Symbiotic Simulation and its Application to Complex Adaptive Systems

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Outline of Talk

- Introduction and Motivation
- Symbiotic Simulation Systems
  - Definition
  - Classification
  - Generic Framework
  - Research Issues
- Complex Adaptive Systems
  - Examples of Symbiotic Simulation
- Conclusions

Introduction and Motivation

- In today's environment, fast and effective response to change is vital for success
- To achieve this, the processes and software must be adaptive and respond quickly to changes
- However, new processes must be analysed thoroughly and shown to be effective, before potential gains can be realized
- Examples include high-tech industries that are subject to high variability, or governments that need to respond to crises

Introduction and Motivation

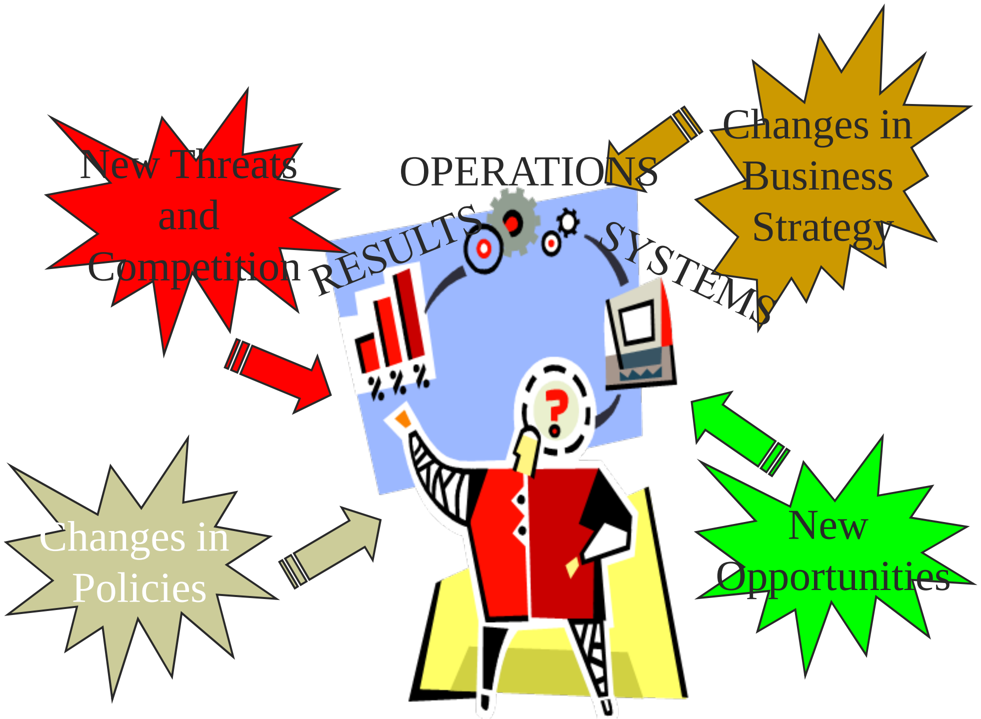
- A*STAR IMSS Project 2006-2009
  - An Integrated and Adaptive Simulation-Based Decision Support Framework for High-Tech Manufacturing and Service Networks
  - Vision: the creation of an adaptive decision support framework that allows the high fidelity representation of all value-creation processes along a supply chain in a unified business model

Introduction and Motivation

- Simulation is an important decision making tool for processes and operations in high-tech industries
- Difficult to model such systems with sufficient fidelity:
  - The physical system is constantly changing
  - Simulation models are only updated with data from the physical system on an ad-hoc basis
  - The manual validation of the simulation model and the analysis of results is a tedious process
- It is very difficult to carry out prompt "what-if" analysis to respond to abrupt changes in the physical system

