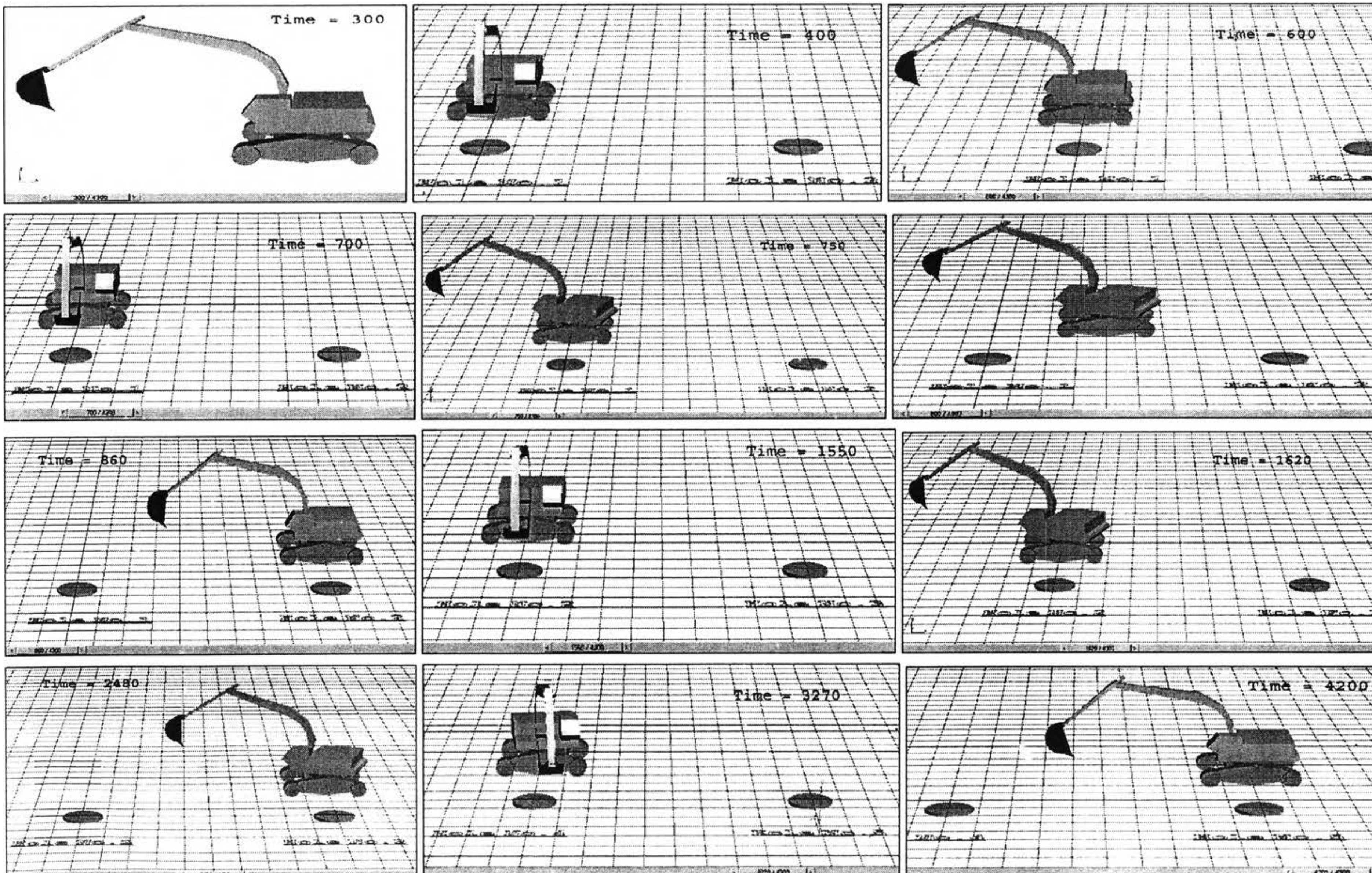

Figure 7.5: 3D models of excavators captured at different simulation times for verifying the time of earth excavation (*continued*)

7.2.1 Verification Method

The method for Integrated System verification is described by a case study, which are presented as follow:

Case Illustration

Case I: Earth excavation by an excavator

In this research, earth excavation activity by an excavator was used as an example of a case study for system validation. The actions of the excavator are verified by comparing actions at a time advanced by system programming with actions at a time advanced by manual calculation.

