Introduction To Modeling & Simulation (Part 1)

Dr.Çağatay ÜNDEĞER

Öğretim Görevlisi
Bilkent Üniversitesi Bilgisayar Mühendisliği Bölümü
&
...

e-mail : cagatay@undeger.com
cagatay@cs.bilkent.edu.tr

Introduction To Modeling and Simulation (Outline)

- What is Modeling and Simulation (M&S) ?
- Complexity Types
- Model Types
- Simulation Types
- M&S Terms and Definitions

What is M&S ?

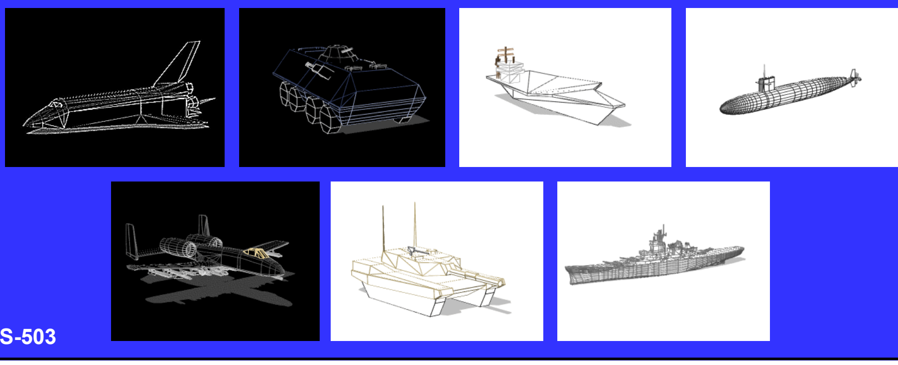
- Discipline of understanding and evaluating the interaction of parts of a real or theoretical system by;
  - Designing its representation (model) and
  - Executing (running) the model including the time and space dimension (simulation).

What is a System ?

- An unit or process, which exists and operates in time and space through the interaction of its parts.

What is a Model ?

- A simplified representation of a real or theoretical system at some particular point in time or space intended to provide understanding of the system.



What Level of Model Detail ?

- Whether a model is good or not depends on the extent to which it provides understanding.
- All the models are simplification of reality.
- Exact copy of a reality can only be the reality itself.
- There is always a trade off as to what level of detail is included in the model:
  - Too little detail: risk of missing relevant interactions.
  - Too much detail: Overly complicated to understand.

What is a Simulation ?

- The manipulation of a model in such a way that it operates in time or space to summarize it.

CS-503 7

Why Simulation ?

- Enable one to percieve the interactions that would otherwise be apparent because of their separation in time or space.

Drawn by Tuğgeneral Baynur Pekar

CS-503 8

Advantages of M&S

- Choose correctly:
  - M&S lets you test every aspect of a proposed change or addition without committing resources to their acquisition.
- Compress and expand time:
  - M&S allows you to speed up or slow down phenomena so that you can investigate them better.

CS-503 9

Advantages of M&S

- Understand why:
  - Managers often want to know why certain phenomena occur in a real system.
  - M&S lets you determine answers to “why” questions by reconstructing (replaying) the scene and taking a closer look at what has happend during the run.

CS-503 10

Advantages of M&S

- Explore possibilities:
  - You can explore new policies, operating procedures or methods without the need of experimenting with the real world systems.
- Diagnose problems:
  - Some systems are so complex that it is impossible to consider all the interactions taking place in a given moment.
  - With M&S, you can better understand the interactions among the variables that make up the complex system.

Advantages of M&S

- Identify constraints:
  - Bottlenecks in a system is an effect rather than a cause.
  - Doing bottleneck analysis with M&S, you can discover the cause of the delays in work process, information, material or other processes.

Advantages of M&S

- Develop understanding:
  - M&S provides understanding about how a system really operates rather than indicating someone's predictions about how a system will operate.
- Visualize the plan:
  - M&S lets you see your system actually running.
  - That allows you to detect design flaws that appear credible.

Advantages of M&S

- Build consensus:
  - Instead of saying one person's opinion about a system, you actually show how the system works, so provide an objective opinion.
- Prepare for change:
  - Using M&S, you can ask what-if questions for determining future improvements and new designs on a system.

Advantages of M&S

- Invest wisely:
  - M&S is a wise investment since
    - Typical cost of a simulation study is substantially less than generally 1% of the total amount being expended for the implementation of a design or redesign.

Advantages of M&S

- Train the team:
  - M&S can provide excellent training when design for that purpose.
  - In training, team provides decision inputs to the simulation as it progress, and observes the outputs.
  - After simulation ends, further evaluation can be provided by after action review (AAR).

Advantages of M&S

- Specify requirements:
  – M&S can be used to determine requirements for a system design by simulating different possible configurations of a system.

Disadvantages of M&S

- Model building requires special training:
  – M&S is an art that is learned over time and through experience.
  – Two models of the same system developed by two different individuals may have similarities, but it is unlikely be the same.
  – Building a realistic model may require domain knowledge that can only be acquired from a subject matter expert.

Disadvantages of M&S

- Simulation results may be difficult to interpret:
  - Since most simulation results are essentially random variables,
    - It may be hard to determine whether an observation is a result of system interrelationships or just randomness.