Symbiotic Simulation System

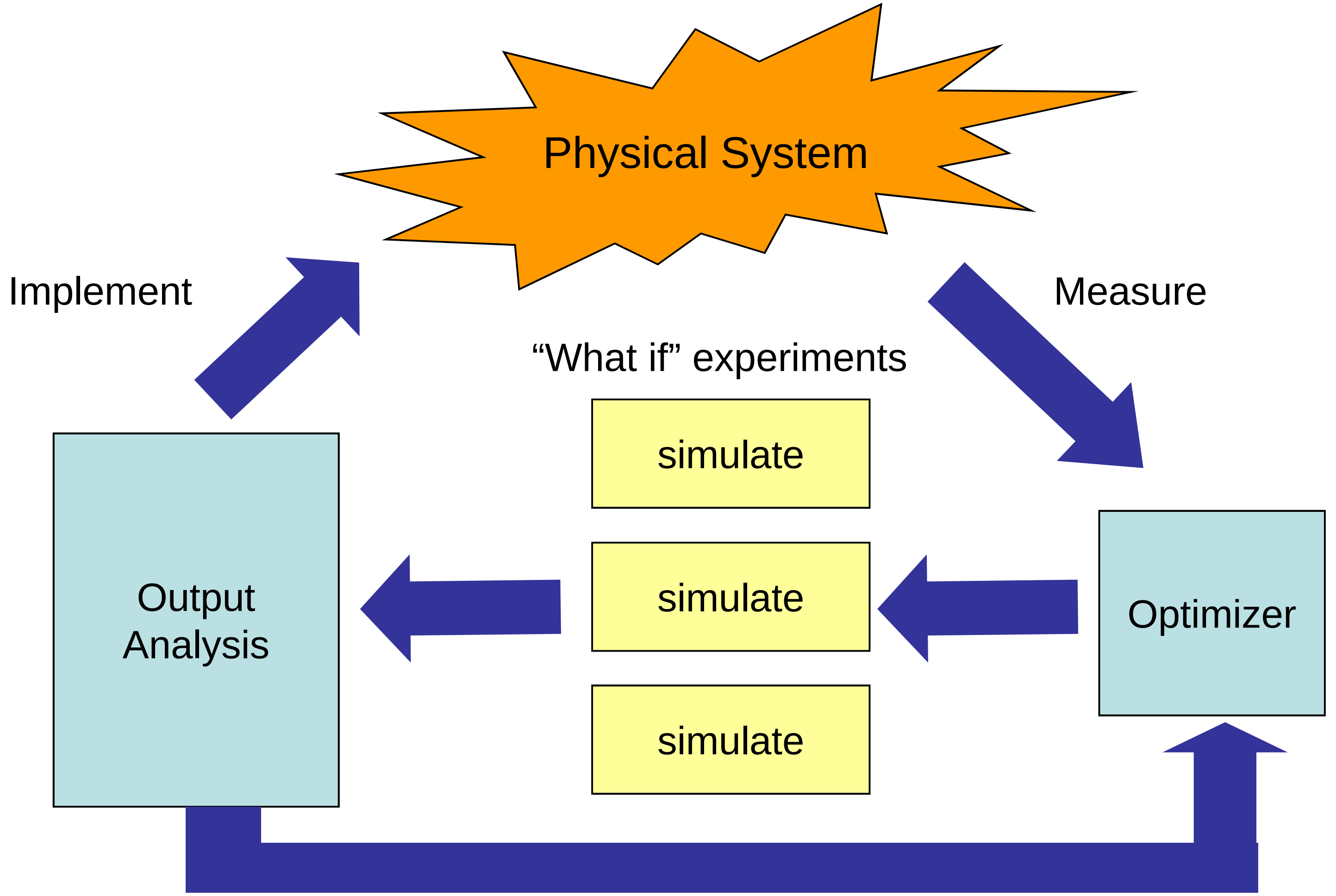
- Symbiotic Simulation
  - Is an appropriate methodology for an adaptive decision-support framework for high tech industry
  - Proposed by the PADS Working Group at the 2002 Dagstuhl Seminar on Grand Challenges for Modeling and Simulation



Symbiotic Simulation System

- A Symbiotic Simulation System is defined as one that interacts with the physical system in a mutually beneficial way:
  - The simulation system benefits from the real-time input data which can be used to adapt the model and validate its simulation outputs
  - The physical system benefits from the optimized performance that is obtained from the analysis of simulation results
- It can thus improve maintenance and adaptation of simulation models for decision support

Symbiotic Simulation System



Symbiotic Simulation System

- Dynamic Data Driven Application Systems
  - DDDAS is an active field of research and used in the context of a variety of disciplines
  - Although many applications are based on ideas related to symbiotic simulation, most DDDAS applications are focused more on the particular domain-specific problem
- Our Research on Symbiotic Simulation
  - An Agent-Based Generic Framework for Symbiotic Simulation

Symbiotic Simulation Extended Definition

- Based on the Meaning of Symbiosis in Biology
  - Mutualism: +/+
  - Commensalism: +/0
  - Parasitism: +/-
- This results in Closed Loop and Open Loop Symbiotic Simulation Systems
  - Closed loop – Simulation system affects the physical system directly or indirectly
  - Open loop – Simulation system does not affect the physical system

