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# A MULTI-PARADIGM MODELING FRAMEWORK FOR MODELING AND SIMULATING PROBLEM SITUATIONS

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## ABSTRACT

This paper proposes a multi-paradigm modeling framework (MPMF) for modeling and simulating problem situations (problems whose specification is not agreed upon). The MPMF allows for a different set of questions to be addressed from a problem situation than is possible through the use of a single modeling paradigm. The framework identifies different levels of granularity (*macro*, *meso*, and *micro*) from what is known and assumed about the problem situation. These levels of granularity are independently mapped to different modeling paradigms. These modeling paradigms are then combined to provide a comprehensive model and corresponding simulation of the problem situation. Finally, the MPMF is implemented to model and simulate the problem situation of representing the spread of obesity.

## 1 INTRODUCTION

When building models and simulations, it is desirable to have a well-defined problem and an agreed upon solution for representing that problem, yet most models depart from this premise. This is difficult to achieve when representing *problem situations* where there is no agreed upon specification due to differences in opinions of the team (Vennix, 1999). Modeling this type of problem has been addressed by reaching a consensus on what the problem is as proposed in soft-systems methodology (Checkland, 2000). This is a major step forward, but it does not help in simulating each of the stakeholders' problem formulations. This is further complicated when the modelers and simulation designers have different interpretations of the problem (the model) along with different interpretations of how to implement the problem's solution (the simulation). These different perspectives, interpretations, and possible implementations of the problem create the underlying *problem situation* and may lead to:

1) convoluting the problem given that differences in perspectives are *not identifiable*,
2) oversimplifying the problem given that differences in perspectives are *not resolvable*,
3) oversimplifying the problem given that differences in perceptions are *not resolved correctly*, or
4) reducing the problem situation to a well-defined problem that is *not relevant* to the case at hand.

According to Vangheluwe, de Lara, and Mosterman (2002, p. 5) and Nilsson, Peterson, and Hudak (2003, p. 1), the need to model systems containing increasingly complex elements as a "whole" is becoming a necessary component in the design, analysis, and implementation of real-world systems. Traditional modeling approaches break the real-world system into less complex elements and then implement a simulation using a *single* modeling paradigm. Individually, a modeling paradigm is usually focused on a specific level of granularity and addresses a unique set of modeling questions.

Multi-paradigm modeling (MPM) provides an avenue for representing interactions between elements at different granularity levels. This allows for a larger range of questions from the problem situation to be addressed. The MPMF is designed to create a simulation of a problem situation that answers the desired modeling question (MQ). The MPMF is based on a methodology designed to capture problem situations presented by Tolk et al. (2013). The authors claim that their methodology facilitates the generation of interoperable simulations which was a major driver for its use to develop the MPMF. However, it does not provide a path for the design or implementation of a simulation which the MPMF seeks to provide. This paper will focus on the following modeling paradigms: (1) agent based modeling (ABM); (2) discrete event modeling (DES); and (3) system dynamics (SD). The purpose of the MPMF is *not* to restrict the modeling process to only these modeling paradigms nor to suggest that all three of these paradigms *must* be used simultaneously for a simulation implementation.

## 2 A FRAMEWORK FOR CONDUCTING MULTI-PARADIGM MODELING

The diversity of opinions, specifications, requirements, goals, etc. contributed from various stakeholders for the system creates a problem situation and can make the modeling of that system a daunting task. MPM offers a number of benefits over the use of a single modeling paradigm. First, MPM allows for interactions between elements at all levels of granularity to be represented. Second, MPM allows for every element to be represented by the paradigm that fits it best. Third, MPM provides a way to lessen the amount of elements that *must* be abstracted from the problem situation. Finally, MPM allows for the model and simulation to answer a different set of questions than a single modeling paradigm will answer.

A number of challenges arise when using MPM. It is difficult to select paradigms which address the MQ without increasing the complexity of the system (Borshchev and Filippov (2004), Lorenz and Jost (2006), Sokolowski and Banks (2010), and Vangheluwe et al. (2002)). Modeling interactions between elements at different levels of granularity increases the complexity of the model. Capturing each component in the paradigm that fits it best can lead to the use of a large number of paradigms. Reducing the number of elements that are abstracted from the problem situation increases the number of elements in the model. This leads to: 1) increased complexity in the model, and 2) increased time for the modeler to compare each element against each other element within the model. Also, formal specifications are needed to describe the classes and components of the different modeling paradigms that will be used (de Lara, Levendovsky, Mosterman, and Vangheluwe (2008) and Vangheluwe et al. (2002)).