CS-503 19

Disadvantages of M&S

- Simulation modeling and analysis can be time consuming and expensive:
  - Economizing on resources for modeling and analysis may result in a simulation not sufficient enough for the problem, and may consume time, effort and money for nothing.

CS-503 20

Disadvantages of M&S

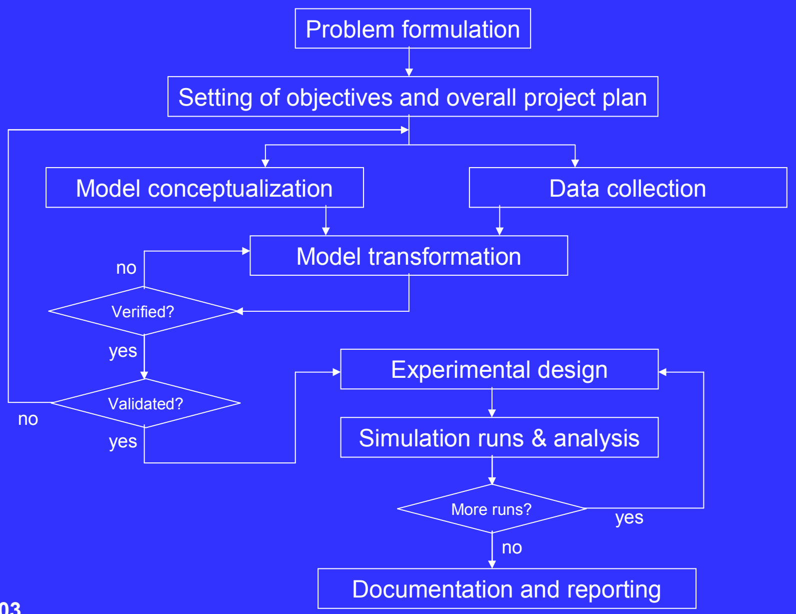
- Simulation may be used inappropriately:
  - Simulation is used in some cases when analitical solution is possible, or even preferable.

How to Use a Simulation ?

- Develop a model,
- Simulate it,
- Analyze the results,
- Learn from the simulation,
- Revise the model & simulation,
- Continue the interactions until adequate level of understanding is developed.

- M&S is a discipline, but it is also very much an art form.

Steps in a M&S Study



Some Application Areas

- Medical research, training & support
- Industrial engineering designs & presentations (Factory process design, manufacturing, ...)
- Civil engineering designs & presentations (Building design, city & infrastructure planning, ...)
- Mechanical engineering designs & presentations (Engine designs, aerodynamic design, ...)
- Nature sciences (Physic, chemistry, biology, meteorology, astronomy, ...)
- Geographic Information Systems (Earth modeling, ...)
- Military Decision Support (War modeling, ...)
- Training (Simulators, games, ...)
- Entertainment (Games, ...)

Practical Lecture Focus

- Modeling & Simulation in;
  - Defense Industry, and
  - Game Programming.
- Includes:
  - Earth modeling,
  - Entity modeling,
  - Behavior modeling,
  - Sensor & weapon systems modeling,
  - Distributed simulations,
  - Simulation based optimization and analysis.

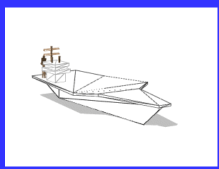
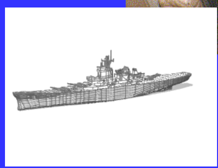
Complexity Types

- Detail Complexity
- Dynamic Complexity

Detail Complexity

- Associated with systems which have many component parts.



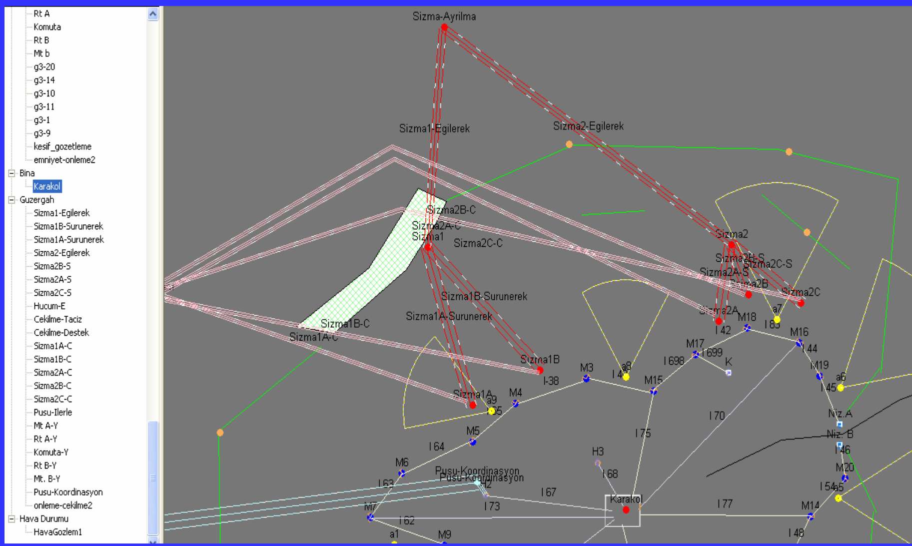
CS-503 27

Dynamic Complexity

- Associated with systems which have cause and effect separated by time and space.
- Great difficulty dealing with.
- Unable to readily see the connections between parts of the systems and their interactions.