Classification of Symbiotic Simulation Systems

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Class	**Purpose**	**Open/Closed Loop**	**Meaning of What-if Analysis**	**Type of Symbiosis**
SSDSS	Support of an external decision maker	Closed Loop (Indirect)	Decision alternatives	Mutualism/Parasitism
SSCS	Control of a physical system	Closed Loop (Direct)	Control alternatives	Mutualism/Parasitism
SSFS	Forecasting of a physical system	Open	Different assumptions for environmental conditions	Commensalism
SSADS	Detection of anomalies either in the physical system or in the simulation model	Open	Reference model	Commensalism
SSMVS	Validation of a simulation model	Open	Alternative models or different parameters	Commensalism

Symbiotic Simulation Decision Support Systems (SSDSS)

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- An SSDSS predicts possible future states of a physical system for a number of scenarios
- Simulation results are analyzed and interpreted in order to draw conclusions which are used to support a decision making process and aim to guide an external decision maker
- Example: Path Planning in UAVs (Kamrani and Ayani 2007)
  - Alternative paths (scenarios) are simulated and evaluated

Symbiotic Simulation Control Systems (SSCS)

- An SSCS predicts possible future states of a physical system for a number of scenarios
- Simulation results are analyzed and interpreted in order to draw conclusions which are directly implemented by the means of corresponding actuators
- Example: Semiconductor Manufacturing Wet Bench Toolset (Aydt et al. 2008)
  - Actuator agents are used to make modifications to machine settings

Symbiotic Simulation Forecasting Systems (SSFS)

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- An SSFS predicts possible future states of a physical system
- Simulations can be dynamically updated with real-time data in order to improve the accuracy of the prediction, but the system does not interpret the simulation results to draw any conclusions from them in order to create feedback
- Example: Weather Forecasting (Plale et al. 2005)
  - Simulation runs are updated with real-time data to improve accuracy of forecast

Symbiotic Simulation Anomaly Detection Systems (SSADS)

- An SSADS compares simulated values and measured values of the physical system with the purpose of detecting discrepancies either in the underlying simulation model or in the physical system
- Detected discrepancies are interpreted as anomalies
- Example: Structural Health Monitoring (Cortial et al. 2007)
  - Measured values of a F-16 wing structure are compared with simulated values
  - An anomaly indicates damage

Symbiotic Simulation Model Validation Systems (SSMVS)

- An SSMVS compares the results of various simulations, each using a different possible model, with the physical system in order to determine a model that describes the physical system with sufficient accuracy
- Example: Model Validation for Radiation Detection (Aydt et al. 2008)
  - Identifying type and position of a radiation source given accurate measurements of radiation intensities

A Generic Framework for Symbiotic Simulation

- Requirements of Generic Framework – It must be:
  - *Applicable* to all symbiotic simulation classes
  - *Extensible* to add new functionality if necessary
  - *Scalable* for use in small-scale (e.g. embedded) systems and large-scale (e.g. enterprise) systems
- Framework is Agent-based and Capability-centric
  - Capability is a concept for modularization in BDI agent systems
  - An agent can be equipped with an arbitrary number of capabilities

A Generic Framework for Symbiotic Simulation

- Applicability
  - Various capabilities can be used to realize the functionality of a particular symbiotic simulation system
    - e.g. Sensor capabilities, Scenario creation capability
- Extensibility
  - The framework functionality can be extended by adding new capabilities
- Scalability
  - Capabilities are deployed to one or more agents depending on the application requirements