Table 7.1: Results of actions and time verification of earth excavation by an excavator

Cycle / Hole	Verified 3D Process	Excavator's Actions in 3D space	Time advanced by		Actions & Time Verification	
			Programming	Manual calculation	Correct	Incorrect
1/1	Start	Start	0	0	√	
1/1	Rotate-z	`$body 90`^{0}	10	10	√	
1/1	Rotate-x	`$arm01 30`^{0}	30	30	√	
1/1	Rotate-x	`$bucket01 60`^{0}	60	60	√	
1/1	Rotate-x	`$arm02 20`^{0}	70	70	√	
1/1	Rotate-x	`$arm01 -30`^{0}	90	90	√	
1/1	Rotate-z	`$body -90`^{0}	110	110	√	
1/1	Rotate-y	`$arm02 20`^{0}	130	130	√	
1/1	Rotate-y	`$bucket01 60`^{0}	150	150	√	
2/1	Rotate-z	`$body 90`^{0}	160	160	√	
2/1	Rotate-x	`$bucket01 60`^{0}	210	210	√	
2/1	Rotate-x	`$arm01 -30`^{0}	240	240	√	
2/1	Rotate-z	`$body -90`^{0}	260	290	√	
2/1	Rotate-y	`$bucket01 60`^{0}	300	300	√	
3/1	Rotate-x	`$arm01 -30`^{0}	400	400	√	
3/1	Rotate-y	`$bucket01 60`^{0}	600	600	√	
4/1	Rotate-x	`$arm01 -30`^{0}	700	700	√	
5/1	Rotate-y	`$bucket01 60`^{0}	750	750	√	
1-2	Move-x	`$wh01`	800	800	√	
1-2	start	start	860	860	√	
4/2	Rotate-x	`$arm01 -30`^{0}	1550	1550	√	
1/2	start	start	1620	1620	√	
1/3	start	start	2480	2480	√	
4/4	Rotate-x	`$arm01 -30`^{0}	3270	3270	√	
5/5	Rotate-y	`$bucket01 60`^{0}	4200	4200	√	

7.2.2 Results of System Verification

The results of the comparison between the actions of the excavator at a time produced by system programming with the actions at time generated by manual calculation are presented in Table 7.1.

7.3 System Validation

In order to validate the system, the productivity of construction activities generated by the system is compared with actual productivity rates recorded from field.

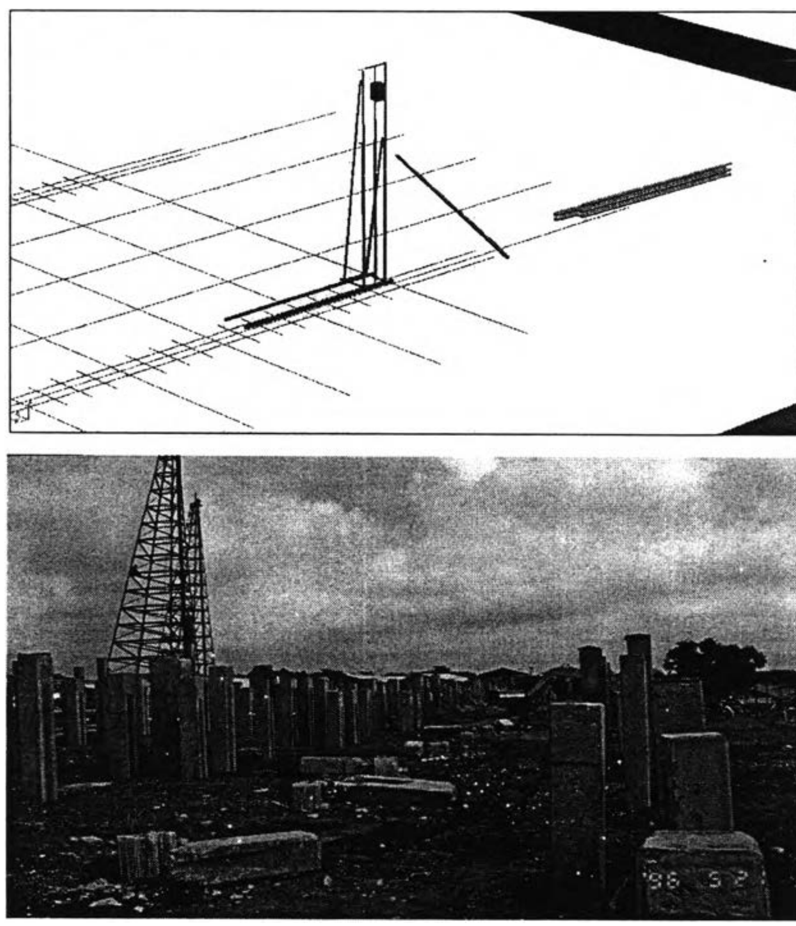

Figure 7.6: Pile-driving activity used as a case study for system validation

7.3.1 Validation Method

Case II: Pile-driving activity

Pile-driving activity was used as a case study for system validation. The results of the validation are illustrated in Table 7.2, Figure 7.7, and Figure 7.8