CS-503 28

Dynamic Complexity (Sample)



Model Types

- Mathematical Models
- Physical Models
- Process Models

Mathematical Models

- Models, properties of which are described by mathematical symbols and relations.
- Constructed using:
  - Procedures (algorithms)
  - Mathematical equations.

CS-503 31

Mathematical Models (Sample)

Chaparral Missile Properties (Parameters)

Type	Surface to air missile
Radius	2.75 inch
Length	58 inch
Guidance	Passive infrared
Range	4 km
Velocity	2.2 mach
War Head	High explosive
Engine	Rocket, 2 phased
Accelaration	2 m/sec

A **= Accelaration**
S = Speed
W **= Effective Radius**
E = Effective Range
S2 **= Target Velocity**
D **= Target Distance**

$$R = A + \frac{D}{(D/S + D/S2)}$$

→ **R = Probability of Hit**

CS-503 32

Physical Models

- Models, properties of which are described by physical structures and relations.
- Usually applied to high fidelity (detailed) system simulations such as simulators.

Physical Models (Sample)

Process Models

- Models the process a system performs.
- Represents dynamic relations by mathematical and logical functions.

CS-503 35

Process Models (Sample)

Target	Take Fire Decision	Perform Fire Computations	Give Fire Command	Fire Missile	Missile Hit Target

Search & Classify Target	Decide To Fire	Compute Fire Direction	Command Fire	Fire	Target Destroyed
T_1	T_2	T_3	T_4	T_5	T_6

(T = Time) $T_1 + T_2 + T_3 + T_4 + T_5 + T_6 =$ Mission Complete

CS-503 36

Simulation Types (WRT Entities Involved)

- Live
- Virtual
- Constructive

CS-503 37

Live Simulations

- Real systems & actors
- Real environment

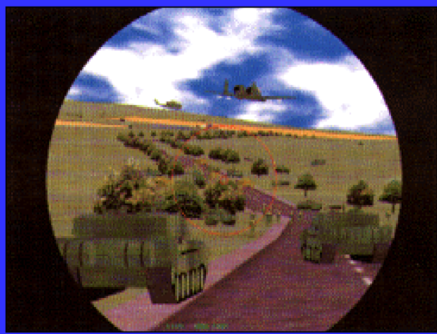
Possible results:

- **Resource Waste**
- **Time Waste**
- **Possible Damages**

CS-503 38

Virtual Simulations

- Real/Virtual systems & actors
- Real/Virtual environment

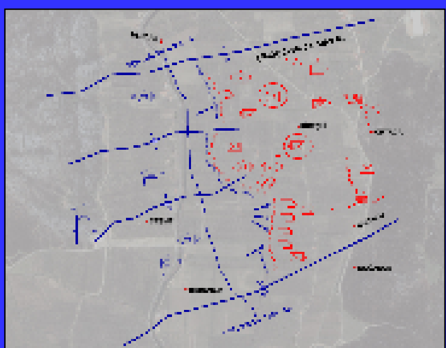



Usually used for training within simulators

CS-503 39

Constructive Simulations

- Virtual systems & actors
- Virtual environment

Objectives:
- Doing measurement, comparison, forcasting & concept analysis,
- Producing statistics

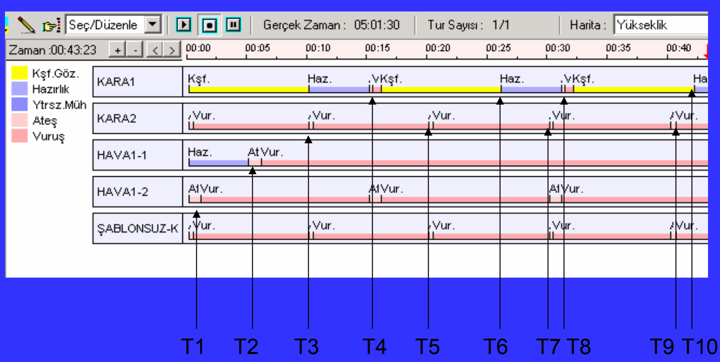
CS-503 40

Simulation Types (WRT Time Advance)

- Discrete
- Continuous

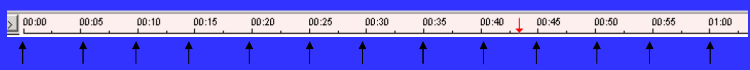
Discrete (Event) Simulations

- Time is advanced from event time to event time rather than using a continuously advancing time clock.



Continuous Simulations

- Something that can only really be accomplished with an analog computer.
- An approximation for continuous simulations (combined discrete continuous sim.) is;
  - Making the time step of the simulation sufficiently small so there are no transitions within the system between time steps.
  - So the simulation is stepped in time increments.



Simulation Types (WRT Results)

- Deterministic
- Stochastic

Deterministic Simulations

- A model that does not contain probability.
- Every run will result the same.
- Single run is enough to evaluate the result.

Stochastic Simulations

- A model that contains probability.
- Units, process, events or their parameters are initiated randomly using random numbers.
- If different runs are initiated with different random number seeds,
  - Every run will result differently.
- Multiple runs are required to evaluate the results.
- Statistics such as averages, standard deviations are used for evaluation.