A Generic Framework for Symbiotic Simulation

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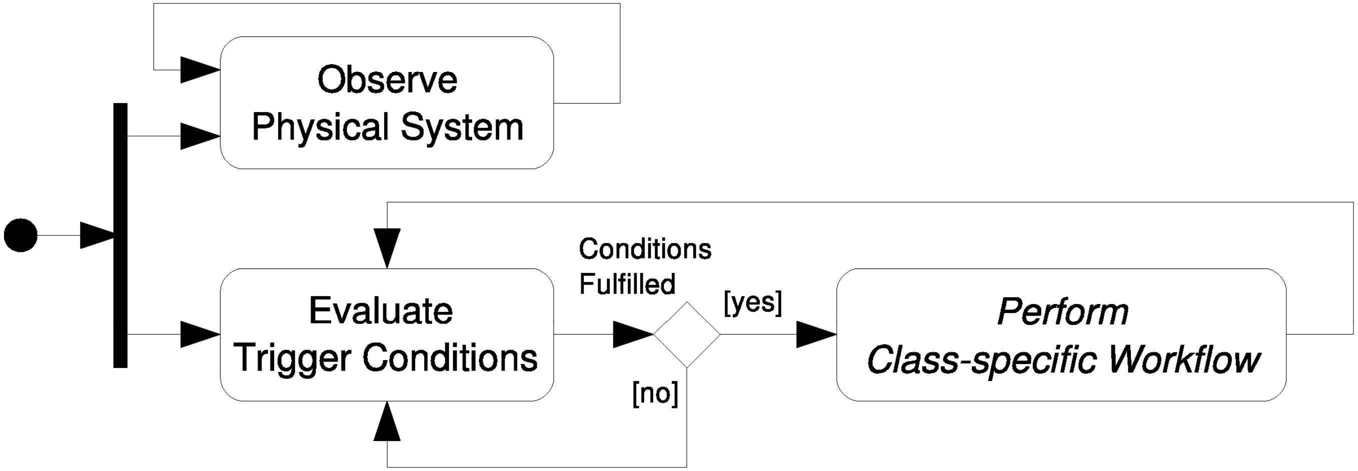
- A reference implementation using Jadex/JADE agent toolkit has been developed
- The reference implementation provides generic solutions for the various capabilities
- If desired, it is also possible to use custom implementations
- To evaluate the prototype an emulator is used to represent the physical system

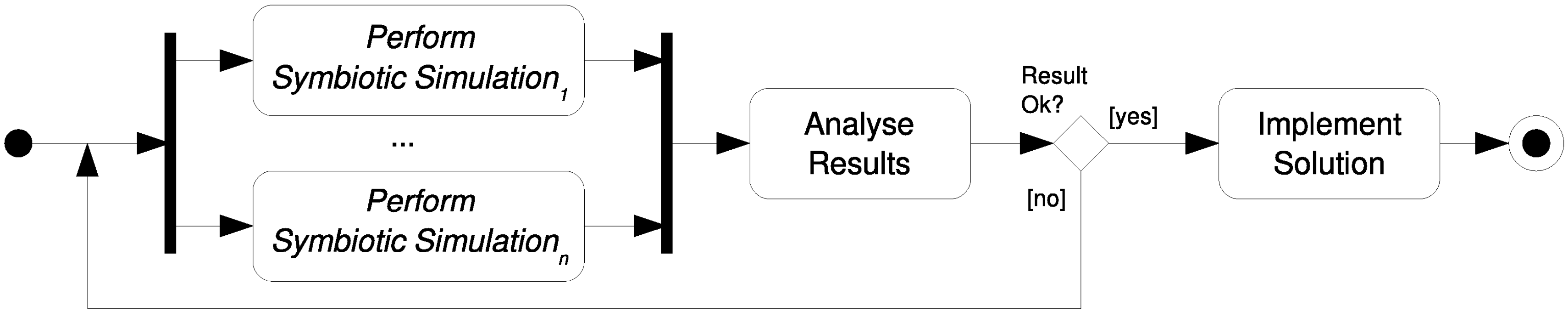
General Workflow of Symbiotic Simulation Systems

- Continuously observe the physical system
- If trigger conditions are fulfilled, trigger class-specific workflow



Class-specific Workflow: SSCS

- Perform a number of "what-if" simulations
- Analyze the results, and
- Implement an appropriate solution



Research Issues

- Detection and Scenario Generation
  - What should trigger "what-if" analysis (WIA)?
  - Efficiency and effectiveness – What scenarios should be generated?
- Initialization of What-if Simulation Model
  - Typically, short-term simulations are performed – No steady state
  - What-if simulations need to be initialized with the current state of the physical system
    - State collection method
    - Base simulation method

Triggering of What-If Analysis

- Three kinds of triggering methods have been used

WIA type	**Purpose**	**Triggering**
Reactive WIA	Problem recovery	Observed triggering condition
Preventive WIA	Problem prevention	Forecasted triggering condition
Pro-active WIA	Continuous performance improvement	Periodically

Efficiency and Effectiveness

- SSDSS & SSCS are essentially simulation-based optimization
  - Potentially many what-if scenarios need to be simulated
- Efficiency
  - Ability of the symbiotic simulation system to finish in time by performing all required WIA efficiently
- Effectiveness
  - Ability of the simulation system to find the optimum alternative, e.g. optimum decision

