Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

TOWARDS A THEORY OF MULTI-METHOD M&S APPROACH: PART I

Mariusz Balaban

MYMIC LLC.
1040 University Blvd.
Portsmouth, VA 23704, USA

Patrick Hester

Old Dominion University
5115 Hampton Blvd.
Norfolk, VA 23539, USA

Saikou Diallo

Virginia Modeling, Analysis and Simulation Center
1030 University Blvd.
Suffolk, VA 23435, USA

ABSTRACT

This paper is the first from a series of papers that aim to develop a theory of multi-method M&S approach. The aim of this paper is to develop ontological basis for multi-method M&S approach. The first part of this paper discusses terms related to the use of more than a single modeling & simulation (M&S) method. This is to show the ontological ambiguity currently present within the M&S field in the context of using more than a single method. Next section provides the philosophical stance of the authors about the main terms in order to provide clarification and context of the term multi-method M&S approach. The last section takes these previous concepts and proposes a set of definitions relevant to a multi-method M&S approach, including its parent and derivative terms.

1 INTRODUCTION

More than four decades ago, Fahrland (1970) introduced the notion of combined discrete event and continuous simulation. Presently, the practice of combining methods has matured and more simulation platforms offer capability beyond the original idea of combining two main modeling methods. Mingers (2001) points at two main reasons for using a multi-method approach: “It is both desirable and feasible to combine together different research methods to gain richer and more reliable research results.” (243). He refers to the principle of complementarity in which “no one paradigm is superior, but that their individual rationalities should be respected within the discipline as a whole.”(241).

Tolk (2013) pointed to ontology, epistemology, and teleology as enablers of a holistic view of M&S as a discipline. This view motivates development of the basis for a multi-method M&S approach in the context of teleological, ontological, epistemological, and axiological beliefs as shown in Figure 1.

The purpose of a multi-method M&S approach was explored by Balaban and Hester (2013). The main purposes identified in the literature pertain to the complementary nature of methods, coupling between method, exploration of multilateral problems, skills and preference of a modeler, stakeholder acceptability, data availability and usability, validity, need for a unique representation, expectation of unique insight, and dimensions and criteria. Clearly, these purposes can overlap. Balaban and Hester (2013) identified also a challenge specific to multi-method M&S approach regarding reasoning for selection of methods aimed at representation of system that includes social phenomena, which is related to human subjectivity.

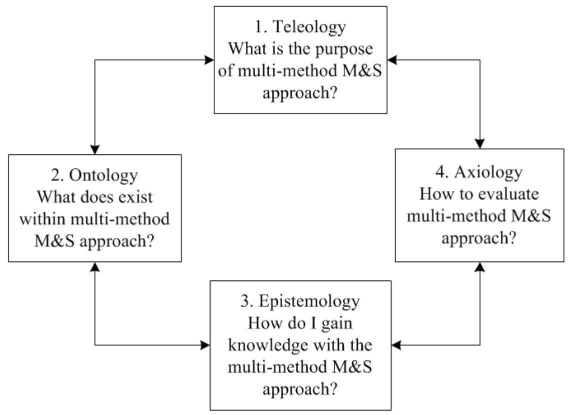

Figure 1: Basis for the multi-method M&S framework.

Hofmann (2013) distinguished two classes of ontologies: methodological, which defines methods, and referential, which focuses on representing real world systems. Partridge, Mitchell, and de Cesare (2013) discussed briefly historical background and different aspects of the use of the word ontology. For instance, they referred to Honderich (1995) who described derivative use of ontology to describe things that exist within a theory. This top-level meta-methodological context of the word ontology is assumed in this work as a base for the clarification of terms relevant to a multi-method theory. Tolk, Heath, et al. (2013) emphasized simulation philosophy as a key to the determination of whether or not current philosophy of science is sufficient or a new pragmatic philosophy of simulation is needed. A multi-method M&S approach assumes pragmatism as its philosophical paradigm. This view focuses on less constrained methodological assumptions that will be discussed in Section 3.

Tolk, Heath, et al. (2013) pointed at the need "…to develop methodologies and standards for the use of simulation in scientific research" (1154). Selection of appropriate methods is one of the hardest problems in the M&S field (Fishwick 1995), and despite recent attention to this problem there is no general guidelines for selection of appropriate methods. Similarly, evaluation of multi-method M&S study should be examined.