Simulation Types (WRT Design)

- Traditional
- Agent-Based

Traditional Simulations

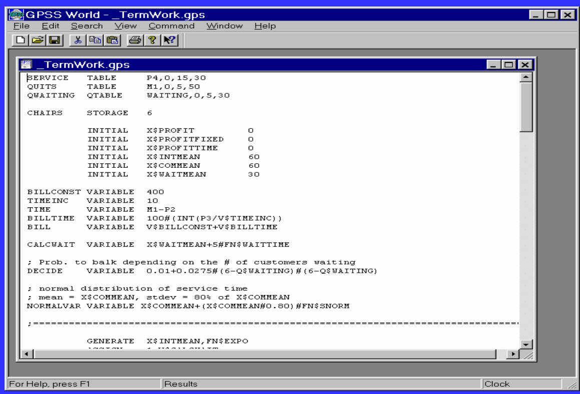
- Simulations where the characteristics of a population are averaged together, and
- The model attempts to simulate changes in these averaged characteristics for the whole population.

Traditional Simulations

(Screen shoot of a GPSS Program)

- GPSS is a traditional computer simulation language that stands for general-purpose simulation systems.

An internet cafe simulation



Traditional Simulations

(A Sample GPSS Program)

- Statistical values are used to model & simulate the system.

Mean inter arrival times for different time of day

9:00 - 10:00	10:00 - 11:00	11:00 - 14:00	14:00 - 18:00	18:00-21:00	21:00-23:00	23:00-24:00	24:00-01:00
60 minutes	45 minutes	30 minutes	25 minutes	20 minutes	30 minutes	40 minutes	60 minutes

```
          INITIAL   X$INTMEAN        60
          INITIAL   X$WAITMEAN       30
CALCWAIT  VARIABLE  X$WAITMEAN+5#FN$WAITTIME
          GENERATE  X$INTMEAN,FN$EXPO
          ASSIGN    1,V$CALCWAIT      ; max waiting time is in parameter 1 of
xact
EXPO      FUNCTION  RN1,C24  ;Exponential Distribution
0,0/.1,0.104/.2,.222/.3,.355/.4,.509/.5,.69/.6,.915/.7,1.2/.75,1.38/
.8,1.6/.84,1.83/.88,2.12/.9,2.3/.92,2.52/.94,2.81/.95,2.99/.96,3.2/
.97,3.5/.98,3.9/.99,4.6/.995,5.3/.998,6.2/.999,7/.9997,8


WAITTIME  FUNCTION  RN3,C25  ;Standard normal dist. function
0,-5/.00003,-4/.00135,-3/.00621,-2.5/.02275,-2
.06681,-1.5/.11507,-1.2/.15866,-1/.21186,-.8/.27425,-.6
.34458,-.4/.42074,-.2/.5,0/.57926,.2/.65542,.4
.72575,.6/.78814,.8/.84134,1/.88493,1.2/.93319,1.5
.97725,2/.99379,2.5/.99865,3/.99997,4/1,5
```

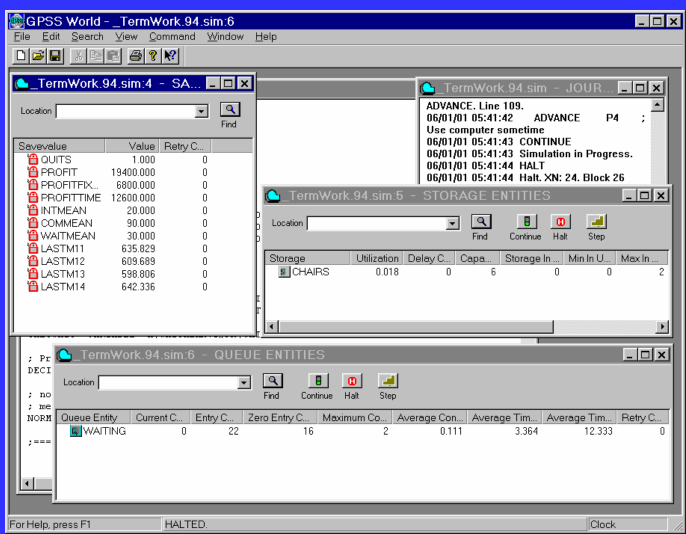
Traditional Simulations
(A Sample GPSS Program)

Simulating 1 day in GPSS

```
ONEDAY                    GENERATE  961,,1 ; Internet Cafe Open at 09:00, 16*60 Min  = 1 Day
      SAVEVALUE INTMEAN,60     ; After 09:00 Inter Arrival Mean = 60 min
      SAVEVALUE COMMEAN,60     ; Computer Usage Mean = 60 min
      ADVANCE   60      ; 1 Hours
      SAVEVALUE INTMEAN,45     ; After 10:00 Inter Arrival Mean = 45 min
      ADVANCE   60      ; 1 Hours
      SAVEVALUE INTMEAN,30     ; After 11:00 Inter Arrival Mean = 30 min
      SAVEVALUE COMMEAN,90     ; Computer Usage Mean = 90 min
      ADVANCE   180     ; 3 Hours
      SAVEVALUE INTMEAN,25     ; After 14:00 Inter Arrival Mean = 25 min
      ADVANCE   240     ; 4 Hours
      SAVEVALUE INTMEAN,20     ; After 18:00 Inter Arrival Mean = 20 min
      ADVANCE   180     ; 3 Hours
      SAVEVALUE INTMEAN,30     ; After 21:00 Inter Arrival Mean = 30 min
      ADVANCE   120     ; 2 Hours
      SAVEVALUE INTMEAN,40     ; After 23:00 Inter Arrival Mean = 40 min
      SAVEVALUE COMMEAN,60     ; Computer Usage Mean = 60 min
      ADVANCE   60      ; 1 Hours
      SAVEVALUE INTMEAN,60     ; After 24:00 Inter Arrival Mean = 60 min
      ADVANCE   60      ; 1 Hours
      TERMINATE 1       ; Internet Cafe Closed At 01:00
```