Efficiency and Effectiveness

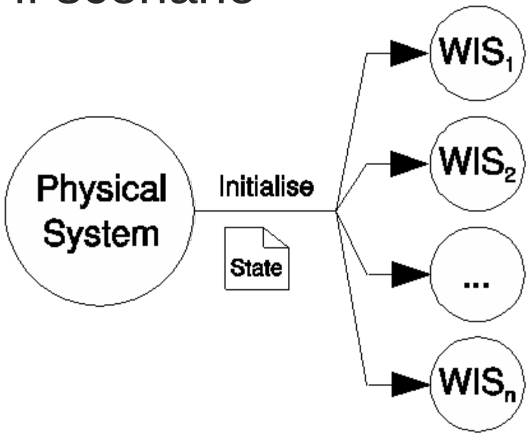
- Simulation Replications
  - Stochastic simulations have to be repeated to obtain statistically meaningful data
  - Simulating many replications for a large number of what-if scenarios can be very time consuming
  - Some work has been done to reduce the number of replications required (Lee et al. 2004)
- Parallelization
  - Parallelization of the WIA process
  - Parallelization of the simulation itself

Efficiency and Effectiveness

- What-if Scenario Generation:
  - Exhaustive search can be performed if the total number of possible what-if scenarios is small
  - If the search space is very large, then an exhaustive search is infeasible
  - Effective search algorithm is crucial
  - Meta-heuristics, such as evolutionary algorithms, can be used to create what-if scenarios
    - Is the algorithm able to find the best (or at least a reasonably good) alternative?
    - How long does the algorithm need to converge?

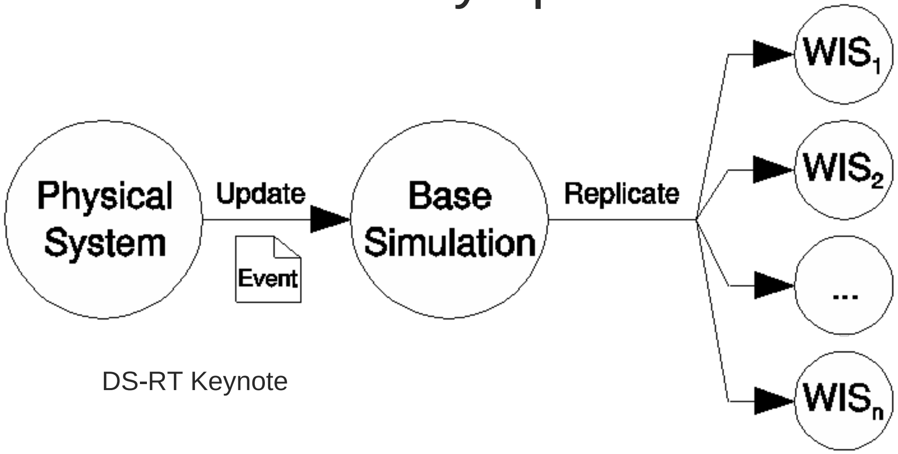
Initialization of What-if Simulation

- State Collection Method
  - Retrieves all necessary information directly from the physical system, but this may take some time
    - Periodically collect state information
    - Use most recent available state and fast-forward simulation before running what-if scenario



Initialization of What-if Simulation

- Base Simulation Method
  - A base simulation emulates the physical system and is paced in real-time
  - If WIA process is triggered, base simulation is replicated and modified to reflect what-if scenario
  - No delays for collecting state information, but base simulation needs to be continuously updated



