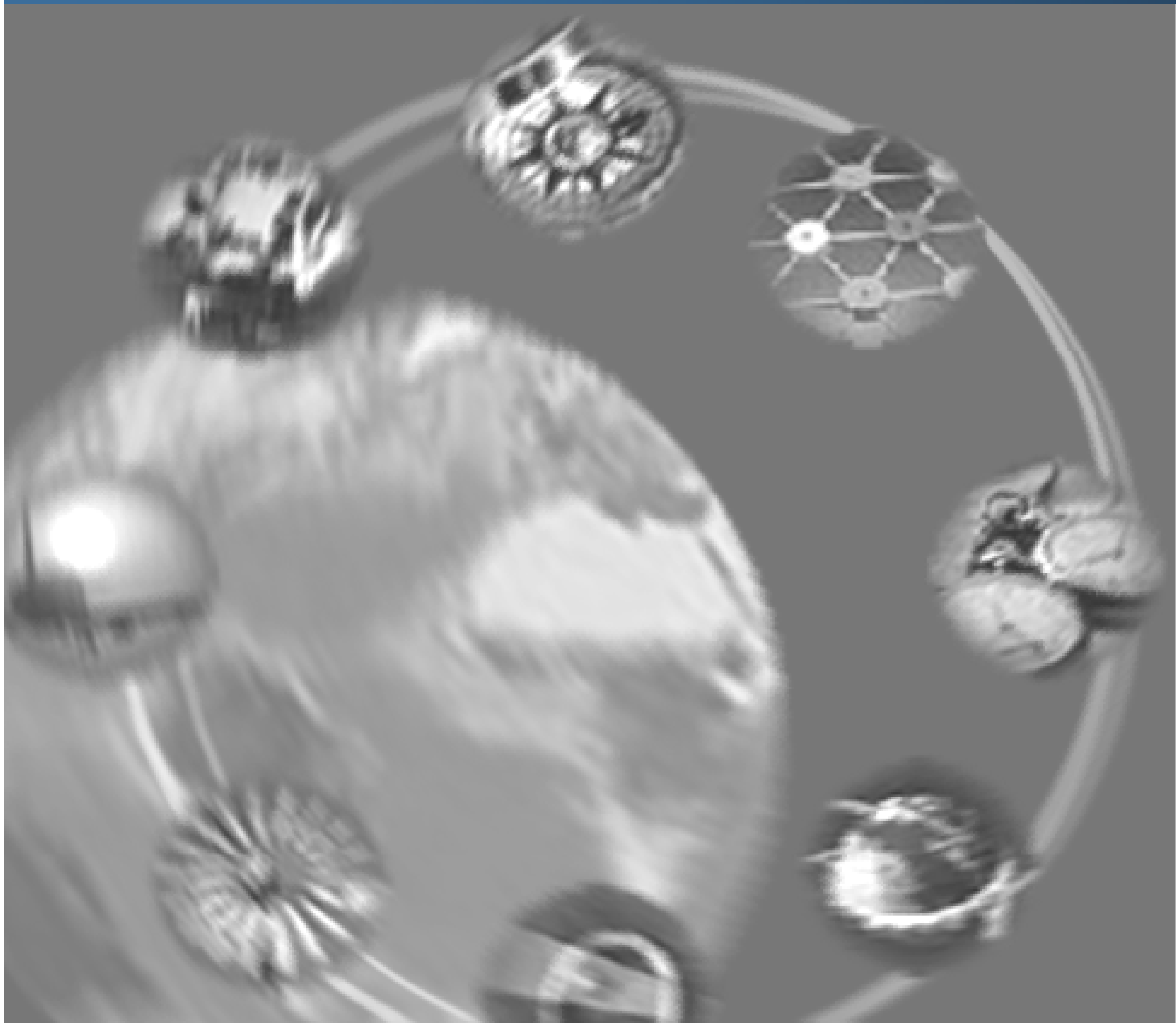
Simulation in construction

4013.407 Construction Technology



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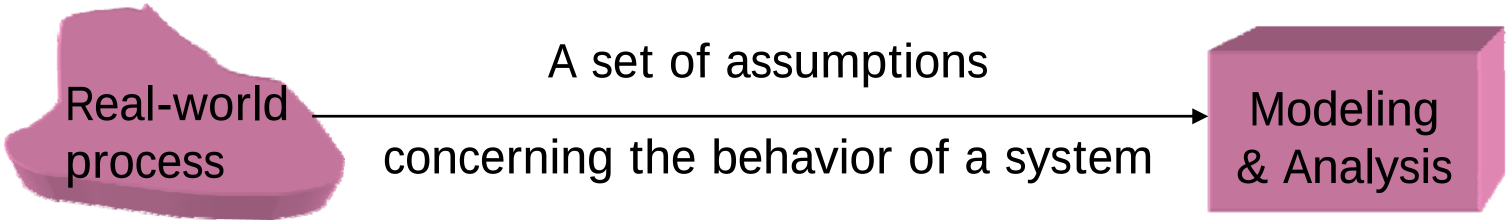
Simulation

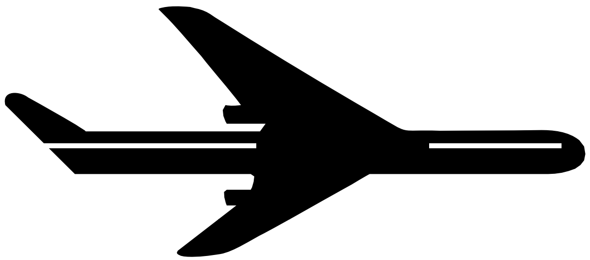


- Simulation
  - the imitation of the operation of a real-world process or system over time
  - to develop a set of assumptions of mathematical, logical, and symbolic relationship between the entities of interest, of the system.
  - to estimate the measures of performance of the system with the simulation-generated data

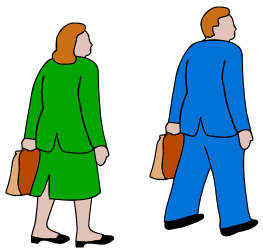
- Simulation modeling can be used
  - as an analysis tool for predicting the effect of changes to existing systems
  - as a design tool to predict the performance of new systems

Application Types

- Training (flight simulation)
- Entertainment (video games, virtual reality)
- Decision-making (Industry)