CS-503 51

Traditional Simulations
(Sample GPSS Execution)



CS-503 52

Traditional Simulations (Sample GPSS Results)

Queue waiting frequencies

Time Range	Frequency	Cumulative %
1 minutes	20	62.50%
1…5 minutes	1	65.63%
5…10 minutes	3	75.00%
10…15 minutes	1	78.13%
15…20 minutes	3	87.50%
20…25 minutes	1	90.63%
25…30 minutes	1	93.75%
30…35 minutes	2	100.00%

Frequency of leaving time for too much waited customers

Time Range	Frequency	Cumulative %
25…30 minutes	1	33.33%
30…35 minutes	2	100.00%

Agent-Based Simulations

- Differs from traditional kinds of simulations in that some or all of the simulated entities are modeled in terms of agents.
- Explicitly attempts to model specific behaviors of specific individuals.
- Contrasted to methods where the characteristics of a population are averaged together.
- Supports structure preserving modeling of the simulated reality.

Agent-Based Simulations (Domain Examples)

- Vehicles and pedestrians in traffic situations.
- Actors in financial markets.
- Consumer behavior.
- Humans and machines in battlefields.
- People in crowds.
- Animals and/or plants in eco-systems.
- Artificial creatures in computer games.

Agent-Based Simulations (Advantages)

- Distributed control, supporting parallel computations on separate machines.
- Supports simulation of pro-active behaviour.
- Ability to add or delete entities during a simulation.
- Easy to swap (exchange) an agent with the corresponding simulated entity,
  - i.e., a real person or a physical machine, (even during a simulation) making the simulation scenarios very dynamic.

Agent-Based Simulations (Advantages)

- Facilitates simulation of group behavior in highly dynamic situations,
  - Thereby allowing the study of "emergent behavior" that is hard to grasp with traditional methods.
- Well-suited for the simulation of situations where there are a large number of hetereogenous individuals who may behave somewhat differently.

Agent-Based Simulations (Agent Characterization)

- What is referred to as an agent covers a spectrum ranging from ordinary objects to full agents.
- May characterize them with the following dimensions:
  - Interaction
  - Communication language
  - Control/autonomy
  - Pro-activeness
  - Spatial explicitness
  - Mobility
  - Adaptivity
  - Modelling concepts

Agent-Based Simulations (Agent Characterization)

- Interaction:
  - From collaborative to no interaction at all.
- Communication language:
  - From KQML via simple signals (e.g. procedure calls) to none at all.
- Control/autonomy:
  - From each agent being a separate process (or thread) to one single process (monolithic system).

Agent-Based Simulations (Agent Characterization)

- Pro-activeness:
  - From pro-active to full reactive.
- Spatial explicitness:
  - From each agent being assigned a location in physical geometrical space to no notion of space.
- Mobility:
  - From each agent being able to move around in the simulated physical space to all agents being stationary.

Agent-Based Simulations (Agent Characterization)

- Adaptivity:
  - From learning to static behaviour.
- Modelling concepts:
  - From mentalistic (e.g., Belief Desire Intention [BDI]) to non-mentalistic.

Frequently Used M&S Terms and Definitions

- Entity, Attributes, State Variables & Event
- Replication
- Pixel, Poligon & Voxel
- Fidelity & Resolution
- Aggregation & Disaggregation
- Interoperability & Reusability
- Frame
- Simulator
- Computer Generated Forces
- Distributed Simulation
- High Level Architecture (HLA)
- Conceptual Model of The Mission Space (CMMS)
- Verification & Validation

Entity

- A representation of an object that requires explicit definition.
- An entity can be:
  - Dynamic: Moves through the system
    - E.g. A customer
  - Static (resource): Serves other entities
    - E.g. A bank teller

Attributes

- Local values that defines the characteristics of an entity.
- A soldier attributes could be:
  - Max running speed: 12 km/h
  - Head direction left limit : -80 degree
  - Head direction right limit : +80 degree
  - Max ammunition level: 20 bullets
  - Max target detection range: 2 km

State Variables

- The collection of all information needed to define what is happening within an entity or system to sufficient level at a given point in time.
- A soldier state variables could be:
  - Body posture: standing, running, ...
  - Head direction : -80 ... +80 degrees
  - Ammunition level: 0 .. 20 bullets
  - Health: alive, injured, dead

Event

- An occurance that changes the state of a system.

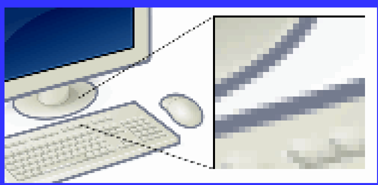
- Event types:
  - Internal (endogenous) events
    - E.g. Beginning of a service at a bank.
  - External (exogenous) events
    - E.g. arrival of customers for service.