The proposed MPMF is based on the Modeling and Simulation – System Development Framework (MS-SDF) (Tolk et al., 2013). The MS-SDF provides a high-level perspective on how to derive a model from a problem situation and a simulation from the model. It addresses traceability in the modeling and simulation process by balancing completeness and consistency. Completeness and consistency are needed to capture the problem situation in a computable form. The MS-SDF does *not* provide the means of building a simulation using MPM. The MPMF specifies a MPM implementation of the MS-SDF that specifies how to arrive at a simulation from a problem situation.

## 3 OVERVIEW OF THE MS-SDF

The MS-SDF captures the problem situation through reference modeling in an implementation-*independent* fashion. The reference model documents what is known and what is assumed (when knowledge is lacking) about the system. The reference model aims to be *complete*, even if it is inconsistent. This inconsistent completeness provides an overall picture of the stakeholders' perspectives. The conceptual model is generated from the reference model and provides the transition from an implementation-*independent* to implementation-*dependent* model. By design, the conceptual model cannot contain statements that are not documented in the reference model. The conceptual model must be *consistent* to be computer implementable. The simulation is then constructed using the conceptual model. The simulation is the finite state machine realization of the conceptual model that answers the MQ. The MS-SDF does not suggest which tool to use or that the implementation ought to be conducted through a single- or multi-paradigm implementation. The overall process is shown in Figure 1.

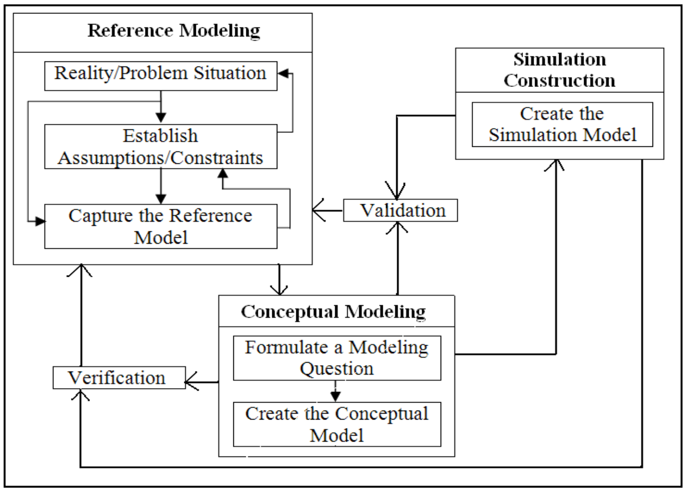


Figure 1: Overview of the MS-SDF (Tolk et al, 2013).

### 3.1 The Proposed Multi-paradigm Modeling Framework

The MPMF follows the three high-level constructs (reference modeling, conceptual modeling, and simulation building) from the MS-SDF. However, the MPMF expands these constructs to allow for simulation implementation. The MPMF aims to maintain the high level of traceability provided by the MS-SDF. The recursive layout of the framework facilitates the traceability in the modeling process. The MPMF focuses on the statements collected and sorted in the reference model. Statements are either *assertions* or *assumptions*. *Assertions* are statements of facts and *assumptions* are statements designed to facilitate abstraction. The statements are then used to select the modeling paradigms within the the conceptual model and the simulation. Figure 2 shows the proposed MPMF. Sections 2.2.1, 2.2.2, and 2.2.3 cover the MPMF's reference modeling, conceptual modeling, and simulation building processes, respectively.