Basic Characteristics



Inputs → BLACK BOX → Outputs

Customer arrivals

Service times

Breakdown times

Customer waiting times

Queue lengths

Performance measures

For dynamic systems

Simulation models are used to study *dynamic* systems

- Capture/mimic the behavior of the system

Examples: a bank operations
a call center

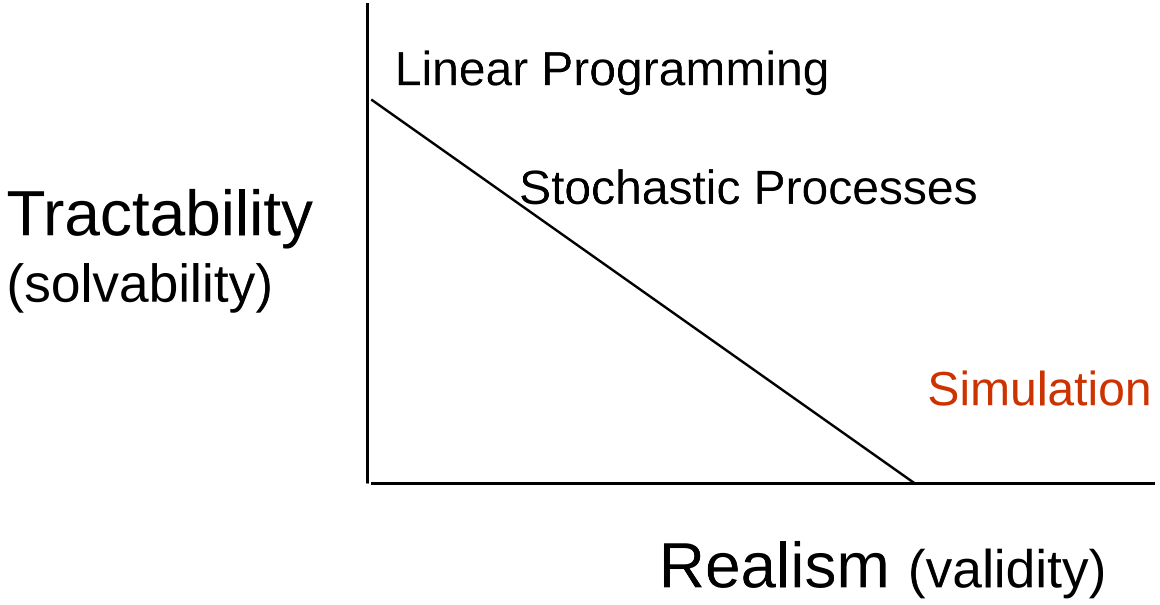
Mathematical programs are used to study *static* systems

- Solve for a solution of the system

Example: a class schedule

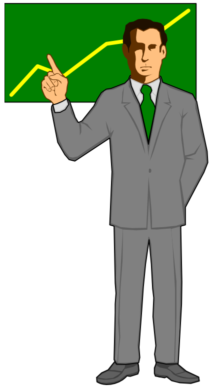
When all else fails, simulate

If a real system cannot be studied using a model which can be solved analytically, we can (must?) turn to simulation models.



Words of wisdom

- Do not simulate unless you absolutely have to (i.e., no other technique can solve your problem).
- Therefore exhaust all your options before considering simulation.



Simulation Models

Model of a System

- Model
  - a representation of a system for the purpose of studying the system
  - a simplification of the system
  - sufficiently detailed to permit valid conclusions to be drawn about the real system

Types of Models

- Static or Dynamic Simulation Models
  - Static simulation model (called Monte Carlo simulation) represents a system at a particular point in time.
  - Dynamic simulation model represents systems as they change over time
- Deterministic or Stochastic Simulation Models
  - Deterministic simulation models contain no random variables and have a known set of inputs which will result in a unique set of outputs
  - Stochastic simulation model has one or more random variables as inputs. Random inputs lead to random outputs.

Types of Models

- Correlational Model
  - The model is assessed to be valid if its output matches the "real" output within some specified range of accuracy, without any questioning of the validity of the individual relationships that exist in the model
- Causal-descriptive Model
  - The model must not only reproduce/predict its behavior, but also explain how the behavior is generated, and possibly suggest ways of changing the existing behavior

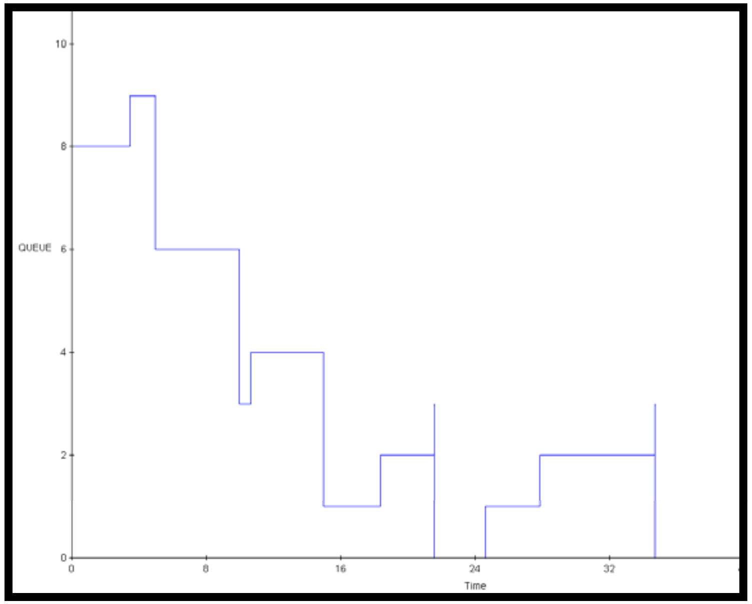
	Correlational	**Causal-descriptive**
Type	Data-driven	Theory-like
Approach	Black-box approach	White-box approach
Main focus	Output behavior	Output behavior Internal structure
Purpose	Forecasting	Forecasting Explanation
Example	Time-series Regression	System Dynamics

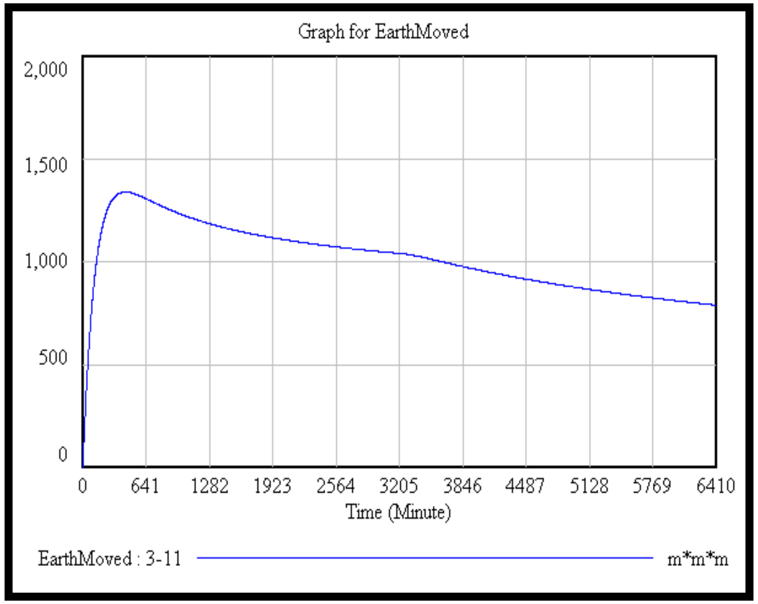
DES vs. Continuous Simulation

Discrete model vs. Continuous model

- Discrete Event Model [Banks et al. 2000]
  - The model in which the state variables change only at a discrete set of points in time

- Continuous Model [Banks et al. 2000]
  - The model in which the state variables change continuously over time





Discrete and Continuous Systems

- Systems can be categorized as discrete or continuous.
  - Bank : a discrete system
  - The head of water behind a dam : a continuous system

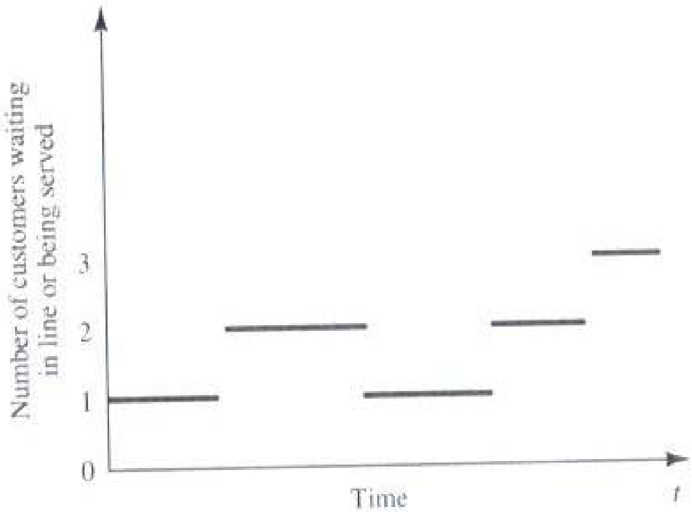


Figure 1.1. Discrete-system state variable.