Replication

- A single simulation run is a random sequence of events that illustrated only one of the brances of all possible event flow combinations.
- Therefore, reaching a conclusion based on just a single run is not an appropriate way of analysis.
- To minimize effect of randomness, simulations are run multiple times with the same scenario and the results are averaged.
- Each of these runs are called a replication.

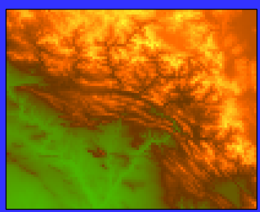
Pixel

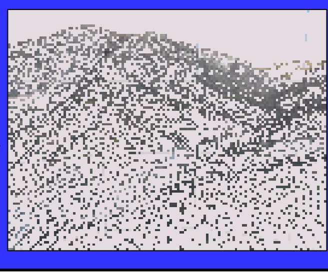
- The smallest piece of information in an image data.
- Normally arranged in a regular 2D grid, and are often represented using dots or squares.



Value of Pixels

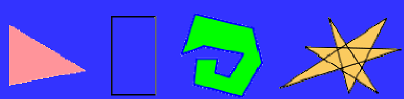
- Intensity/value of each pixel is variable:
  - In color systems, each pixel has typically 3 or 4 components such as red, green, blue and alpha.
  - In digital elevation models, each pixel is typically a height value such as elevation from sea level.





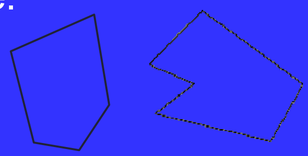
Polygon

- A plane figure that is bounded by a closed path or circuit, composed of a finite sequence of straight line segments.
- Segments are called edges or sides.
- Points where two edges meet are the polygon's vertices or corners.
- Interior of the polygon is called its body.

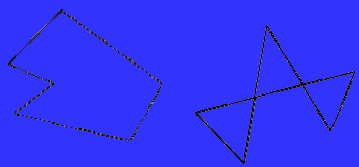


Characterization of Polygons

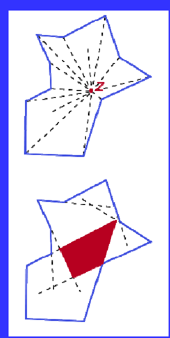
- Convex: Any line drawn through the polygon (and not tangent to an edge or corner) meets its boundary exactly twice.
- Concave: Non-convex.



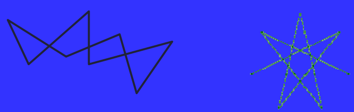
- Simple: The boundary of the polygon does not cross itself. All convex polygons are simple.



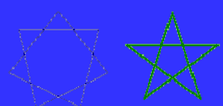
Characterization of Polygons



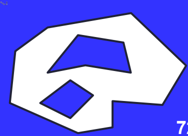
- Star-shaped: There exists a point that whole interior is visible from without crossing any edge. The polygon must be simple.
- Self-intersecting: Boundary of the polygon crosses itself.



- Star-Polygon: A polygon which self-intersects in a regular way.

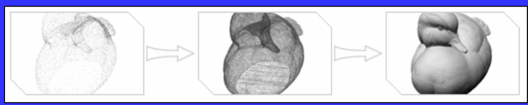


- Polygon with Holes: A polygon having interior boundaries that generates holes.



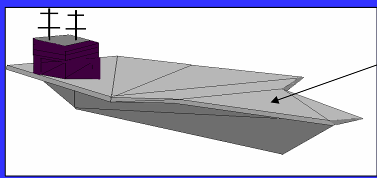
Polygonal Models

- A three dimentional model of an object that is created by building polygons (usually triangles) from the points in a point cloud.



Point cloud model   Wireframe model   Solid (surface) model

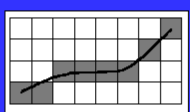
- A faceted three dimentional model of an object.



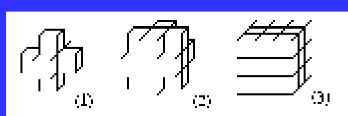
A face (triangle)

Voxel

- A volume element, representing a value on a regular grid in three dimensional space.
- This is analogous to a pixel, which represents 2D image data.
- Voxels are frequently used in the visualization and analysis of medical and scientific data.



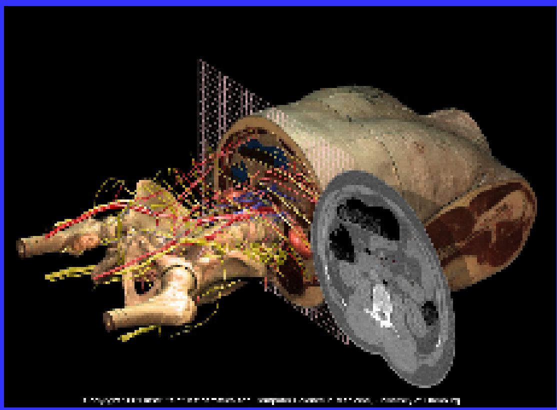
pixels

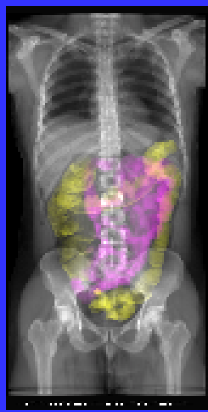


voxels

Voxel Models

- A three dimentional model of an object that is represented by voxels (created with voxelization).