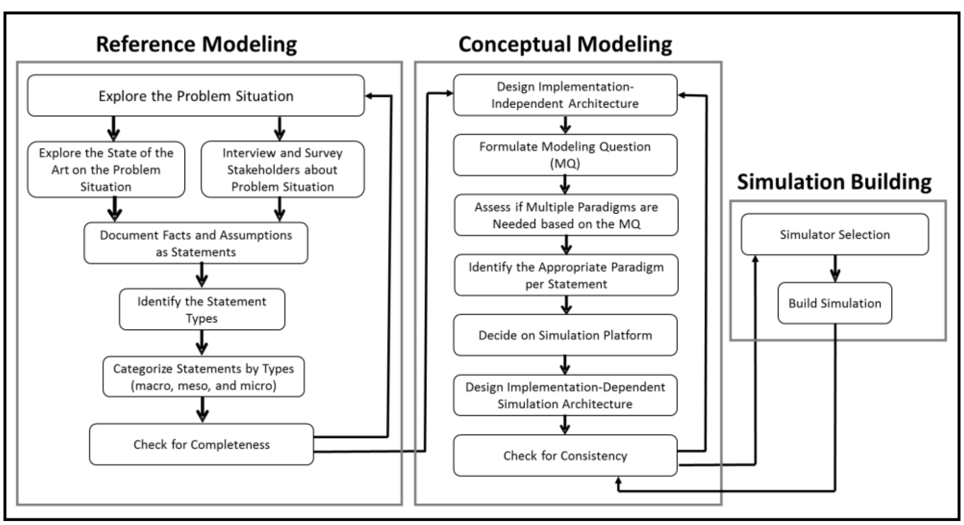


Figure 2: The MPMF.

#### 3.1.1 Reference Modeling

In the reference modeling process, the most important steps to consider are how to capture the data and how to categorize the data based on levels of granularity at the *micro*, *mesa*, and *macro* levels. To capture data from stakeholders, combine it with the theoretical and empirical work facilitating simulation construction, and categorize it into levels of granularity requires a combination of at least three professional skills:

1) a systems engineer or management professional, who elicits and captures requirements from the stakeholders;
2) a subject matter expert (SME) on the topic being modeled, who knows about the topic of interest and who knows what assumptions are permitted when data is not available; and
3) a modeler, who categorizes the data in different levels of granularity and captures data in the form of statements or in a formal manner using tools such as ontologies.

The goal of using statements is the ability to assign truth values (true or false) to each individual statement. This is important when capturing multiple perspectives because it allows opportunities for stakeholders to reach consensus in the truth value of a statement. Ultimately, the following questions need to be answered. Have we captured all of the perspectives? Do we have enough information to model the problem? The answers provide an idea of the level of completeness achieved in this modeling process. This process is iterative and requires a good line of communication between all involved parties.

Categorizing the captured data (the statements) into *micro*, *meso*, and *macro* levels facilitates exploration into the problem situation. The *micro* level deals with components or processes that *cannot* or *should not* be further broken into sub-components or sub-processes. *Micro* level components and processes can affect each other but do not directly affect the system performance (*macro* level). An aggregated *micro* level component is classified as a *meso*- or *macro*-level component. The *meso* level deals with components or processes that are viewed as a single unit. *Meso* level components are aggregates of *micro* level components that can also be further aggregated into higher level components. The *micro* level components can be affected by the behaviors and interactions among the *meso* level components they form, as well as the higher *macro* level components. The *macro* level deals with components that affect the overall system performance. The system performance can be *affected by* and *affect* the components at lower levels. The *macro* level components interact with other *macro* level components and are not part of a larger set of components. A *macro* level component is *not* required to have any sub-components that comprise it.

The modeler relies on knowledge and on assumptions to connect these levels of granularity. The list of assumptions gathered from the problem situation is compared against each granularity level to determine which assumptions are considered true at each level. The use of assumptions meets the needs of Lorenz and Jost (2006) who state that a set of assumptions based on the interactions between paradigms would enhance the modeling process. The use of assumptions also meets the need to address complex system behavior at varying levels of abstraction identified by Vangheluwe et al. (2002). The MPMF *requires* that a reference model be captured formally to evaluate consistency. As mentioned, ontologies can help in this process.

#### 3.1.2 Conceptual Modeling

Conceptual modeling within the MPMF involves three important parts. Selecting a MQ that portrays what the stakeholders' want to know. Selecting the modeling paradigms to facilitate the implementation-*dependent* simulation architecture. Aligning the paradigm selection with the different levels of granularity to maintain consistency. The MPMF contains criteria that drive the selection of the ABM, DES, and SD paradigms. The statements, now categorized by granularity, drive the selection of the paradigms. Each statement is analyzed to determine which paradigms can model it. Several criteria are presented here for determining the paradigm that best fits the statement. This is *not* intended to be an exhaustive list of criteria. If a statement fits multiple paradigms, each should be marked to later assist in reducing the total number of paradigms needed when creating the simulation. The focus at this point is still implementation-*independent*.

**Criterion 1** is the most important criterion. If a single modeling paradigm is sufficient to answer the MQ, then MPM *should not* be used.

**Criterion 2** deals with the perspectives of the stakeholders. A holistic view of the problem situation is obtained by considering all of the system components and the relationships between them.

**Criterion 3** deals with the *timing mechanisms* for each statement. If the MQ and the associated statements require the use of continuous time, then SD is usually the best choice to select. Otherwise, DES or ABM is likely more appropriate. However, ABM can also contain elements that are continuous and may be an appropriate choice for certain statements.