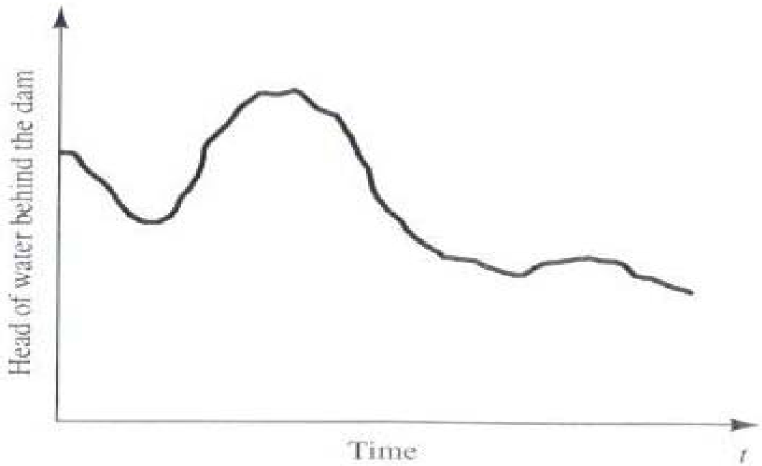
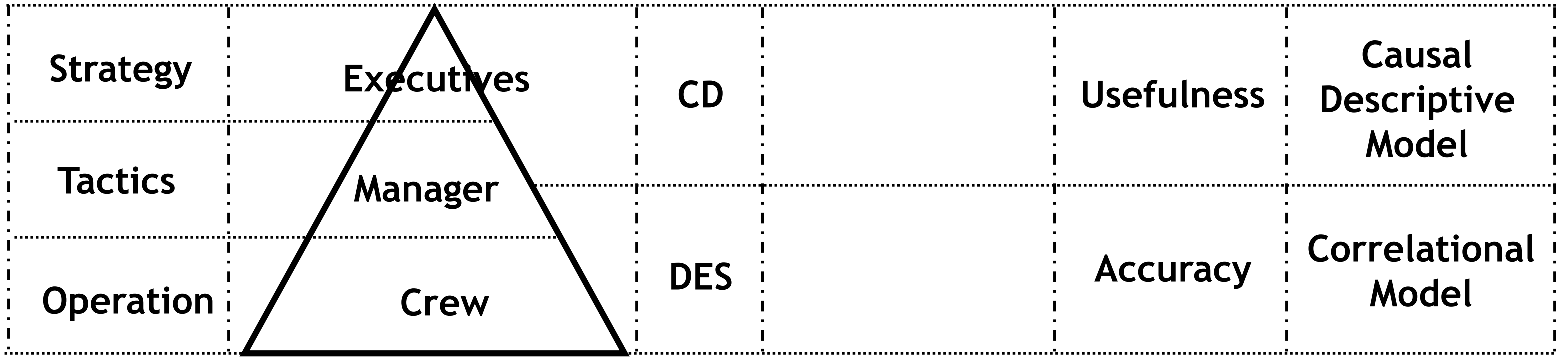


Figure 1.2. Continuous-system state variable.

Discrete model vs. Continuous model



	Discrete	Continuous *System Dynamics**
Mostly used Language	SLAM, ARENA, SIMAN	Vensim, Stella, Dynamo
Main Concept	Queuing theory / Statistics	Stock and Flow / Feed-Back Structure
Focus	Accuracy	Behavior & Pattern
Main Concern	Prediction (point)	Prediction (pattern) & Explanation
Principle determinant	Input data	System Structure
Calculation Method	Summation	Integral
Application Level	Lower Level *Operational / Tactics*	Higher Level *Tactics / Strategy*

Why DES have been used widely?

- Construction industry has tried to reduce the complexity of construction projects by subdividing it into smaller parts according to the *Work Breakdown Structure (WBS)* or the *Organization Breakdown Structure (OBS)*
- As a result, in the construction industry, there have been much effort for Discrete Event Simulation (DES), which focuses on
  - Discrete processes, rather than overall project
  - Operational level, rather than Strategic level
- Recently, there are needs to broaden simulation focus from 'process level' to 'project level' in order to understand project behavior
  - Much research is still needed to provide a simple, efficient, workable, and accurate method for construction project simulation [Abourizk et al, 1992]
  - Process-based simulation results should be integrated to a higher project level [Shi, 2001]

Analysis of Construction DES

- Strength of DES
  - Suitable for Process Level (Micro-View)
  - Being used as a Productivity Improvement Analysis Tool
  - Similarity to CPM/PERT methodology
  - Guarantee Higher Accuracy within simple process
- Weakness of DES
  - Difficult to capture the Project Complexity or Ripple Effect from interrelation among each process
  - Difficult to explain the real cause of deviation in detail
  - Difficult to model "softer" aspects of projects such as fatigue, moral, schedule pressure, and so on