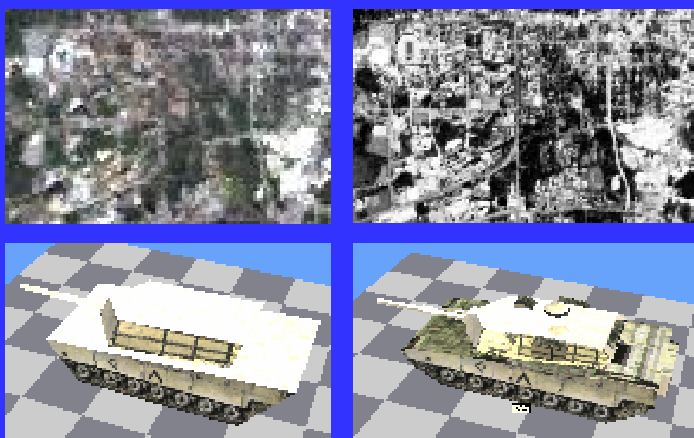


Resolution

- The level of detail a model is represented.

Image

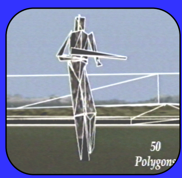
3D model



Low resolution High resolution

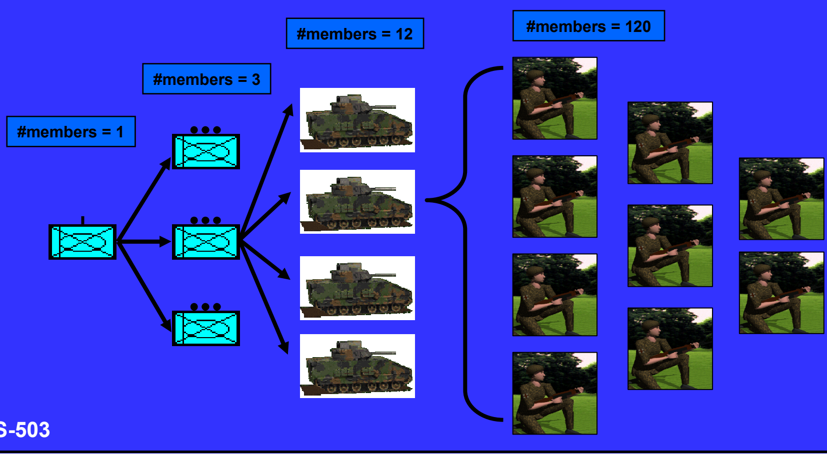
Fidelity

- The degree to which a model or simulation reproduces the state and behaviour of a real world system.
- Fidelity is therefore a measure of the realism of a model or simulation.
- A high resolution model does not always mean a high fidelity model.



Aggregation & Disaggregation

- The grouping/ungrouping of a number of entities for low/high fidelity modeling and/or visualization



Interoperability

- The ability of diverse systems to work together (inter-operate).

If two systems are interoperable, they can work together.

Simulation “A”

Simulation “B”

Reusability

- The likelihood a segment of source code can be used again to add new functionalities with slight or no modification.
- Reusable modules and classes;
  - Reduce implementation time,
  - Increase the likelihood that prior testing and use has eliminated bugs,
  - Localizes code modifications when a change in implementation is required.

Frame

- One of the many single;
  - Photographic images in a motion picture, or
  - Time instant in a simulation run.

T1

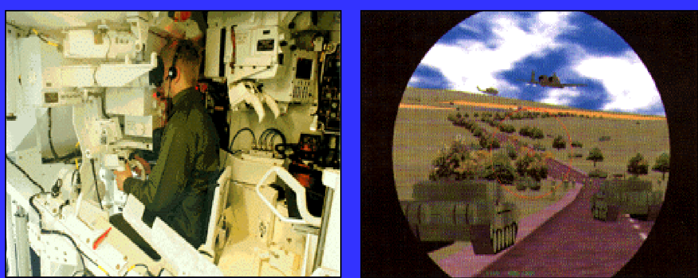
T2

T3

Simulator

- A software & hardware intergrated system that creates an environment that is as close as possible to reality for the purpose of training or research.

A flight simulator



A tank simulator

Computer Generated Forces

- Simulated military entities (e.g. soldiers, tanks) capable of acting autonomously in a simulation environment using artificial intelligence techniques.

Distributed Simulation

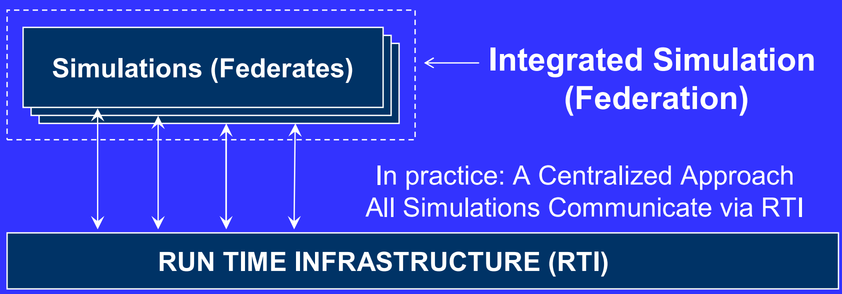
- An integrated simulation that is partitioned into a number of smaller simulations over different computational units (e.g. processors, computers).
- Provides higher scalability and multi user interaction.
- A system, whose performance improves proportional to the computational capacity added, is said to be a scalable system.