**Criterion 4** deals with the *type of interactions* associated with the statement. System dynamics should be used if the statement focuses on cause-and-effect relationships. DES or ABM should be considered if the statement deals with event-driven changes. Agent-based modeling should be selected if the statement deals with element-element interactions or element-environment interactions.

**Criterion 5** deals with the *granularity level* of the statement. The identification of granularity levels can become largely subjective. SD is generally associated with a high level of granularity and focuses on system level changes. Both DES and ABM can have statements associated with both high and low granularity levels. Refer to Section 2.2.1 for a more in-depth discussion on the granularity levels.

**Criterion 6** deals with the *type of data* involved with the statement. If the statement is equation-based then it may be a good fit for SD. DES is a good fit for statements involving empirical data. ABM is a good candidate for representing theory. However, ABM can also be used with empirical data.

**Criterion 7** deals with the *aggregation level* of the entities in the statement. SD is generally focused on entities at the level of the entire population. DES focuses on entities at the individual level or possibly at the level of groups of individuals. ABM strictly deals with entities at the individual level.

It is extremely complicated to generate a comprehensive list of criteria for identifying the paradigm connected to a statement. Increasing the number of criteria can cause conflicts in identifying paradigms. The selected paradigms should reflect the criteria listed above that are relevant to the conceptual model.

#### 3.1.3 Simulation Building

The final process of the MPMF (mirroring the MS-SDF) consists of constructing the simulation from the conceptual model. A simulation tool is selected to build the simulation. The modeler is free to select any software package or tool to facilitate the simulation construction. The modeler can use a tool that allows for building a simulation with all of the selected paradigms simultaneously or the modeler can use different tools (one per paradigm) and create a multi-simulation environment where data from one tool can be sent to another. The MS-SDF dictates that the simulation should be consistent with the conceptual model (Tolk et al., 2013).

## 4 USE CASE

The following Use Case presents how the MPMF is applied to a problem situation of how to decrease the prevalence of obesity within an area. The formation of this problem situation results from the different perspectives on the cause of obesity from the stakeholders (i.e. healthcare professionals, policy makers, etc.) that deal with obesity. Each perspective needs to be captured when examining the problem. The purpose of this section is to highlight how the statements from the problem situation were categorized by granularity levels and how they were assigned modeling paradigms. It is *not* the purpose of this section to answer the specific MQs or to display the results from the simulation.

### 4.1 Constructing the Reference and Conceptual Models

The selection of the granularity levels and the possible modeling paradigms associated with each statement is the main point of this section. This section presents a number of examples that outline the specification of granularities and modeling paradigms based on statements for representing obesity. Table 1 provides example statements and their corresponding assigned granularity levels and possible modeling paradigm representations. These statements were selected to show a range of potential granularity and modeling paradigm combinations. As a reminder, statements from the problem situation are *not* made with respect to a preselected modeling paradigm, thus the statements are implementation-*independent*.

The causes of obesity within an individual are specified by the Centers for Disease Control and Prevention (CDC, 2010), the National Institutes of Health (NIH, 1998), and the U.S. Department of Health and Human Services (NIH, 2005) as the net calorie gain of an individual due to eating and exercising. These sources contributed **statements 1, 2, 3, 4, and 5** from Table 1. Each of these statements refer to a supporting attribute of the people and are thus classified at the *micro* level. Additionally, each of these statements refers to individual level entities which points towards the modeling paradigms of ABM and DES.

Table 1: Use Case Statements and Corresponding Granularity Levels and Potential Modeling Paradigms.