Hybrid Simulation

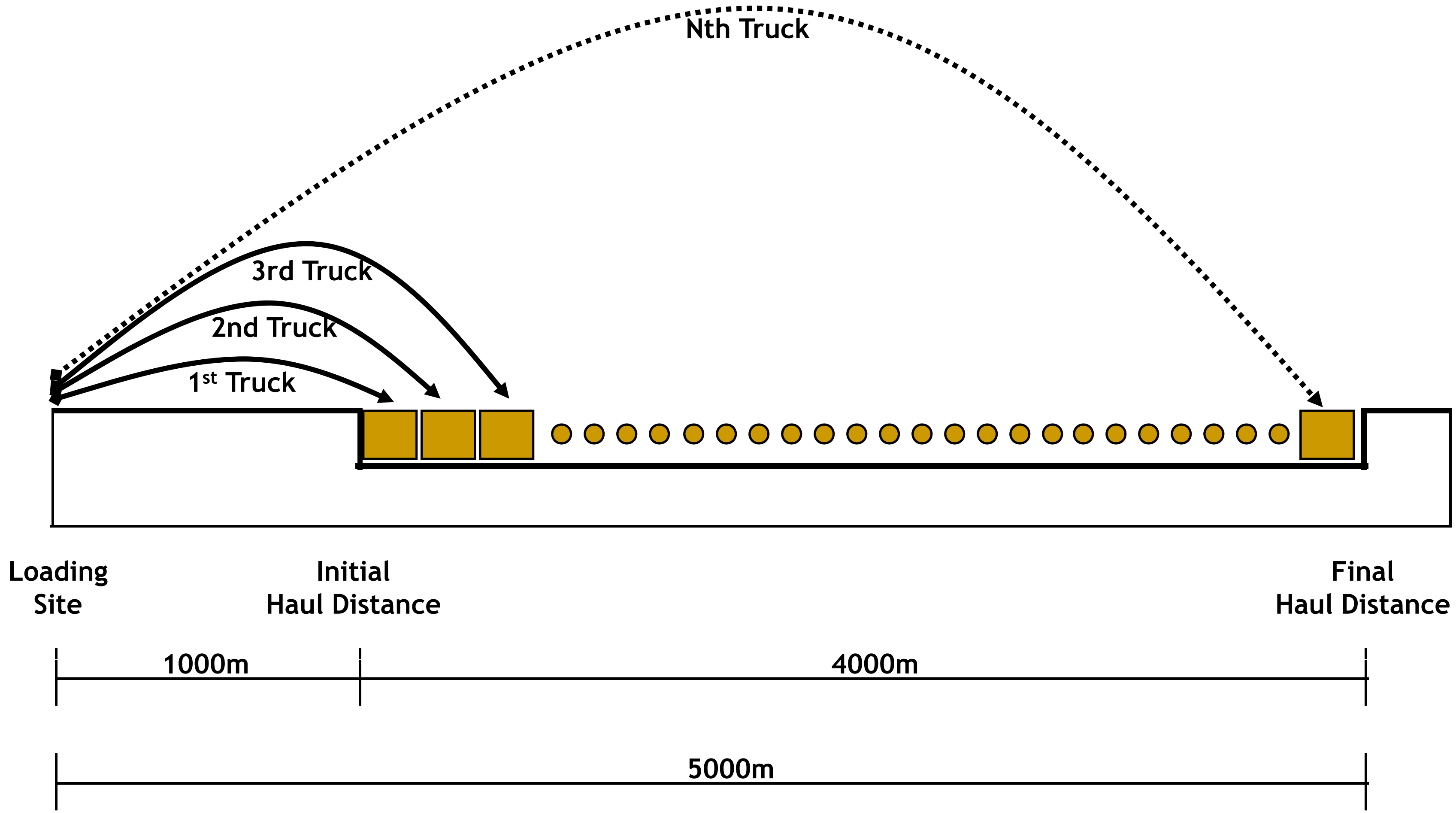
System Dynamics as a complementary tool

- Advantages
  - Identifies cause and effect relationships between process variables
  - continuously analyzes the process behavior at every time step
  - Could be more responsive to a change of the process environment by decreasing time step size [Park 2005]
- Disadvantages
  - Inherently limited in representing operational details [Rodrigues and Bowers 1996]
  - Difficult to analyze how the simulation results might be incorporated into a detailed operational management [Williams 2001]

Earthmoving Process & STROBOSCOPE

- Earthmoving Process
  - Considered to be an indicator to the success or failure of many construction projects as a whole, due to its labor and plant intensity [Smith et al. 2000]
  - Based on this recognition, it has been studied by various sources, including
- STROBOSCOPE [Martinez et al 1994]
  - Regarded as a highly established construction process simulation model
  - Has been utilized in various research effort as the core simulation engine
- Validation Process through comparing with STROBOSCOPE
  - Develop an initial process model, called 'FIXED MODEL', using the same process logic and simulation data as Martinez et al. (1994)
  - Test whether the FIXED MODEL simulation results are highly consistent with STROBOSCOPE
  - Incorporate managerial decision processes to the initial model – 'EVOLVING MODEL'
  - Examine whether the EVOLVING MODEL generate plausible simulation results

Process Logic



Process Elements

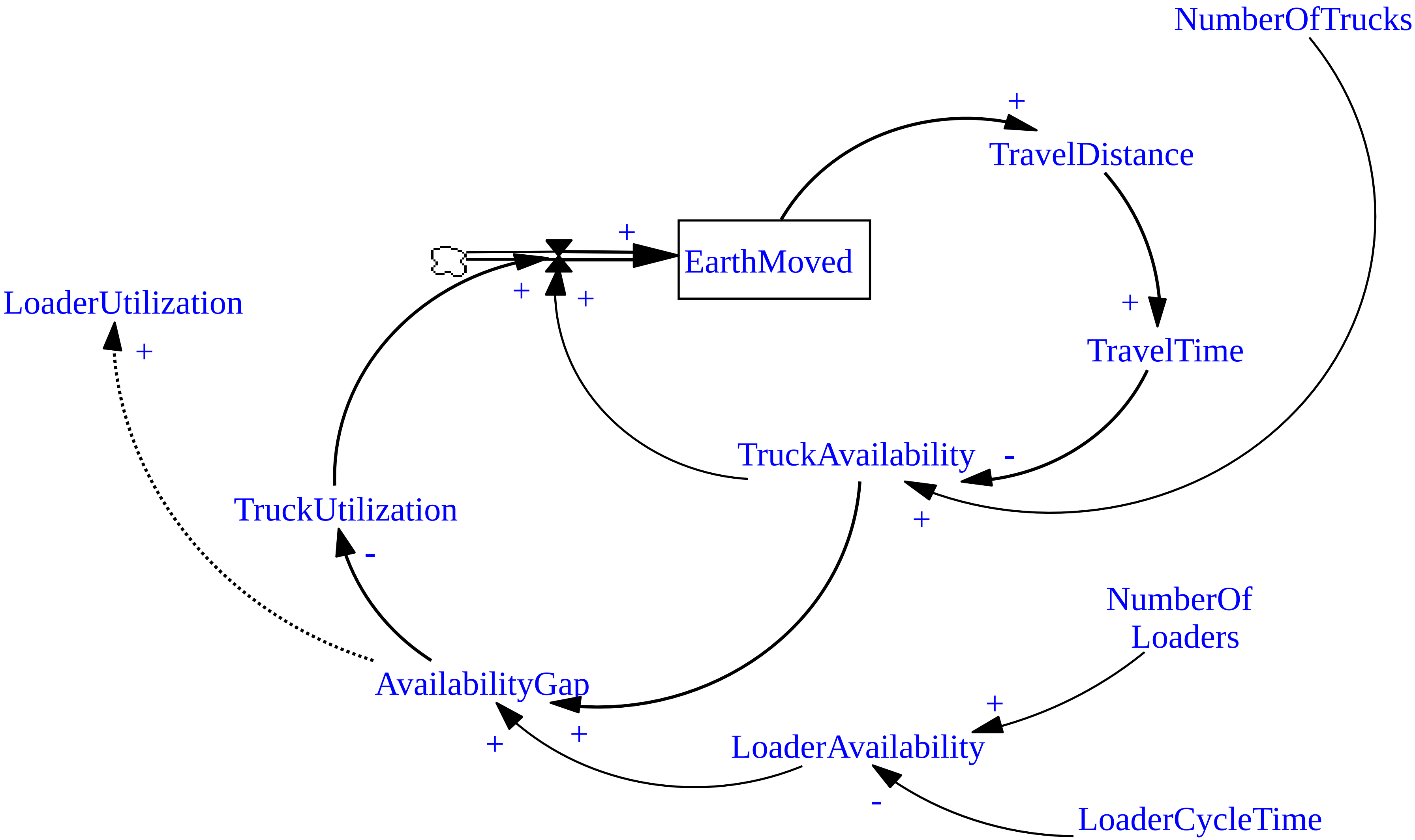
- Entity
  - The items processed through the system [Harrel et al. 2003]
  - Earth
- Resources
  - The means by which activities are performed [Harrel et al. 2003]
  - Trucks (Customers) and Loaders (Servers)
- Activities
  - The tasks performed in the system [Harrel et al. 2003]
  - Load, Haul, Dump, Return, and BackTrack