7.3.2 Results of system validation

The results of the comparison between the productivity of pile-driving machines generated by Integrated System simulation with the productivity of pile-driving machines from the field (actual construction) are presented in table 7.2, Figure 7.7, and Figure 7.8.

Table 7.2: Results of pile-driving validation

Pile driving duration (days)	Driven pile by using Integrated System simulation (piles)	Actual driven pile per day from field record (piles)	Accumulated driven pile (simulation) (piles)	Accumulated actual driven pile per day (piles)	Difference between simulation and actual operation
1	20	11	20	11	9
2	15	10	35	21	5
3	17	12	52	33	5
4	18	14	70	47	4
5	13	19	83	66	-6
6	16	6	99	72	10
7	15	10	114	82	5
8	18	12	132	94	6
9	17	8	159	102	9
10	17	11	176	113	6

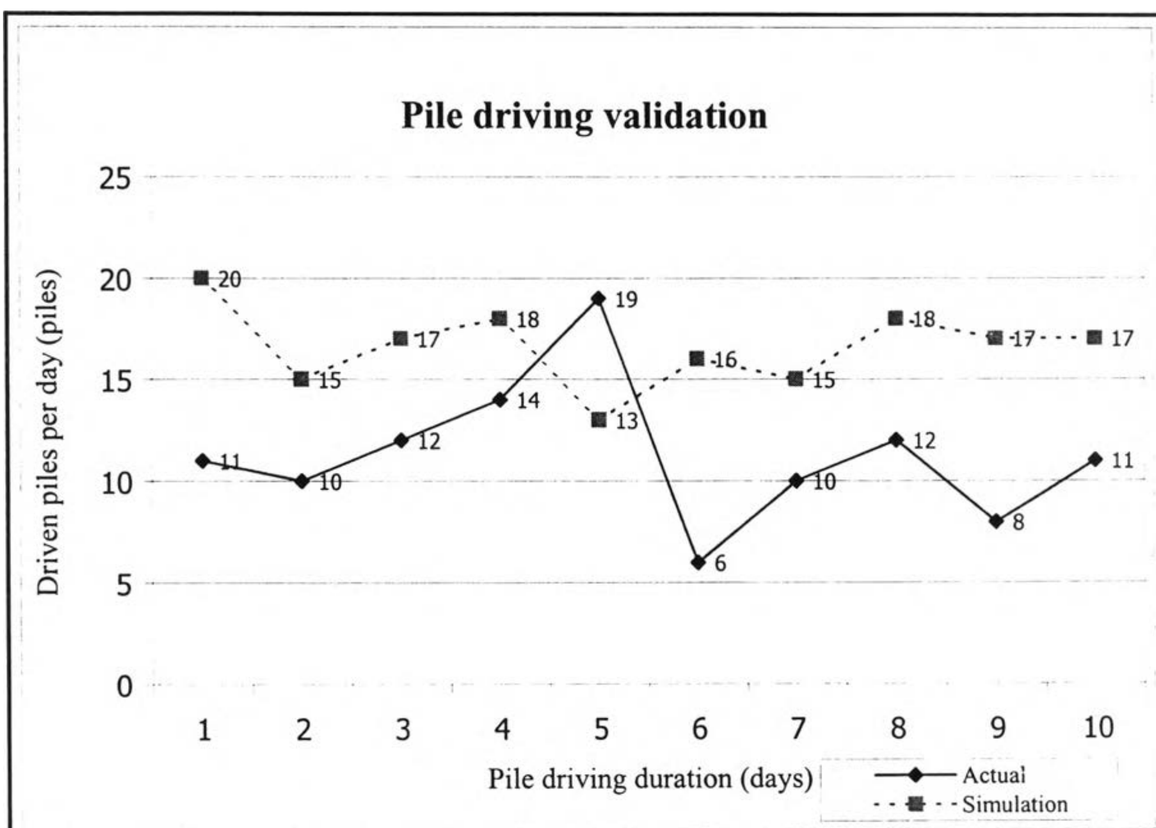

Figure 7.7: The comparison of pile-driving productivity between actual construction and results generated by simulation