The remainder of this paper is organized as follows. Section 2 provides review of relevant literature, which looks at vocabulary used for similar and relevant to multi-method M&S approach concepts. Section 3 discusses philosophical stance of the authors about the main terms exposed in previous section. The last section proposes definitions as foundations for development of a multi-method M&S theory.

2 USE OF DIFFERENT TERMS

As with many fast growing application fields, it takes time to clarify and categorize terms, definitions, and knowledge within new branches of the multidisciplinary M&S field. This is also due to a variety of applicable M&S methods in different domains (Hester and Tolk 2010). Discrete Event Simulation (DES), System Dynamics (SD), Agent Based Modeling (ABM) and other approaches are called methods, paradigms, techniques, formalisms and methodologies. The literature consists of different terms describing concepts related to the situation where more than a single method is used, e.g. multi-method, multi-methodology, multi-paradigm, hybrid, mixed-method, multi-model and multi-formalism. Most often, several of these terms are used as synonyms solely for readability purposes, while sometimes only a single term is used, and still other times, different meanings of those terms are intended. In many cases, the purpose of using multiple terms is difficult to determine. A few examples below are presented to show the need for more consistency in using different terms that may or may not mean the same thing in the M&S field. The following review is only a sample of the vast extent of relevant literature. It is hoped that this short review illustrates the scope of this problem. It should be stressed that the purpose here is not to criticize, but to present the current situation, discuss it, and later on propose a more unified taxonomy.

Balaban and Hester (2013) use the terms method and paradigm without discussing possible differences between them. Chahal (2010) refers to hybrid simulations and models as integrated DES and SD and described hybrid simulation as a form of mixed methods. He also uses the term multi-method in sentence "Through an extensive review of existing literature in hybrid simulation, the thesis has also contributed to knowledge in multi-method approaches." (ii). This may indicate a parent-child relation between multi-method approaches to a hybrid. Finally, Chahal (2010) referred also to SD and DES as paradigms, e.g., "…deployment of SD and DES in an integrated way, where both paradigms symbiotically enhance…" (2). Rabelo et al. (2005) and Rabelo et al. (2003) call SD and DES methods but also a methodology, and integrated SD and DES a hybrid or a methodology. Glazner (2009) refers to DES, SD, and ABM as simulation methodologies, but also as paradigms: "In other cases, this paradigm might not make sense…"(127). It is difficult to determine if he equates the words hybrid and multi-methodology by saying: "others have gone on to argue that a portfolio of stand-alone simulation models does not accurately convey the system's dynamics, and that a hybrid, multi-methodology approach to simulation should be used."(25).

Helal (2008) refers to hybrid as a more than a single form of abstraction used to represent e.g. cars, robots, cell phones, digital watches, medical devices microwaves, and washing machines because they fall under a hybrid systems umbrella. He defines a hybrid simulation as "combined discrete-continuous simulations, which gives modelers the ability to reach better fidelity and fit the characteristics of all sections of the system being modeled." (42). Moreover, he refers to SD and DES as a methodology or a method. The word method is also used to connote numerical methods, synchronization methods in distributed simulations, and methods within Run-Time Interface (RTI) implementation of High-Level Architecture (HLA) standard. Martin and Raffo (2000) described a hybrid as a combined continuous and discrete model and two main modeling paradigms, allowing examining phenomena that are not reproducible in either continuous or discrete models alone. Choi, Bae, and Kim (2006) describe the combination of SD and DES paradigms as a hybrid, whereas the word method was used in reference to numerical integration. Levin and Levin (2003) use a word paradigm to refer to continuous differential equation and discrete finite state machine (FSM) parts. They use the word hybrid based on "…hybrid system theory [that] connects two models of change, one described by continuous differential equations and the other by discrete logical transitions." (1). Osgood (2007) uses the word hybrid to mean combined discrete and continuous rules and hybrid automata from analog-digital control theory and refers to SD and ABM as paradigms. Henzinger (2000) defined a hybrid system a dynamical system with both discrete and continuous components and developed a formal model of a mixed discrete-continuous system called hybrid automaton. Setamanit, Wakeland, and Raffo (2007) call hybrid a combined SD and DES. Swinerd and McNaught (2012) call SD and ABM as both paradigms and methodologies, while combined SD and ABM hybrid or multi-methodology. They define "hybrid approaches [as those] which combine at least two of the three methodologies discussed [SD, ABM, and DES]."(118). Venkateswaran and Son (2005) refer to hybrid simulation as "the work carried out in using together discrete and continuous aspects for analyzing a system."(4407). Wakeland, Martin, and Raffo (2004) call hybrid combined SD and DES, while machine learning approaches are called methods. Heath et al. (2011) refer to SD, DES, and ABM as paradigms, and examine cross-paradigm modeling. In the same paper, the word method is used for DES and a naïve Euler, Runge-Kutta algorithms. Rabelo et al. (2007) describe initially a hybrid approach as a combination of SD and DES, while analytic hierarchy approach (AHP) is listed as separate item, not as a part of hybrid. In the conclusion of their paper, the authors change this structure: "This paper presents a preliminary analysis of the potentials of integrating the group analytic hierarchy process (AHP) technique, system dynamics (SD) and discrete-event simulation (DES) in a comprehensive hybrid approach." (546). They refer to AHP as a methodology but also as a method and technique. This example may indicate evolution of the use of the word hybrid beyond continuous and discrete methods. In this context, the term hybrid can be synonymous to the term multi-method since it has evolved from its original meaning as the combination of two discrete and continues views into more general meaning. Zulkepli, Eldabi, and Mustafee (2012) also expand meaning of original world hybrid to include OR/ simulation methods "such as Optimization, Markov Chains, Linear Programming, DES, SD, Forecasting, Just-In-Time, Decision Trees and Soft Systems Analysis, to facilitate better and more informed decision making."(758).