	Earth	Truck	Loader
Load	O	O	O
Haul	O	O	X
Dump	O	O	X
Return	X	O	X
BackTrack	X	X	O

Simulation Data

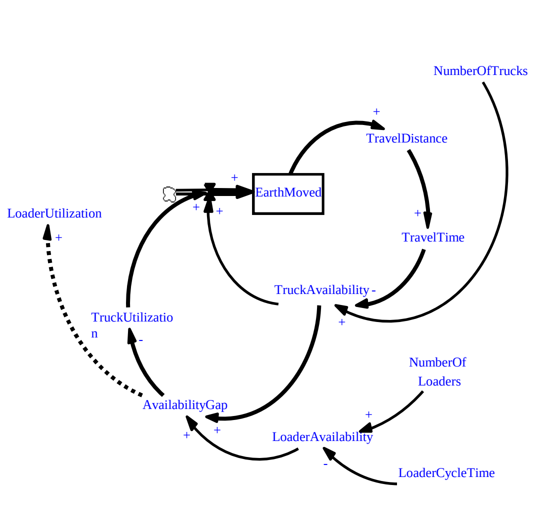
Data Row	Earth-Moving Example Data						
1	Scraper	Weight	Power	Capacity	Max Speed	Cost/Hr	Efficiency
	621E	299	256	10.7	51	48	80%
	651E	583	410	24.5	55	103	83%
2	Fleet: Three Pushers, Two 651E scrapers, Nine 621E Scrapers						
3	Pusher Cost: $55/hr - Other Costs: $200/hr						
4	Earth Weight: 15.7kN/m3 - Shrinkage Factor: 0.95						
5	Initial Haul Distance: 1000m - Final Distance: 5000m Road Cross Section Area: 12.5m2 Rolling Resistance:3% - Grade: 2%						
6	Optimum Load-time (secs) = 125*(1+0.48*Ln(0.08*Distance/Power)) Optimum Payload (bcm) = Capacity*(1+Capacity/60*Ln(Distance/5000))						
7	Time to spot (secs) = Beta(24, 36, 95) Time to load (secs) = Beta(95% Opt Time, Opt Time, 110% Opt Time) Payload = Normal (Optimum Payload, 30% Optimum Payload)						
8	Boost plus transfer time (secs) = 15 Backtrack time (secs) = 40% of Optimum load-time						
9	Actual haul time (secs) = Normal (Theoretic, 25% Theoretic)						
10	Dump Time (secs) = Beta(24, 36, 78)						
11	Actual return time (secs) = Normal (Theoretic, 15% Theoretic)						

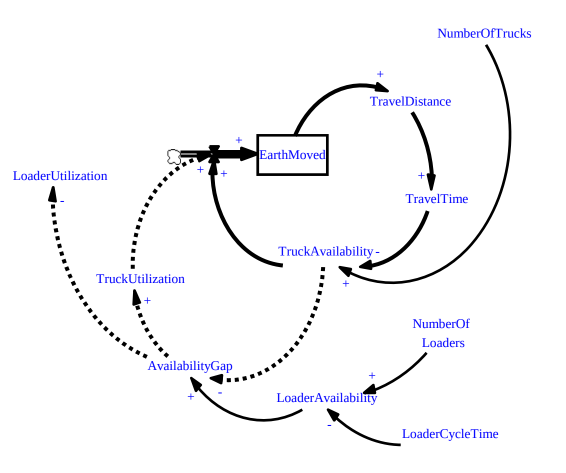
Adopted from 'Martinez (1994)'

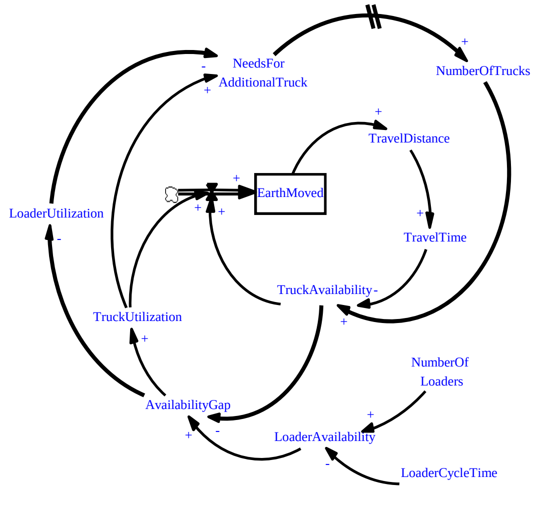

NumberOfTrucks
+
TravelDistance
+
EarthMoved
LoaderUtilization
+
+
+
TravelTime
+
TruckAvailability
-
+
TruckUtilization
-
NumberOf
Loaders
AvailabilityGap
+
+
+
LoaderAvailability
-
LoaderCycleTime

Process Dynamics in Earthmoving

Without Managerial Action		With Managerial Action
(a) Truck Availability > Loader Availability	(b) Truck Availability < Loader Availability	(c) Truck Availability ≈ Loader Availability







TruckAvailability = NumberOfTrucks / TruckCycleTime

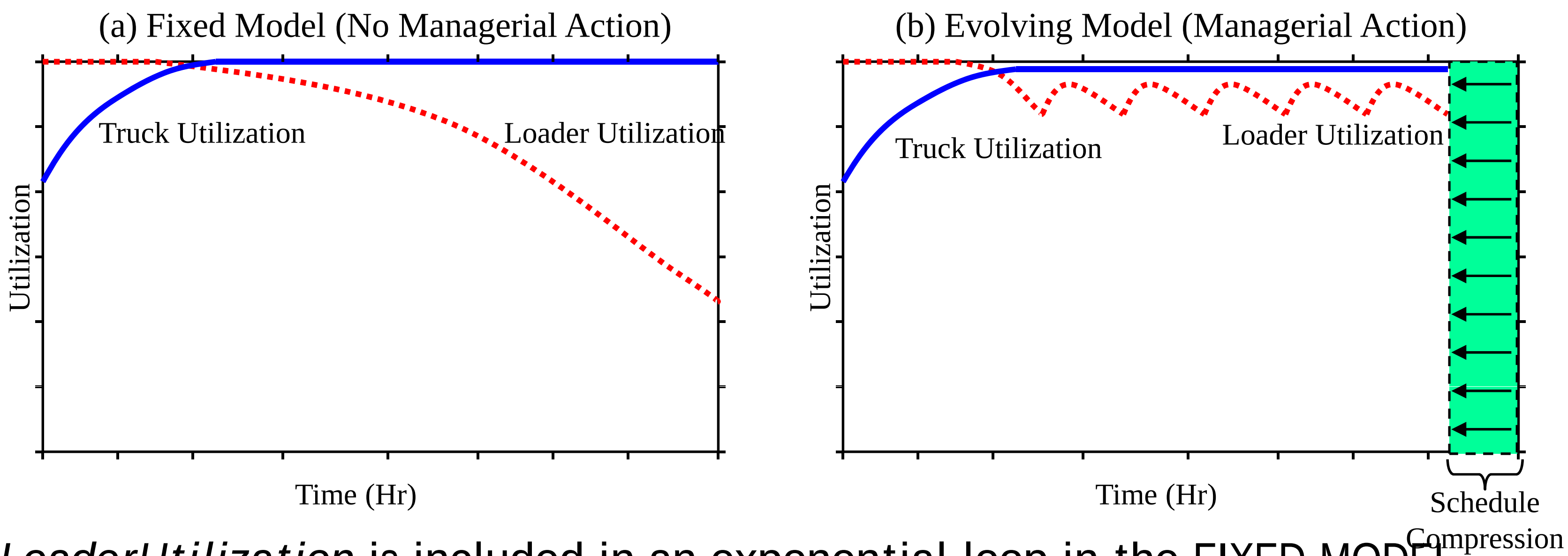
LoaderAvailability = NumberOfLoaders / LoaderCycleTime