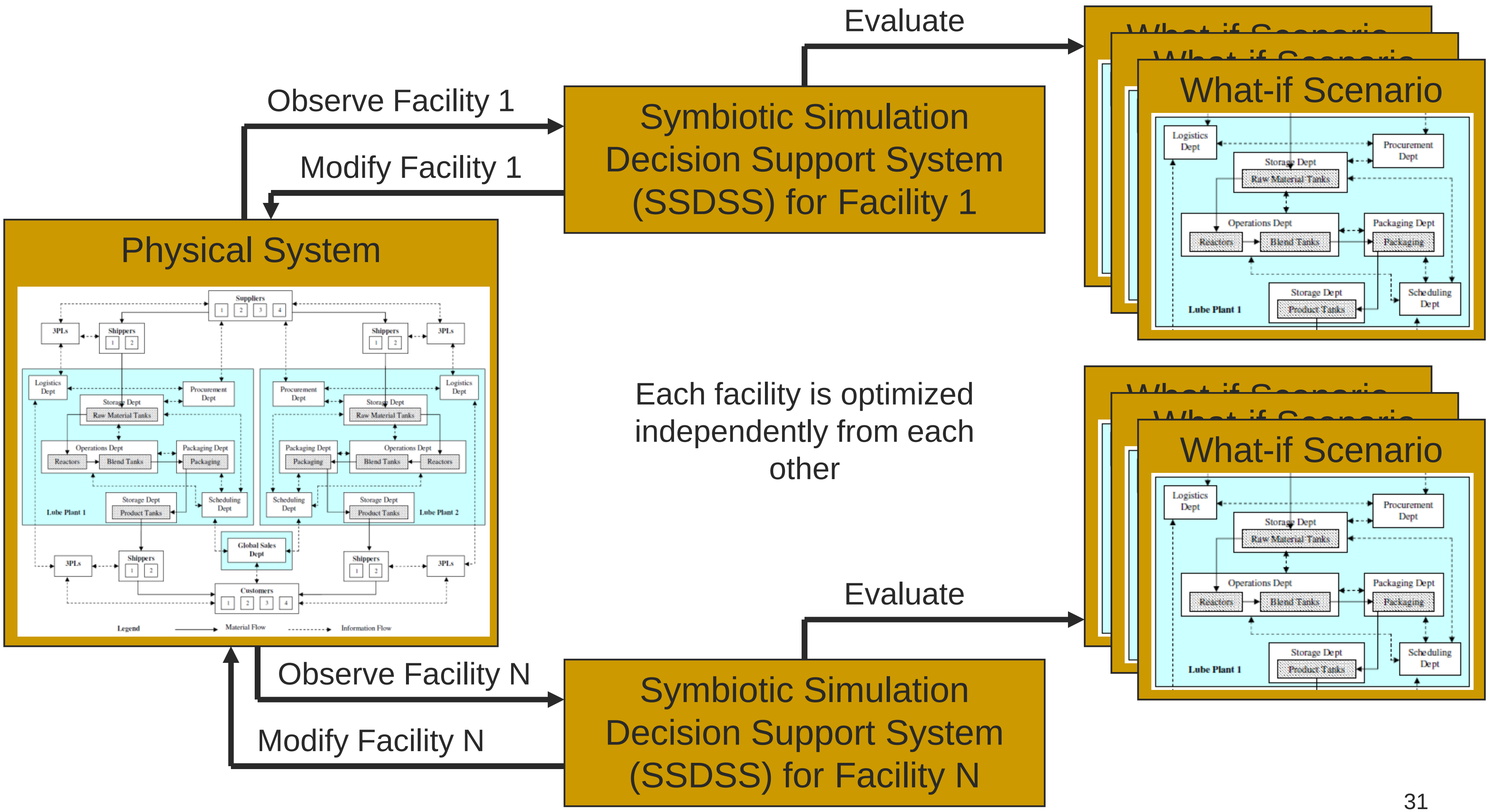
Complex Adaptive Systems

- Some Characteristics of Complex Systems
  - Many components and individual agents/actors
  - Multi spatial and temporal scales
  - Strongly coupled/interacting
  - Non-linear
  - Sensitive to boundary conditions
  - Emergent behaviour and unintended consequences
  - Behaviour can be historically dependent
  - Adaptive and evolving
  - Non-equilibrium

Complex Adaptive Systems

- Examples of the Use of Symbiotic Simulation in Complex Adaptive Systems
  - Logistics – Dynamic optimization of supply chain in manufacturing
  - Pandemics – Analysis of the effect of different policies in the event of outbreaks, e.g. SARS
  - Crowd Behaviour – Evacuation from a building in the event of fire