Lee, Cho, and Kim (2002) call integrated SD and DES simply combined SD and DES. They also used combination of different words like hybrid, method, paradigm, and technique for writing convenience: "This hybrid algorithm is developed to combine the nested partitions methods with the paradigm of an efficient ranking and selection technique."(322). This shows how puzzling the writing about application of multiple methods can become. Hester and Tolk (2010) discussed M&S methods in the context of their use for systems engineering (SE), providing an overview of M&S methods. The two sentences "…(M&S) methods in support of complex systems engineering has become integral part of the "tool box" used today by engineers."(1) and "…the different M&S methods used to improve systems engineering efforts are often perceived to be based on fundamentally different paradigms" (1) indicate that paradigm can be seen as a more established method, but both terms are used later in the paper often as synonyms.

Zeigler, Praehofer, and Kim (2000) refer to use of different methods (formalisms) as multi-formalism: "…they require a combined discrete/continuous modeling and simulation methodology that supports a multi-formalism modeling approach…"(203). Moreover, "…a model that subsumes several different models is termed multi-model. The DEV&DESS formalism is an appropriate means to implement multi-models." (214) Fishwick (1995) refers to multi-model as "…a collection of individual models, each characterizing an abstraction level- connected together in a seamless fashion to promote level traversal." (5), and mixes the words model and method: "It is better to choose a variety of well-utilized and proven modelling methods and then search for ways to glue them together to yield a multi-model rather than always to view the world to be modeled through a single-model colored lens perspective." (10) The use of term multi-model clearly indicates model as its level of analysis, which does not convey the idea of using multiple methods within research or simulation model. This means that multi-model is not necessarily a multi-method approach. Holm, Dahl, and Barra (2012) define multi-methodology as "…the combination of methodologies, often from different paradigms." (11). They discussed combination of hard positivistic method e.g. DES with interpretivistic soft method e.g. Soft Systems Methodology (SSM). It is prohibitive to present all examples in more detail because of amount of material and allowed length of paper. The tabular summary is provided in the Appendix A.

3 PHILOSOPHICAL PRAGMATIC STANCE ON TERMS

Three ways of looking at the term methodology are presented by Mingers (2001). The first way refers to methodology as a study of methods (Wahyuni 2012, Checkland 1981). The second meaning is the most specific and pertains to a particular research study (Tashakkori and Teddlie 1998), while the third one is a generalization of the second. Using the word methodology as a combination of methods or techniques is more general and less prescriptive but "it can be difficult to precisely delineate the boundaries between method and methodology" (Mingers 2001, 242). He also states that the use of the terms methodology and multi-methodology in the UK are synonymous with method and multi-method, respectively.