TruckUtilizaiton = Min(TruckAvailability, LoaderAvailability) / TruckAvailability

LoaderUtilization = Min(TruckAvailability, LoaderAvailability) / LoaderAvailability

Reference Mode for process behavior

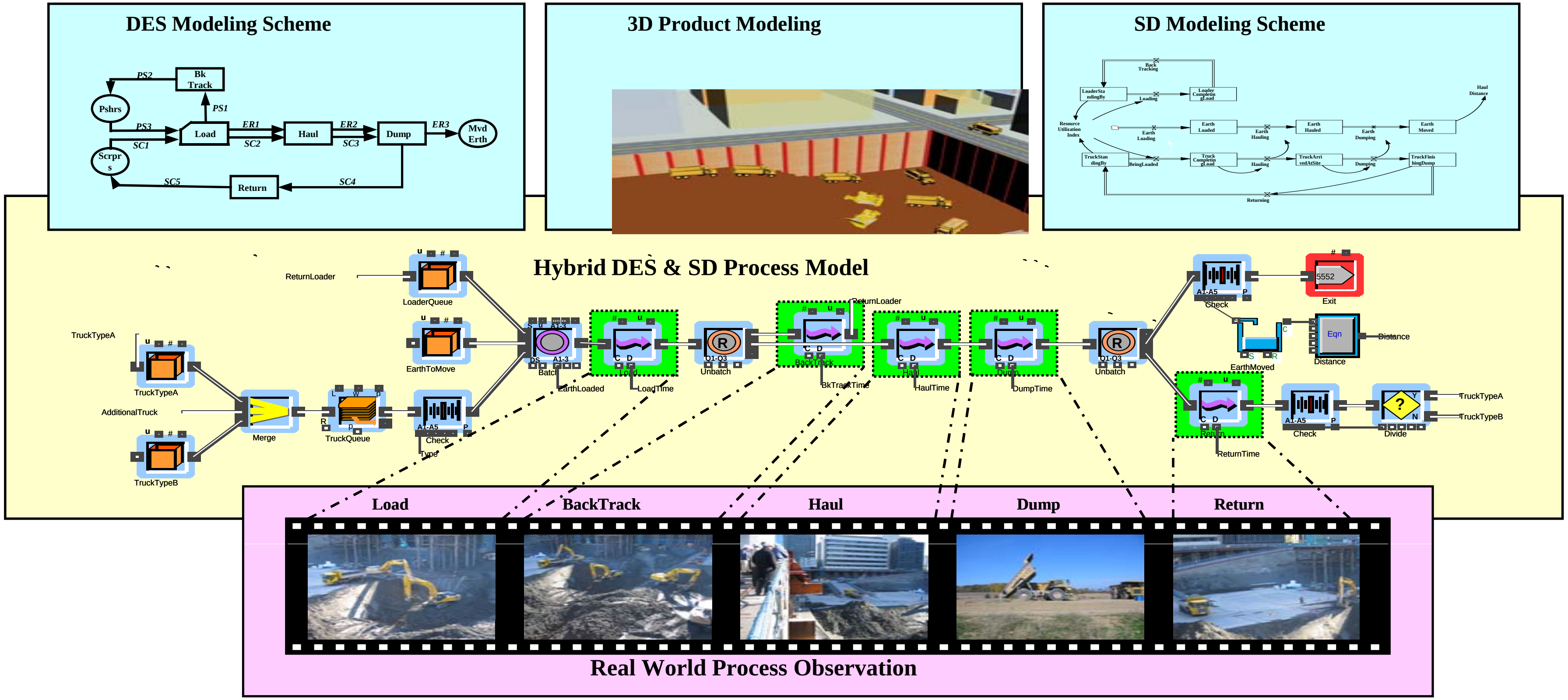
- A reference mode is the expected patterns of key variables over time, which can be deduced from process structure
- It is developed to give clues to appropriate model structure and check plausibility once the model is built [Stephanie 1997]



LoaderUtilization is included in an exponential loop in the FIXED MODEL

while in a balancing loop in the EVOLVING MODEL

Process Hybrid Simulation Model



The process model was develped using EXTEND^{TM} [Iamginethat Inc. 2001]

Simulation clock was modified to update process variables

at not only every event time but also constant time step

Fixed Model Validation

- For validating purpose, the *fixed model* will be first compared with STROBOSCOPE (Martinez et al. 1994) under various simulation contexts such as
  - no resource constraint
  - deterministic settings
  - stochastic environments

- No Resource Constraint Model

Loader	STROBOSCOPE	Fixed Model	Comparison
3	**100.28 hr**	**100.27 hr**	**0.9999**

Comparison with STROBOSCOPE

- Deterministic Model

Loader-Truck	STROBOSCOPE		Fixed Model		Comparison	
	Duration	Total Cost	Duration	Total Cost	Time Ratio	Cost Ratio
5	**219.19**	**132,609**	**219.17**	**132,598**	**0.9999**	**0.9999**
6	**182.67**	**119,281**	**182.65**	**119,271**	**0.9999**	**0.9999**
7	**156.58**	**109,762**	**156.57**	**109,756**	**0.9999**	**0.9999**
8	**136.99**	**102,609**	**137.01**	**102,621**	**1.0001**	**1.0001**
9	**122.93**	**97,977**	**123.01**	**98,039**	**1.0007**	**1.0006**
10	**113.29**	**95,729**	**113.34**	**95,772**	**1.0004**	**1.0004**
11	106.83	95,403	106.88	95,444	1.0005	1.0004
12	**102.81**	**96,748**	**102.88**	**96,810**	**1.0007**	**1.0006**
13	**100.79**	**99,681**	**100.83**	**99,721**	**1.0004**	**1.0004**

Optimal truck number is 11 when 3 loaders are allocated

Comparison with STROBOSCOPE

- Stochastic Model
  - 1,000 simulation runs with random seeds

	STROBOSCOPE		Fixed Model		Comparison	
	Duration	Cost	Duration	Cost	Duration	Cost
Mean	**109.98**	**98,197**	**109.94**	**98,177**	**0.9997**	**0.9998**
Standard Deviation	**0.47**	**410**	**0.49**	**436**	**1.0396**	**1.0639**
Min	**108.92**	**97,265**	**108.99**	**97,328**	**1.0006**	**1.0006**
Max	**111.06**	**99,172**	**111.11**	**99,221**	**1.0005**	**1.0005**
Median	**109.96**	**98,195**	**109.92**	**98,159**	**0.9996**	**0.9996**

  - Chi-Square Test
    - No statical evidence showing the difference between two simulation models with a confidential level of 95%