| Index | Statement (Implementation-Independent) | Granularity Level | Possible Modeling Paradigm Representation | Assertion or Assumption |
|---|---|---|---|---|
| 1 | People eat three meals per day | Micro | ABM, DES | Assumption |
| 2 | People have the opportunity to conduct physical activity | Micro | ABM, DES | Assertion |
| 3 | The focus will be on employed people | Micro | ABM, DES | Assertion |
| 4 | Biking and walking to work burns calories | Micro | ABM, DES | Assertion |
| 5 | Driving to work does not burn calories | Micro | ABM, DES | Assumption |
| 6 | Weight gain is dependent on calorie consumption | Micro | ABM, DES, SD | Assertion |
| 7 | Weight loss is dependent on calorie expenditure | Micro | ABM, DES, SD | Assertion |
| 8 | The prevalence of obesity in an area changes over time (historically increasing) | Macro | ABM, SD | Assertion |
| 9 | Restaurants and markets provide food to people | Meso | ABM, DES | Assertion |
| 10 | Gyms are locations that provide physical exercise opportunities to people | Meso | ABM, DES | Assertion |
| 11 | Primary care physicians and specialists treat people with obesity-related diseases | Meso | ABM, DES | Assertion |
| 12 | Obesity-related diseases affect the life expectancy of the people that are afflicted with the diseases | Micro, Macro | ABM, SD | Assertion |
| 13 | Workplaces contribute to the physical activity levels of the employees | Meso, Macro | ABM, DES, SD | Assertion |
| 14 | Body Mass Index values that are greater than 30 are considered Obese | Micro, Meso, Macro | ABM, DES, SD | Assertion |
| 15 | Travel methods are divided into biking, walking, and driving | Micro, Meso, Macro | ABM, DES, SD | Assumption |

**Statements 6 and 7** are classified at the *micro* level because they are once again attributes of the people. As before, these statements point towards ABM and DES. These statements were pulled from the Body Mass Index calculation that classifies people as obese. This process takes the weight and height of the individual and determines the obesity classification of that person (NIH, 1998). These statements were additionally categorized under SD, since equations can represent calorie gains and losses.

**Statement 8** is classified at the *macro* level because it looks at system level behavior which also points to the selection of SD. The statement can also be represented in ABM because collections of agents can also convey a system level statistic of this sort.

**Statements 9, 10, and 11** are classified at the *meso* levels. These statements were also considered for classification at the *micro* granularity level as well, since each of the elements within these statements (restaurants, gyms, etc.) could potentially be represented as individual entities. However, this was rejected since each of these elements require additional information to be properly defined. These statements can be implemented through ABM as individuals and also through DES as sets of processes.

**Statement 12** is classified at the *micro* and *macro* levels. This statement can be considered at the *micro* level since life expectancy and diseases can be assigned as attributes to an individual person. Viewed as an attribute this statement also contributes to selecting ABM. Alternatively, if the person is viewed as a system from the perspective of the disease, then the effect of the disease over time can be captured at the *macro* granularity level. Also, viewing the population in separate groups that are sorted by obesity levels (normal versus obese versus severely obese) would allow for the life expectancy of each group to also be captured at the *macro* granularity level. Both of the *macro*-related cases can be captured using SD.

**Statement 13** is classified at the *meso* and *macro* levels. The description of the workplaces within this statement can be captured as a discrete event process. This is a *meso* level statement pointing to ABM or DES. The statement can also be reflected as a variable within an equation, where the workplace contributes to the amount of calories burned by all of the people who work there. This is a *macro* granularity level statement that can be represented by SD.

**Statements 14 and 15** are classified at the *micro*, *meso*, and *macro* levels. Both of these statements apply at the individual level (resulting in *micro* or *meso* granularity) and the system level (resulting in *macro* granularity). The resulting paradigm could be ABM for any of the granularity levels. DES can represent these statements at the *micro* or *meso* levels and SD can represent the statements at the *macro* level.

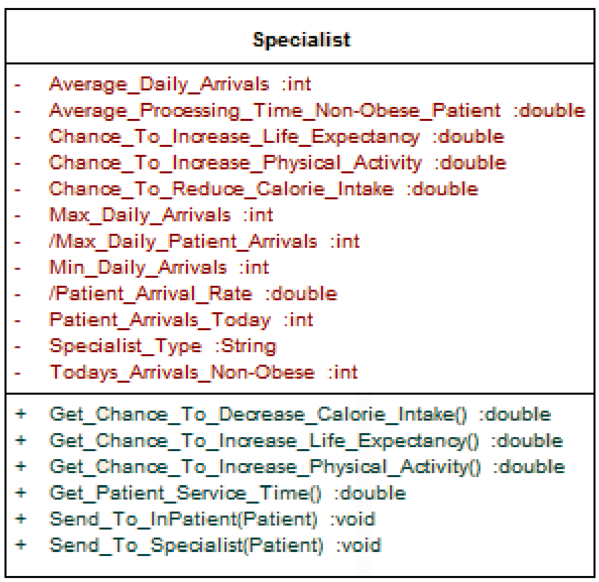


Figure 3: UML Class Diagram of the Specialists.