Mingers (2001) defines a paradigm as "a construct that specifies a general set of philosophical assumptions covering, for example, ontology (what is assumed to exist), epistemology (the nature of valid knowledge), ethics or axiology (what is valued or considered right), and methodology" (242). For example, research paradigms in social science are positivism, post positivism, interpretivism, and pragmatism. These were characterized through the dimensions of fundamental beliefs that affect ways to conduct research, i.e., ontology, epistemology, axiology, and methodology (Wahyuni 2012). Moreover, Mingers (2001) argues that "the paradigm concept is useful as a shorthand for a particular constellation of assumptions, theories, and methods, but it is purely a heuristic device." (243). This means that we can "detach research methods (and perhaps even methodologies) from a paradigm and use them, *critically and knowledgeably,* within a context that makes different assumptions." (243). This concept is examined by Lorenz and Jost (2006), who analyzed assumptions of DES, SD and, ABM and differences between them. The authors leave the modeler with two options: first, to use methods within a single established methodology, or second, to combine methods within methodologies of different paradigms. This can be pictured as a possibility to combine methods between different paradigms. Lorenz and Jost (2006) add that a paradigm "…is characterized by the fact that it is to a large extent not questioned within its scientific community." (3). This means that the assumption of whether a method becomes a paradigm can be questioned by an individual's personal set of beliefs, but what really matters is that the supporting community agrees upon terms and definitions and shares fundamental beliefs that affect ways of conducting research.

M&S theory and practice echelons need to provide more guidelines on what should be considered a paradigm and why and whether this term is even correct to convey what is meant. Considering ABM as a paradigm can be problematic because it has not reached the point of sufficient agreement about its epistemological and axiological bases as compared to SD and DES. On the other hand, it would be easier to assume SD and DES as paradigms because these methods have a long tradition and dedicated development communities, e.g., System Dynamics Society and SIGSIM PADS (recently extended to other areas), respectively. When looking more formally at methods Zeigler, Praehofer, and Kim (2000) distinguish three main formalisms: discrete event system specification (DEVS), discrete time system specification (DTSS), and differential equation system specification (DESS). They are used to provide general dynamic system formalism. Moreover, the authors give examples of SD and Bond Graph methods as sub-formalisms of DESS, and Petri Nets and Statecharts as sub-formalisms of DEVS. Combination of different methods is called multi-formalism modeling. Within this theoretical, formal view, DEVS, DESS, and DTSS could be considered M&S paradigms, while SD, Bond Graph, Statecharts and Petri Nets would be sub-paradigms or methods. On the other hand, Fishwick (1995) discounts continuous and discrete time simulations as main categories and focuses on distinctions that pertain to modeling, i.e. conceptual, declarative, functional, constraint, and spatial. The groups provide different way to categorize simulation methods as compared to Zeigler, Praehofer, and Kim (2000). Fishwick (1995) says that formal specification can be very useful to convey M&S bases and it is mathematically pleasing, but the use of formalisms by scientists and modelers is less intuitive and can be even deceiving. The inclusive character of the word "method" versus the philosophical-assumption-constrained "paradigm" can be beneficial in this context. Additionally, use of the word "multi-formalism" or "multi-specification," grounded in predicate logic or a mathematical theory, can be less intuitive to modelers and scientist.

Many methods, e.g., Bayesian Networks, Neural Networks, and Fuzzy Methods, can be complementary within simulation-based methods, and should not be excluded during conceptualization. It is important to point at the inclusive character of the word method as a unit of consideration in description of a multi-method M&S approach. For instance, because methods evolve, the word multi-method seems more inclusive and specific over multi-paradigm because the considered method may not be established in the M&S field as a paradigm, yet it can contribute its desirable unique characteristic. Besides, the unique paradigmatic perspectives are not always desirable, but only some methods within an M&S paradigm are complementary and may not change the perspective of the original complemented part. In this case, we can draw a relation that a paradigm is or has one or more methods, while a method is not necessarily a paradigm.

Sokolowski and Banks (2009) refer to combination quantitative and qualitative data gathering as mixed-method research pointing at M&S for the quantitative part. When considering M&S as a multi-disciplinary field built from different domains, pragmatism seems the most appropriate paradigm to follow because it integrates quantitative methods (simulation model) and often-qualitative methods (conceptual model). Expansion of simulation research to other domains of science, e.g., social sciences, can be a little confusing if methods are called paradigms, because the word paradigm has been used there at a different, higher-level. For instance, if M&S is a part of mixed method research that exists within a pragmatic paradigm, naming SD and DES paradigms within the same piece of work can be confusing. Clearly, some sort of structure to terminology is needed to avoid using the same terms at different levels.