Distributed Simulation

High Level Architecture (HLA)

- An IEEE (1516) standard for developing distributed simulations.
- The concept was developed by Defense Modeling & Simulation Office (DMSO).
  - Current technology was not providing tools necessary to achieve DoD M&S Master Plan.
  - A standard was needed for the interoperability of developed simulations.

High Level Architecture (HLA)



- Federation Management
- Declaration Management
- Object Management
- Ownership Management
- Time Management
- Data Distribution Management

Conceptual Model of The Mission Space (CMMS)

- Developing simulations for some specific domains such as military operations requires knowledge of the domain (mission space).
- But that mission space knowledge is not usually readily available for the developers.
  - It is incomplete, ambiguous or defined in an informal way.
- In such a case,
  - It is not possible to develop a high fidelity model and simulation.

Conceptual Model of The Mission Space (CMMS)

- CMMS is a bridge between subject matter experts (SME*) and developers, which describes in a consistent way how the real world runs within a particular domain.

SME* : A person who is an expert in a particular area.

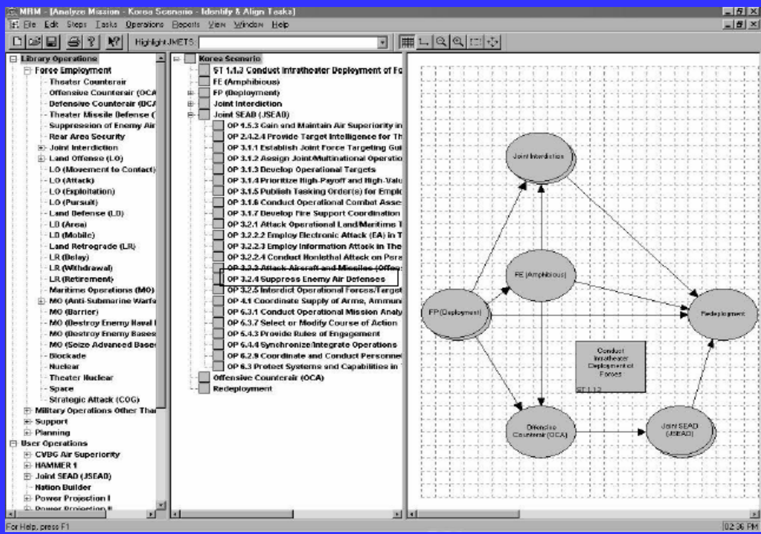
Real World	CMMI	System Design	System Implementation

Implementation Independent — Implementation Dependent

Steps of CMMS Development

- Collect authoritative simulation context information;
  To develop scope of simulation, which describes the domain that a simulation is to adress.
- Identify entities and processes;
  That must be represented for the simulation to accomplish its objectives.
- Develop simulation elements;
  To represent entities and processes.
- Address relationships among simulation elements;
  To ensure that constraints and boundary conditions imposed by the simulation context are accommodated.

Representing CMMS Formally



Verification & Validation

- Real-world system under investigation is abstracted by a conceptual model.
- Conceptual model is then coded into operational model.
- Hopefully, operation model is a correct representation of real-world system.
- We need more than hope.
- To ensure correctness, we have to perform verification and validation.

Verification

- Determination of whether the computer implementation of the conceptual model is correct.
- Question:
  - Does the operational model accurately reflects the conceptual model?
- To get an answer:
  - Examine the simulation program in details and compare to the conceptual model.

Verification

- Commonsense ways to perform verification:
  - Follow the principles of structured programming (detailed plans, top-down design, flow charts, etc.).
  - Make operational model as self-documenting as possible (comments, graphical software).
  - Have computer code checked by more than one person.

Verification

- Commonsense ways to perform verification:
  - Check to see that values of input data are being used appropriately (e.g. units).
  - For a variety of input-data values, ensure that outputs are reasonable.
  - Use an interactive run controller or debugger to check that program operates as intended (e.g. execute model step by step).
  - Visualisation is a very useful verification tool (e.g. detect actions that are illogical).

Validation

- Determination of whether the conceptual model can be substituted for the real system for the purpose of experimentation.
- A variety of subjective and objective techniques can be used to validate the conceptual model.

Validation

- Subjective techniques to perform validation:
  - Face validation: Model must appear reasonable to the subject matter experts.
  - Sensitivity analysis: When model input is changed, output should change in a predictable direction.
  - Extreme condition test: Check whether model behaves properly when input data are at the extremes.

Validation

- Subjective techniques to perform validation:
  - Validation of conceptual model assumptions:
    - Check structural and data assumptions with appropriate personnel (experts, consultants).
    - No one person knows everything about the entire system.
    - So, many people are required.

Validation

- Subjective techniques to perform validation:
  - Consistency checks:
    - Continue to examine operation model over time.
    - Detect significant changes in real-system that would effect correctness of simulation model.

Validation

- Subjective techniques to perform validation:
  - Turing tests:
    - Experimentally compare model outputs to system outputs with experts.
    - Make experts distinguish the ones that are simulated.
    - If a substantial number of simulated ones are identified, simulation model is inadequate.

Validation

- Objective techniques to perform validation:
  - Validating input-output transformations:
    - Compare model output to the output of real-system if possible (e.g. using t-test).
  - Validation using historical input data:
    - Drive operational model with historical records.
    - Output should stay within acceptable statistical error of those observed from real-world system.