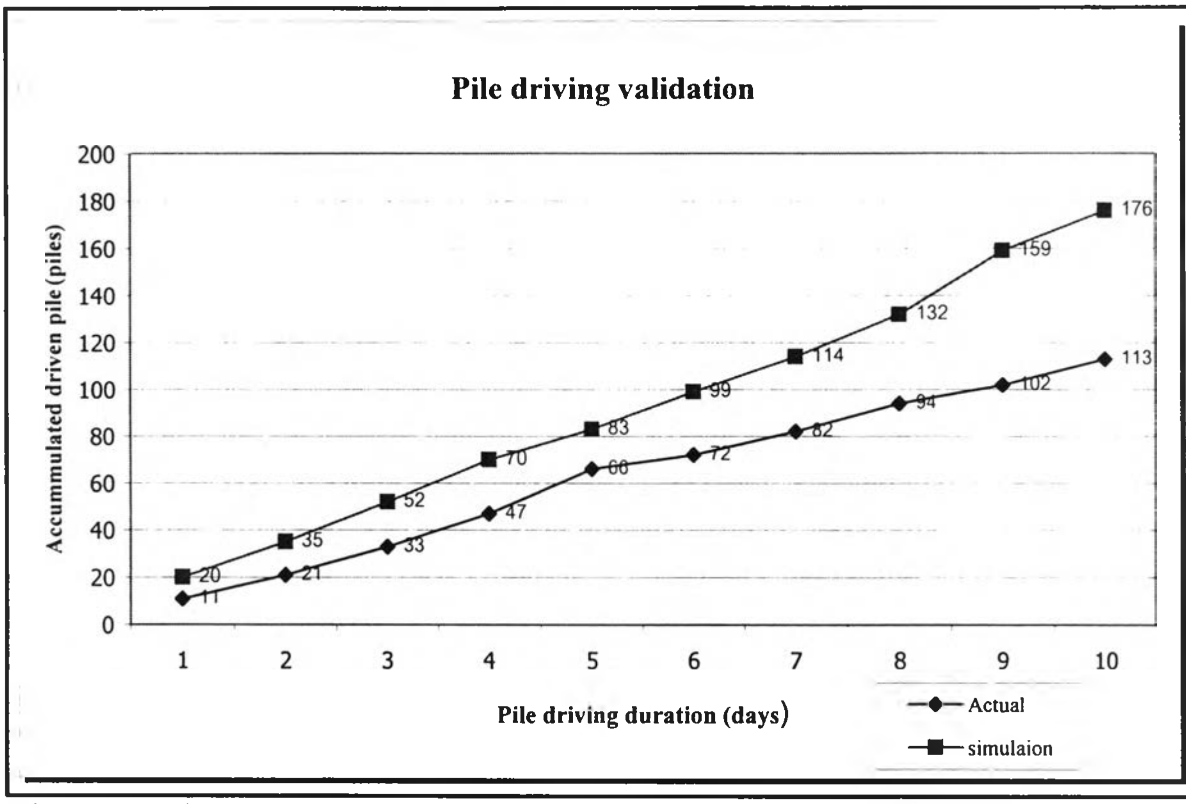

Figure 7.8: The comparison of accumulated productivity between actual construction and results generated by simulation

7.4 Conclusion

The accuracy of the system is tested via system verification and system validation. In order to verify the accuracy of the system development, points of time and the action of the 3D models of construction activities generated by using visualizer scripts programming are tested. Earth excavation activity by an excavator was used as a case study for system validation. The results of the validation show that all points of time are able to generate the correct actions of construction activities.

The Integrated System was validated by comparing the productivity rate of construction activities generated by the system and the actual productivity rates recorded from the field. Pile driving activity was used as a case study to validate the system. The results of system validation showed that the productivity of pile-driving machine according to the system simulation is higher than the productivity of pile-driving machines from actual construction project due to 1) unforeseen conditions such as machine down, accidents, worker's delay, and rainfall which are not included in the system simulation.

In order to verify and validate the Integrated System, the other construction activities, e.g., steel column installation, and roof-structure installation were also verified and validated using similar methods as shown in the above examples.