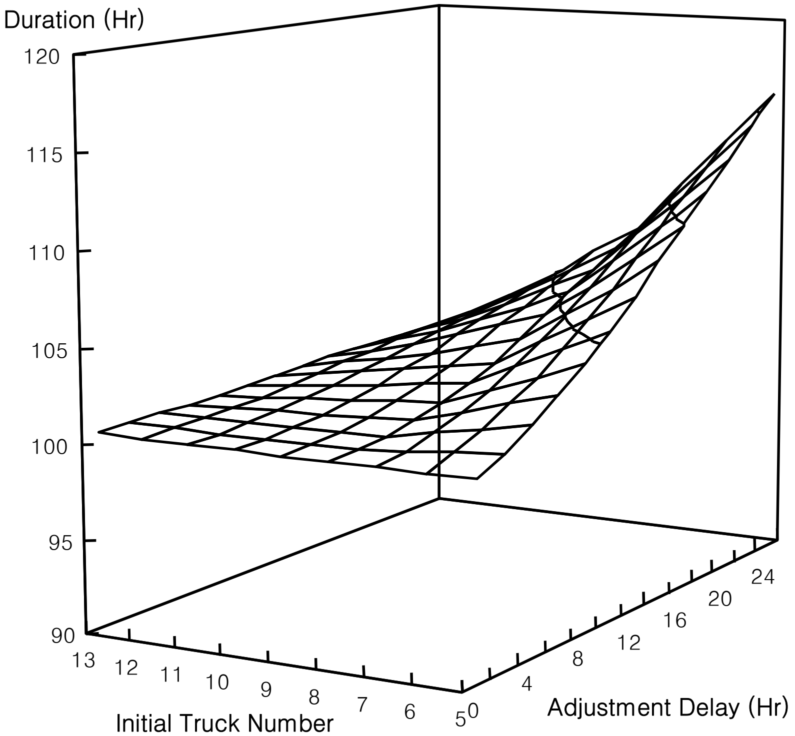
Chi-Square Test (Q)

= Σ((Oi-Ei)2 / Ei) = 24.86 (<< $x^2_{0.05,100}$ = 124.3)

Evolving Model Simulation

- EVOLVING Model
  - Based on the FIXED model
  - Incorporate managerial action process
  - Adjust truck number for process performance enhancement in the earthmoving example
  - Using Response Surface Methodology, examine the effect of two main decision factors
    - Initial Truck Allocation
    - Adjustment Delay
  - Judge the effectiveness of managerial actions by measuring the improvement from the optimal performance which is generated from the FIXED model
  - Deduce strategical lesson from the simulation results
  - Represent operational details for taking a proper managerial actions

Schedule Performance

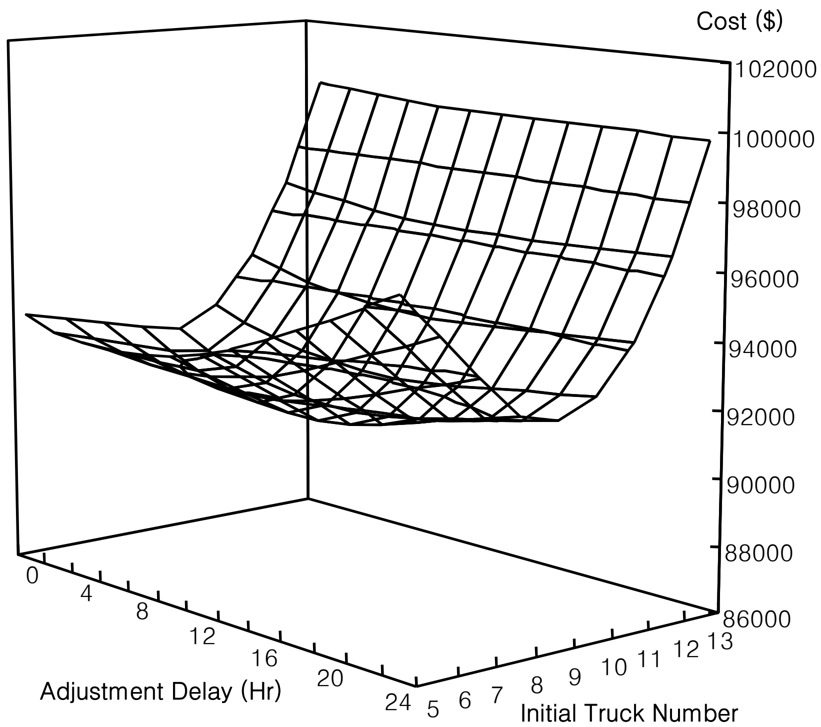


The schedule performance gets better with shorter delay and more initial truck

Simulation results indicate that when one of the decision factors gets worse, the sensitivity of the other factor on the schedule performance gets bigger

Thus, to ameliorate schedule performance, a construction manager should try to adjust one decision factor which is easier to control

Cost Performance

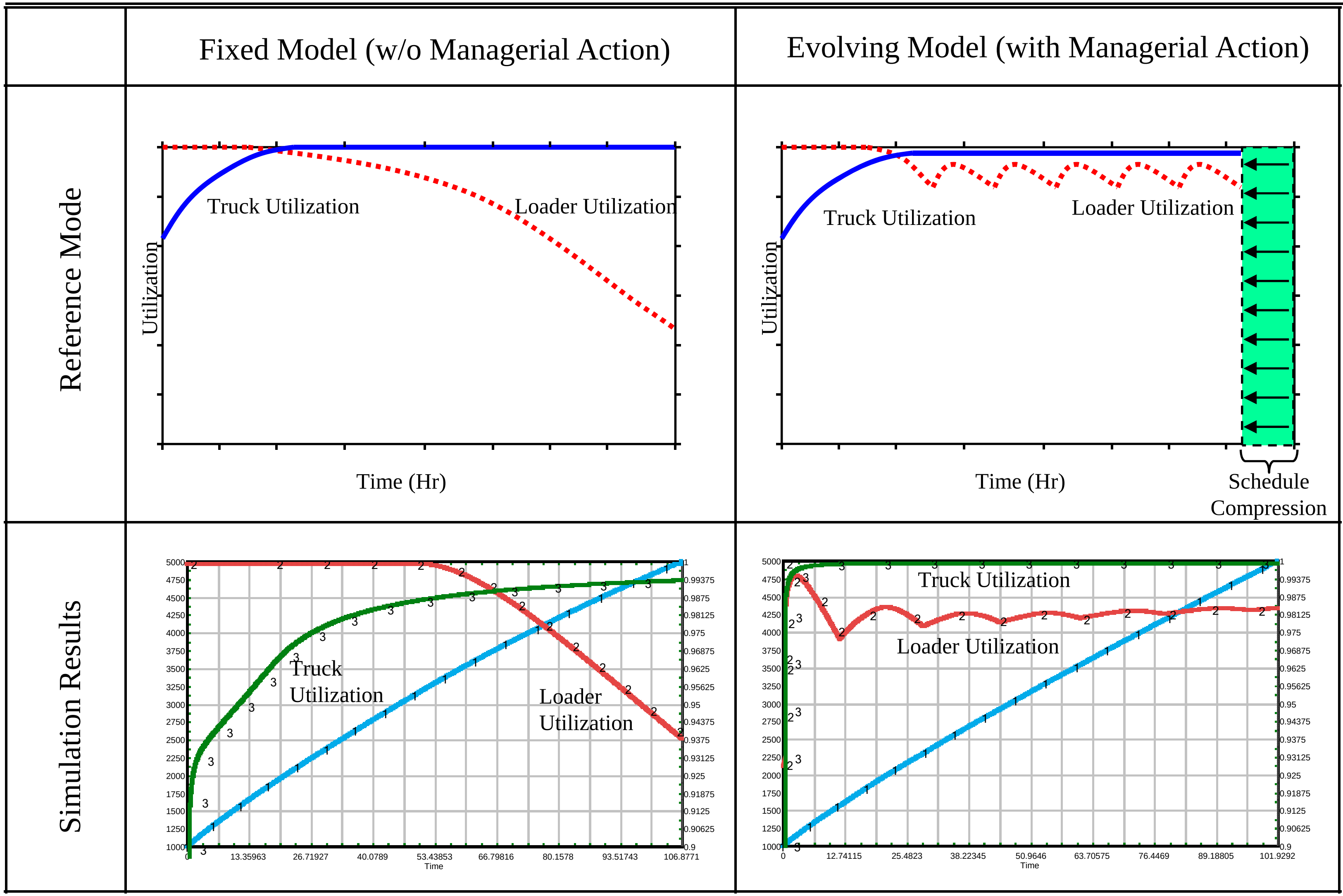


The cost performance produces a convex curve in terms of initial truck number because redundant trucks will cause idling cost and deficient trucks will interrupt the process and thus worse the cost performance

The cost performance also produces a convex curve in terms of adjustment delay. Contrary to a general perception that the shorter the adjustment delay, the better cost performance can be obtained, the simulation results show that there is a certain threshold that gives a maximum cost performance.