Both the implementation-*independent* and the implementation-*dependent* architectures were constructed using the Unified Modeling Language (UML). Figure 3 is the UML Class Diagram for the obesity-related medical *specialists*. This figure provides the attributes and functions that were attributed to the *specialist* from the reference model. The identification of medical *specialists* from *statement 11* of Table 1 led to the construction of this class diagram. Each entity identified from the reference model contain a similar diagram. From an implementation-*independent* viewpoint, the class diagram collects all of an object's attributes and function in one place along with the data type and function type of each attribute. The same class diagram is used when converting this into the implementation-*dependent* architecture, but the names are changed to reflect the exact name that will be used within the simulation (the naming convention in Figure 3 reflects this implementation-*dependent* naming convention). Class diagrams can also be linked to each other to display the relationships between them. This is not reflected in Figure 3, but it was reflected in the overall architecture for the model.

## 4.2 Constructing the Simulation

The MQ for this Use Case is how to decrease the prevalence of obesity within an area. This MQ is too broad to specify the set of modeling paradigms and an examination of the statements in the conceptual model is needed. The examination of the statements revealed that this specific MQ placed a significant value on tracking certain attributes of the individuals (i.e. weight and exercise) and looking at the population level statistics of the individuals. This initially pointed to all three of the modeling paradigms. However, it was determined that the desired system level information could be obtained through aggregate data of the population. Therefore, SD was discarded as there were no specific statements that uniquely fit SD. DES captured the processes involved with visits to healthcare professionals from the conceptual model. ABM captured the individuals (people, restaurants, gyms, etc.), as well as the system level factors that track the prevalence of obesity. All of the UML diagrams from the conceptual model were used to implement the final simulation.

AnyLogic Professional version 6.9 was selected to create the simulation. AnyLogic provided an avenue for the creation of the simulation using the ABM and DES paradigms while also allowing for *calibration* and *sensitivity analysis* experiments to be constructed. Figure 4 and Figure 5 show ABM-driven and DES-driven implementations from the conceptual model, respectively. Figure 4 displays a portion of the decision process for people (represented as agents) for deciding whether they need to visit a medical facility. This implementation design was pulled straight from a UML statechart within the conceptual model. As stated within the reference model, once a person becomes obese, that person obtains an obesity-related disease and can seek treatment for that disease through various medical facilities (such as *hospitals* or *specialists*). When an individual from Figure 4 enters the *GoToSpecialist* state that individual is transferred to the *specialist* for treatment. However, this causes an issue within the MPM environment as the *specialist* is represented using DES and AnyLogic 6.9 does not allow for direct transferal of agents into a DES system.

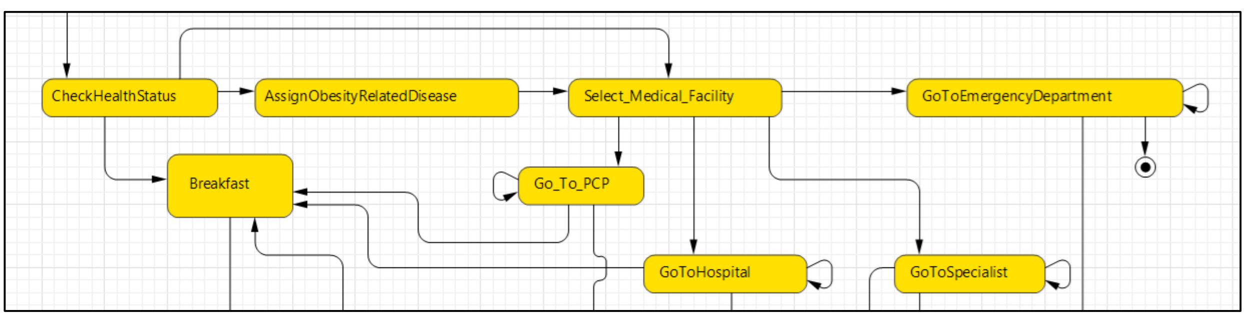


Figure 4: ABM Statechart Implementation of a Person's Medical Decision Process.

In order to send the person (an agent) to the *specialist* (a DES system) to seek treatment, the agent had to first be transformed into an entity. This required that a separate Java Class be created in AnyLogic to create an entity to mirror the agent. The entity traverses the DES system and then updates the agent version of itself on the results of the *specialist* visit before the entity is destroyed. Possible end states of the visit include scheduling a return appointment with the *specialist* or scheduling an operation which will take place at the hospital's inpatient system. The outcome of the entity's interaction through the DES system has to be communicated back to the agent to ensure that the temporal balance between the paradigms is maintained. While the entity is interacting with the *specialist*, its corresponding agent does nothing but wait for the entity to complete its interaction within the DES system. This is reflected in Figure 4 by the

*GoToSpecialist* state looping back to itself. This prevents the agent from executing any additional logic while its mirror (the entity) is interacting with the DES system. Figure 5 shows the design of the DES representation of the *specialist*.