Mingers (2000) uses the term multi-method in reference to a general plurality of methods and techniques, both qualitative and quantitative, and within a real-world intervention. He pointed at many logical possibilities about whether methods come from different paradigms, are combined within the same intervention, and if methods may be combined. This work adopts the position on paradigms proposed by Mingers (2001), which allows us to remove constraints related to paradigms at the level of methods, while assuming a pragmatic paradigm within the whole M&S domain. This directs the focus on M&S methods, whether taken from an established M&S method, often called a paradigm, or not. Obviously, commensurability of methods is not assumed in all cases, because not all methods can be used together. This also depends on method computability and the study context itself. Reducing level of analysis from a multi-paradigm to multi-method M&S approach allows it to be more flexible, specific and inclusive.

4 PROPOSED DEFINITIONS

The following set of definitions reflects pragmatic philosophical stance and its implications discussed in Section 3, and provides a starting point for theory development. Figure 2 illustrates dependencies between these terms. It would be also beneficial to know what philosophical views in relation to multi-method M&S approach are claimed by authors of the papers presented in Section 2 and other members of M&S field. This would allow in the future for a reflection on the proposed definitions and necessary corrections or refinement. The body of each definition is presented in cursive, while relevant information about references that may follow is not.

Definition 1 *A **methodology** is the ideological and theoretical foundation of a method. It is a model to conduct a research within the context of a particular paradigm, but closer to research practice than philosophical concepts found in paradigms. It can properly refer to the theoretical analysis of the methods appropriate to a field of study or to the body of methods and principles particular to a branch of knowledge. It does not set out to provide solutions but offers a theoretical underpinning for understanding which method, or which set of methods, can be useful to a specific case.* Definition 1 is refined based on work of Wahyuni (2012).

Definition 2 *A **method** can be understood as a procedure, technique, systemic way of instruction, or means of scientific inquiry or scientific experimentation if based on theoretical principles.*

Definition 3 *A special case of a method is called a **Turing-computable method** if it is computable. This is also called a **constructive modeling method**.* For a definition of systematic method in relation to Turing machine see Turing (2004); for a definition of a model as a computable function and its implications see Weisel, Petty, and Mielke (2003) and Weisel, Petty, and Mielke (2005).

Definition 4 *A special case of a method is called a **modeling method** if it is capable of producing a conceptual model or an analytical output in the form of a single value or a not sequential set of values (no simulation engine).* For a definition of a conceptual model, see Robinson (2007).

Definition 5 ***A Modeling and Simulation (M&S) method** is a modeling method capable of producing an output in the form of a trajectory $\omega_{\langle t_1, t_2 \rangle}$.* For a definition of a trajectory see work of Zeigler, Praehofer, and Kim (2000, 101).

Definition 6 *A special case of a M&S method is called a **constructive M&S method** if it is also a constructive modeling method capable of producing a (computable) trajectory with a finite sequence of states $q_1, \dots, q_n$ with $n \geq 2, q_i \in Q$ for $1 \leq i \leq n,$ and $q_i \rightarrow q_{i+1} \in \delta$* for $1 \leq i \leq n-1$. This definition is based on work of Weisel, Petty, and Mielke (2005).

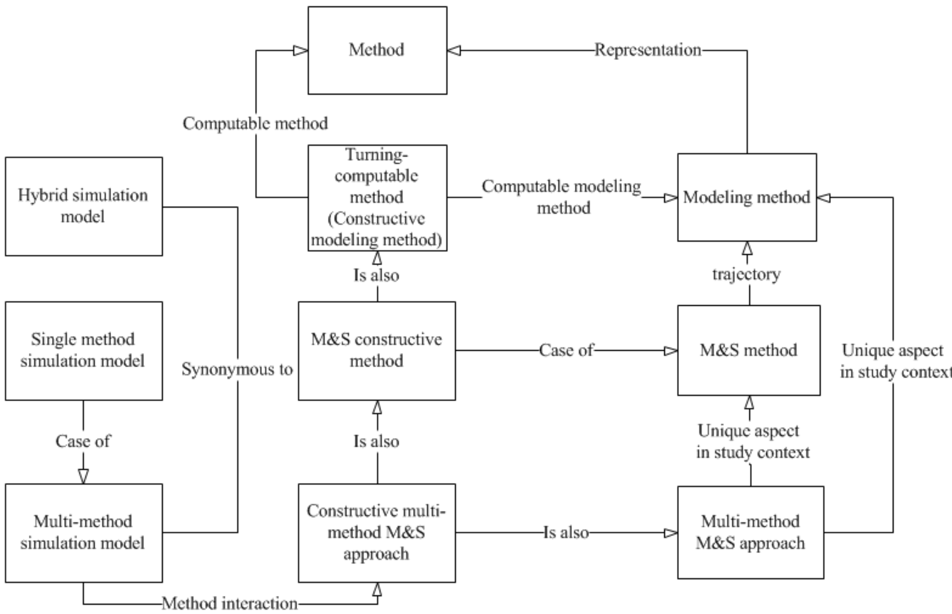

Figure 2: Dependencies between definitions and relevant terms.