Dynamic Facility Optimization in Lube Oil Supply Chain



Dynamic Facility Optimization in Lube Oil Supply Chain

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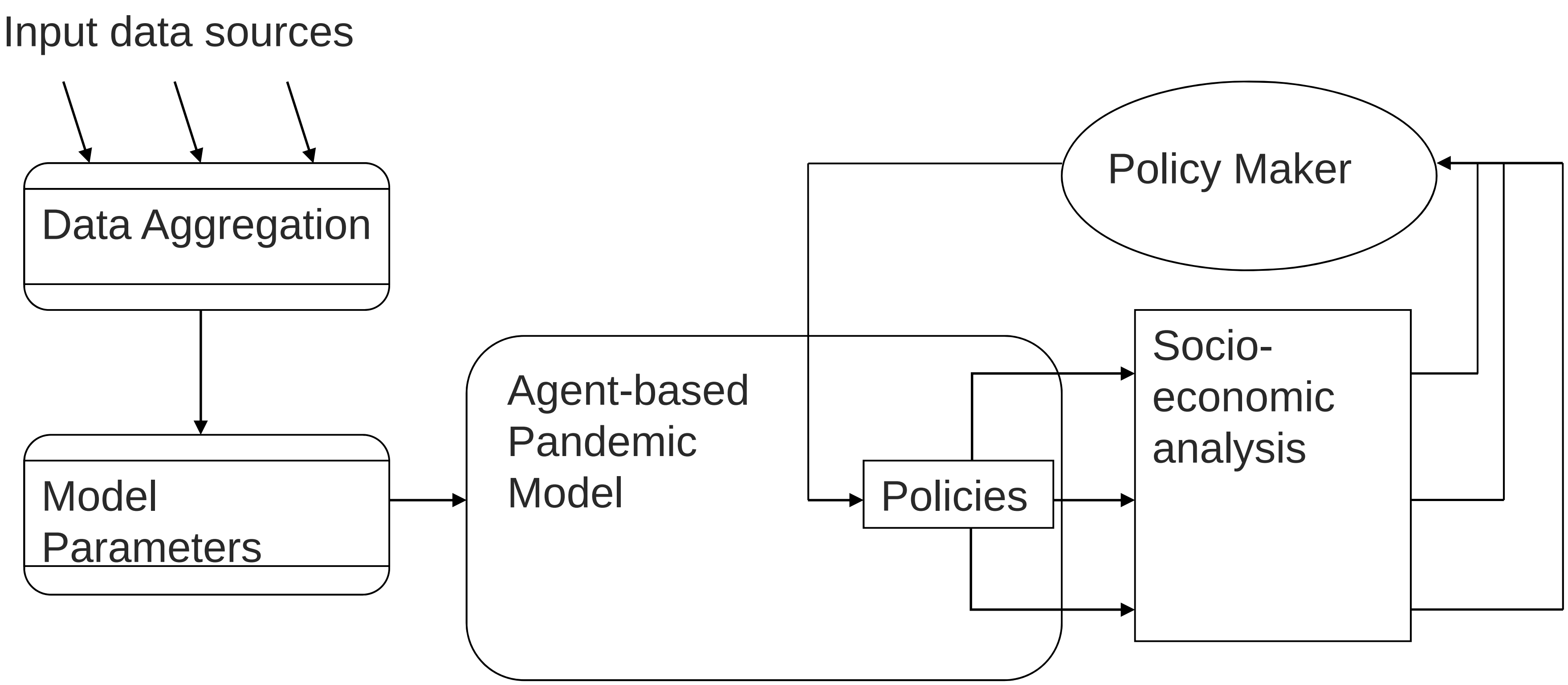
- Business Process
  - A global lubricant additive supply chain has a global sales department which passes customer orders to local facilities
  - Jobs are assigned based on a facility's ability to deliver the product on time (among other criteria)
  - Job scheduling within the facility is vital for an efficient manufacturing flow and needs to be dynamically optimized
- Outcome
  - Improved performance (e.g. cycle time, etc)