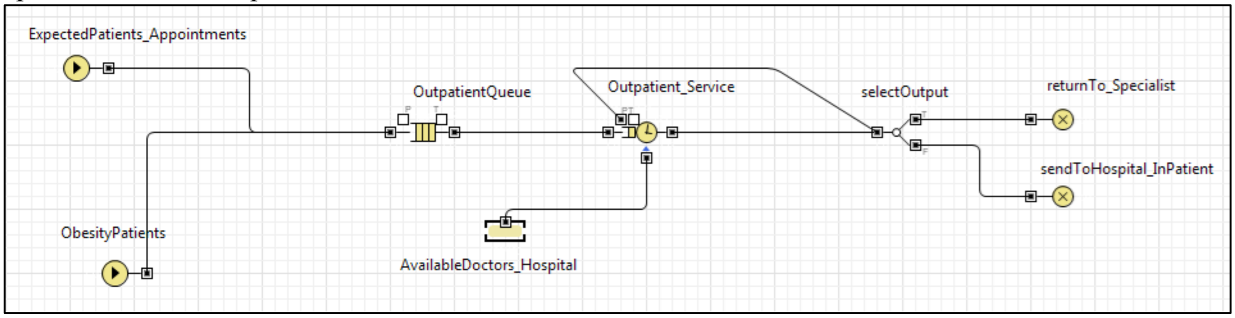


Figure 5: DES Implementation of a Visit to a Specialist.

## 5 VERIFICATION AND VALIDATION

The verification and validation (V&V) process becomes more complicated in MPM. This is largely in part to the MPMF dealing with interactions at different levels of granularity. Therefore, several tests were used to assist in the V&V process. Bharathy and Silverman (2010) identified several tests for validating social systems models. These tests include external validation tests for providing statistical confidence in the model at varying levels of granularity. Additional tests include a methodological validation test to reduce human errors and cognitive biases and internal validation tests for ensuring "adherence of structure and functions to specifications" (Bharathy & Silverman, 2010, p. 450). Railsback and Grimm (2011) discuss the use of calibrating the model's initial parameters to assist in producing outputs that match the real data for the system. The V&V processes that were applied to the Use Case are presented in the following sub-sections.

### 5.1 Traceability

The advantage of the MS-SDF is that it provides traceability from *problem situation* to *simulation*. This traceability is highlighted in Figure 1. It shows that a reference *assertion* from the reference model can be seen in the UML conceptual model and later becomes part of the simulation implementation in the associated pseudo-code. This process is conducted throughout the design and implementation process with the advantage of facilitating reproducibility of the simulation building process by providing explicit models as proposed by Epstein (2008). In other words, if we consider that a model is a system of premises, then those premises and the relationships between them facilitate the replication of the models and eventually the results. Bharathy and Silverman (2010, p. 445) propose a validation approach that looks at the construction of the model itself through a systematic, "defensible" process that controls error and cognitive biases. This directly connects with the goal of traceability through the use of MS-SDF.

Knowledge elicitation for the Use Case involved discussions with SMEs as well as pulling information from *authoritative sources* that deal with obesity, such as the Centers for Disease Control and Prevention, the World Health Organization, and County Health Ranking. The MS-SDF presents an avenue for constructing a reference model from multiple sources that is *complete* and then integrating that information into a conceptual model that is *consistent*. Thus, the simulation design process is *traceable* back to the reference model and the problem situation. The MPMF inherently satisfies the requirement of being systematic and controlling bias through the use of the reference and conceptual models.

### 5.2 Verification

*Trace validation* (a verification technique) determines if any internal components of the simulation are behaving in a manner that contradicts the conceptual or reference models. Therefore, this technique is specifically targeting the *micro* level components of the simulation. However, these components can also be viewed from their aggregated components (*meso* level) to see if any additional insight is provided into what is happening in the simulation. In order to conduct *trace validation*, the simulation must have the ability to produce data during the simulation run. Two techniques were applied to the data generated during the *trace validation* for the Use Case: *visual validation* and *statistical debugging*. *Visual validation* is an informal validation technique that involves the use of graphs to gain visual insight into the happenings of the simulation. *Statistical debugging* is a semi-automatic method for looking at the *suspiciousness* of simulation results as presented by Gore and Diallo (2013).