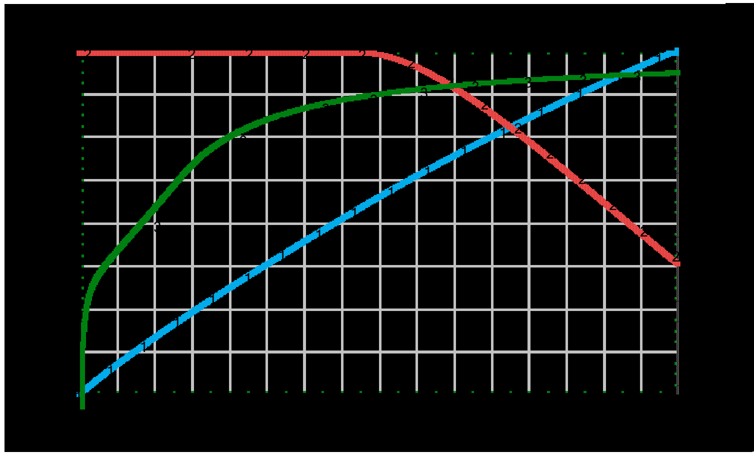
Therefore, a construction manager should pay attention to find an optimal delay size, not to reduce it as much as possible

Simulation results and Reference Mode

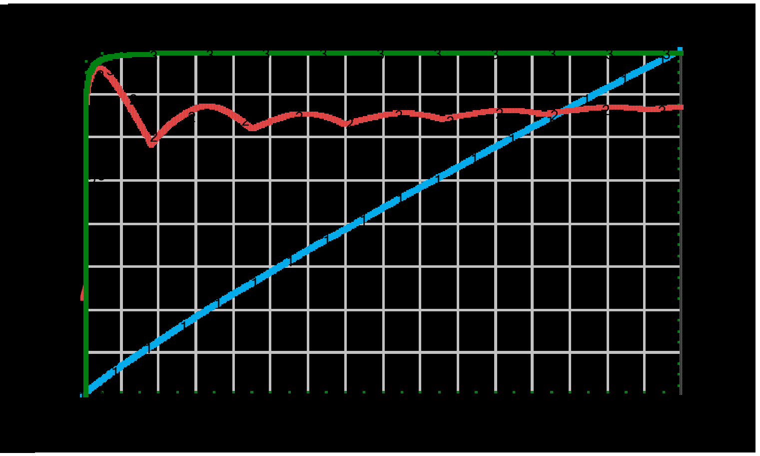


Enhancement of Process Performance

	Fixed Model	Evolving Model	Comparison
# of Loaders	3	3	-
# of initial trucks	11	8	-
# of final trucks	11	14	-
Truck Adjustment	No	Yes	-
Adjustment Delay	N/A	10 hr	-
Duration	106.88 hr	101.93 hr	-4.59%
Cost	$ 95,444	$ 91,155	-4.45%



Fixed Model



Evolving Model

Hypothesis Test

- Managerial action will enhance the process performance
  - Performance of EVOLVING model > Performance of FIXED model
- Pure SD model will underestimate the process performance due to its continuous feature
  - Performance of pure SD model > Performance of EVOLVING model
- Connecting above two argument
  - Hypothesis; Fp < Ep < Sp

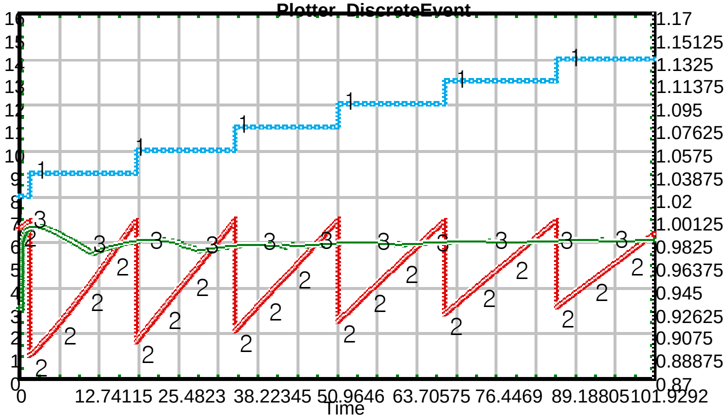
    where Fp = performance of FIXED model, Ep = perfomance of EVOLVING model, Sp = Performance of pure SD model

	FIXED model	Pure SD model	Evolving model
Initial Configuration (Loader-Truck)	**3-11**	**3-8**	**3-8**
Truck Adjusting	**No**	**Yes**	**Yes**
Timing of Managerial Action	**N/A**	**Continuous**	**Discrete**
Schedule Performance (Hour)	**106.83**	**100.43**	**101.93**
Cost Performance ($)	**95,403**	**91,234**	**91,155**

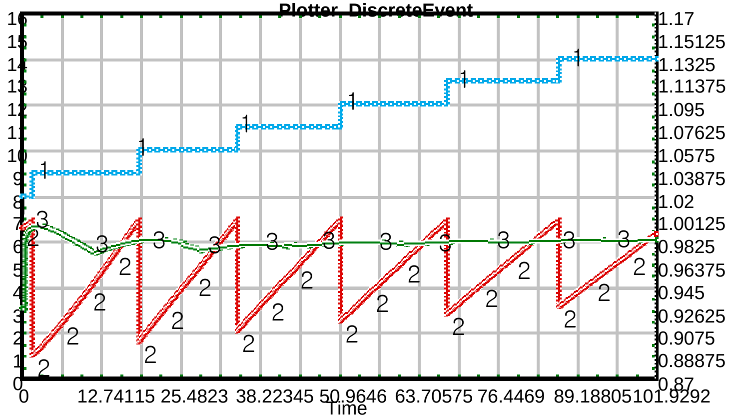
The hypothesis test shows the model generates simulation results within an expected range

Reverse Calculation using FIXED model

- The main difference between FIXED model and EVOLVING model is
  - Evolving model can generates when and how much additional truck will be assigned to the process
  - While Fixed model can't
- Fixed model is validated through comparing with a highly established model under various contexts
- For validation purpose, the Fixed model was simulated with details for managerial actions (when and how much additional truck should be assigned generated from Evolving model)
- The Fixed model simulation results with details for managerial actions and those of the Evolving model generate exactly same performance



Fixed model Simulation Result
with details for managerial actions



Evolving model Simulation Result

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