Pandemics

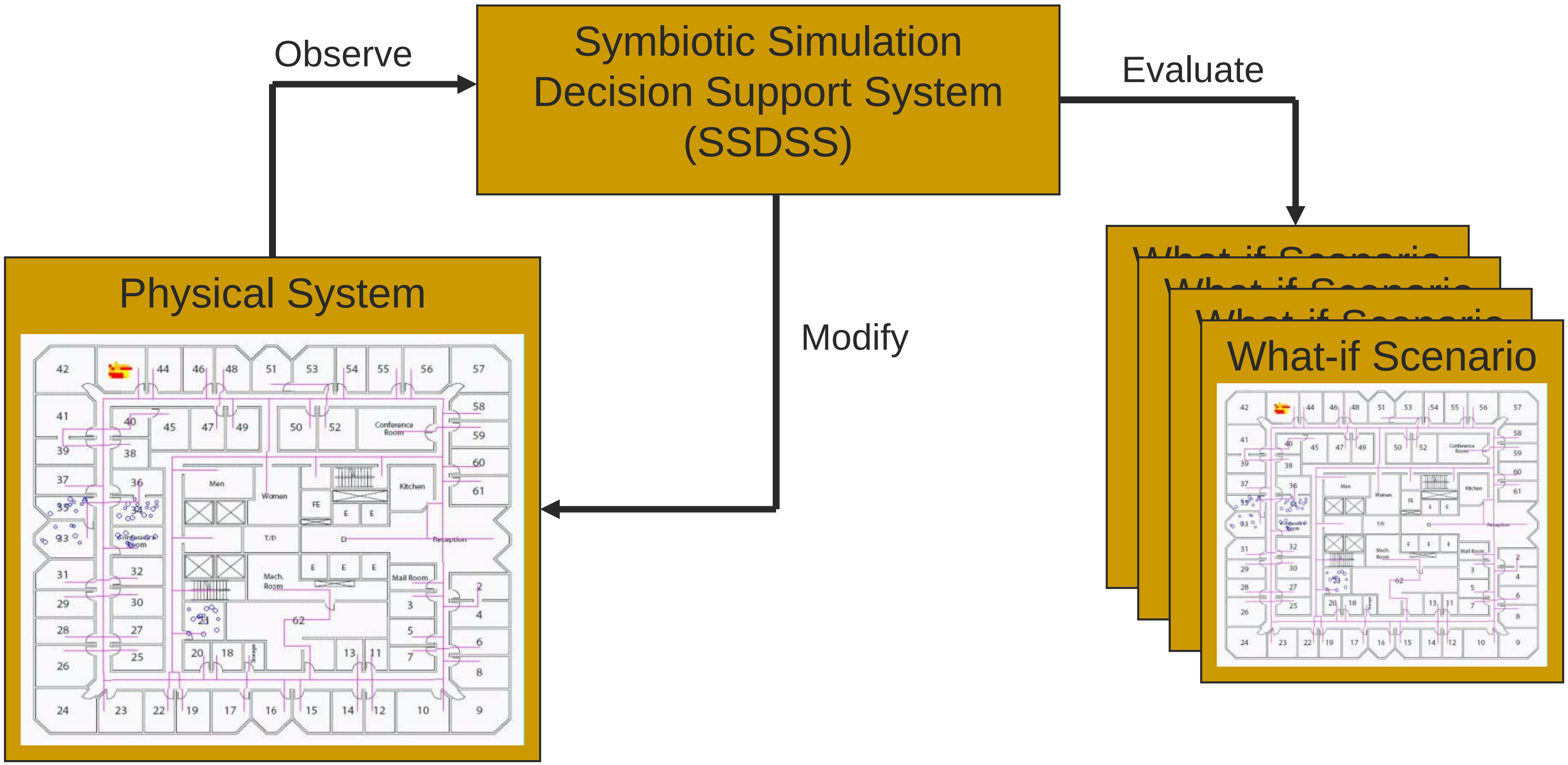

Input data sources
Data Aggregation
Model Parameters
Agent-based Pandemic Model
Policies
Policy Maker
Socio-economic analysis

Pandemics Research Issues

- Data Acquisition and Analysis
  - Data aggregation for detailed modeling
- Multi-Resolution Modeling
  - Phenomena and resolution definition
  - Model coupling and interoperability
  - Synchronization (multi-resolution, temporal scales)
- Socio-economic Analysis
  - Identification of possible counter-measure/policies
  - Development of risk assessment models
  - Development of resilience measures and indicators

Crowd Behaviour

- Evacuation from a building in the event of fire



Conclusions

- A Classification and Terminology for Symbiotic Simulation Systems has been presented
- An Agent-based Generic Framework for Symbiotic Simulation Systems has been described
- The SSCS Prototype has been evaluated with various Manufacturing Applications
- Results indicate that SSCS can significantly improve the performance compared to Common Practice
- Symbiotic Simulation is now being used to understand and steer Complex Adaptive Systems

Conclusions

- SSDSS & SSCS need suitable optimization methods
  - Efficient simulation of a potentially large number of scenarios
  - A good solution in time is better than an optimum solution too late
  - Dynamic and robust optimization methods needed
- Modeling Issues
  - Model needs to accurately reflect the physical system in all its relevant details
  - Model needs to be kept up-to-date in real-time

Thank you for your attention!

Questions & Answers