*Trace validation* was conducted on the obesity model by outputting the current weight levels, calorie intake levels, and calorie expenditure levels of a random set of individuals each week within the simulation. Each individual is bounded to gain or lose at most two pounds per week according to an assertion contained in the reference model. The purpose of the trace validation was to confirm that the weight gain was occurring correctly and that the people were not violating the two-pound weight gain assertion. First, the informal technique of *visual validation* was applied. This technique involved the use of heat maps to observe the distribution of obese people within the area. This showed that the average weight levels in the area were much higher than expected and provided insight on where to target the *statistical debugging*. Next, *statistical debugging* was used to confirm that many individuals were reaching the maximum weight gain value of two pounds every week. Following this identification, an error was quickly found that allowed the individuals to eat more often than allowed by the reference model. This error was fixed and the trace validation experiment was conducted again to ensure that the suspicious behavior was no longer occurring.

### 5.3 Sensitivity Analysis

*Sensitivity analysis* is the process of determining whether varying the input values of the model parameters produces a significant change in the model outputs. The *sensitivity analysis* tests were applied to check the *macro* level effects of the simulation. In this case the individual parameters were varied to check their sensitivity against the overall percentage of people that became obese within the simulation over time. Each parameter was checked separately while the other parameters remained at fixed values. This allows the sensitivity analysis to check model components at the *micro* (i.e. varying the activity level of the people), *meso* (i.e. varying the percent male and female of the population), and *macro* (i.e. varying the initial level of the population that is obese) levels. Overall, 80 parameters were tested to determine if the final percent of the population that was obese was sensitive to the initial value of each parameter. Unsurprisingly, it was found that the level of obesity was sensitive to the parameters that deal with the caloric levels of the people. The MQ dictates the output value that the inputs are compared against when testing for sensitivity.

### 5.4 Calibration

*Calibration* experiments test the validity of the simulation through its ability to recreate a desired trend or pattern from the modeled system. These experiments use objective functions to try to minimize or maximize the difference between the simulation outputs and the historical data. The input values of the simulation are varied collectively to find a solution that best matches the trend data. The *calibration* experiment deals with *micro*, *meso*, and *macro* level components since the parameters at all levels can be varied throughout the experiment. However, the *calibration* experiment can be designed so that only the parameters at a specific granularity level are varied. External validation tests were conducted by calibrating the model against 15 years of existing historical data from the CDC on the prevalence of obesity. These tests were conducted at the state level following the historical levels of obesity from 1995 to 2010 for each of the 50 U.S. states. Known starting values for 1995 were kept static for the experiments (i.e. the percent of the population that was obese or overweight) and unknown values (i.e. the percent of the population that was very physically active or moderately physically active) were varied. It was found that the simulation was very good at reproducing the trends of obesity over the 15 year period in question for each of the states.

## 6 CONCLUSION

The MPMF creates a firm basis upon which to design and implement a multi-paradigm simulation that addresses the interactions between elements of the problem situation at different levels of resolution. The use of the MS-SDF provides an effective approach for capturing the needed information about the problem situation and representing it in a manner that benefits the design and implementation of the simulation. The identification of contradictions and inconsistencies that the MS-SDF provides through the use of a reference model becomes much more beneficial in a MPM environment. Verification and validation techniques in a multi-paradigm environment are also assisted through the use of the reference model and conceptual model as defined by the MS-SDF. To help manage the total level of complexity added to the modeling process, it is advantageous to use the minimum number of modeling paradigms required to implement the simulation.

The Use Case presented in this paper was constructed from a single MQ, but it will often be the case that more than one MQ is asked of the problem situation. Multiple MQs can help to narrow down the paradigm selection process or they can increase the total number of paradigms selected. This is largely in part to the ability of the MPMF to address interactions of elements at different granularity levels which a single modeling paradigm is ill-suited to handle. It is advisable to use the minimum number of paradigms possible without jeopardizing the ability to answer the desired MQ. The Use Case was presented to highlight the reference and conceptual model creations and present the level of effort that is required to capture and classify the statements from the problem situation. A number of V&V processes were applied to the Use Case which can assist in verifying and validating multi-paradigm models. Ultimately, the MPMF was successfully used to model and simulate a problem situation involving obesity. The Use Case highlighted the traceability that is achieved by following the reference modeling, conceptual modeling, and simulation building constructs of the MS-SDF. Overall, the MPMF successfully provides a MPM-driven implementation of the MS-SDF.

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