Definition 7 ***Complementarity of methods*** *is a purpose for using different methods within mental, analytical or simulation space to enhance the expansion of studied phenomena or systems inward (generalization and refinement), enhance the expansion outward to combine different phenomena or systems (scope), or enhance comparison. Multiple inward and outward expansions are possible.* This definition is refined based on work of Balaban and Hester (2013).

Definition 8 *A* ***multi-method M&S approach*** *is as a combination of at least two modeling methods, where at least one modeling method is also a M&S method that combined allow for a unique system or phenomena evaluation, representation or insight.* This definition is refined based on work of Balaban and Hester (2013). Epistemologically, a multi-method M&S approach embraces complementarity of methods as research justification. At a more abstract mental dimension, the multi-method M&S approach could be perceived as a way of diverse representation through different mental models that direct to use of different modeling and M&S methods. Moreover, combined methods are chosen from a set of a total of n methods that is greater or equal to the number of methods known and used during conceptualization.

Definition 9 *A special case of multi-method M&S approach is called a* ***constructive multi-method M&S approach*** *if all methods are constructive.*

Definition 10 *A special case of a constructive multi-method M&S approach is called a* ***multi-method simulation model*** *if at least one of at least two M&S constructive methods is design to interact with another during the computer simulation run.*

The complementarity of methods can be also internally driven by a set of practical reasons, e.g. required computational efficiency, data availability, skills and preferences of modeler, and origination of research related to and managerial and organizational circumstances, e.g. preferences of stakeholders (Balaban and Hester 2013). A multi-method M&S approach is focused on the M&S field and requires at least one M&S method, but it is philosophically synonymous with a pragmatism-based mixed method approach (Fetters, Curry, and Creswell 2013, Greene 2007, Greene, Caracelli, and Graham 1989, Tashakkori and Teddlie 1998). Moreover, combination of a conceptual method, e.g. qualitative analysis, and a simulation model (Sokolowski and Banks 2009) can be considered a mixed method approach as defined by Greene (2007). In this context, we can see the major difference between a mixed method approach and multi-method M&S approach. A mixed method is a multi-method M&S approach if, among all methods mixed, at least a single simulation method is used. Additionally, definition of a multi-method M&S approach specifies an important aspect that can distinguish the terms multi, mixed, or hybrid. Terms mixed or hybrid captures a study characteristic where methods are combined, while multi indicates multiplicity of methods considered, but not necessarily determines its status. Definition of multi-method M&S approach combines both aspects: multiplicity of methods considered, and actually mixed methods as its subset. If methods considered and methods used are equal, then a multi-method M&S approach is also mixed or hybrid. Moreover, a single method simulation model is a special case of a multi-method simulation model. A single method model can be also considered a multi-method M&S approach depending on conceptual method used.

CONCLUSIONS

This paper has explored the problem of ontological ambiguity for the use of the term "multi-method M&S approach." Current reasoning or often lack of it displayed perspectives on different terms used to convey meaning that pertains to the use of more than a single method. The authors presented their philosophical stance about chosen terminology providing foundations for defining multi-method M&S approach and relevant terms. This paper and earlier work by the authors related to purpose of multi-method M&S approach (Balaban and Hester 2013) provide a road map for research related to the epistemological and axiological aspects of the multi-method M&S approach.

APPENDIX A

Table 1: Summary of terms used: (1) Multi-methodology; (2) Multi-method; (3) Multi-paradigm; (4) Multi-model[ing]; (5) Hybrid; (6) Mixed-method; (7) Cross-paradigm; (8) Multi-formalism; (9) Method; (10) Paradigm; (11) Methodology

Author(s)	1	2	3	4	5	6	7	8	9	10	11
Balaban and Hester (2013); Chahal (2010)		2			5	6			9	10	11
Rabelo et al. (2003); Rabelo et al. (2005); Helal (2008)					5				9		11
Glazner (2009)	1				5					10	11
Martin and Raffo (2000); Levin and Levin (2003); Osgood (2007)					5					10	
Choi, Bae, and Kim (2006)					5				9	10	
Henzinger (2000); Setamanit, Wakeland, and Raffo (2007); Baoding and Yian-Kui (2002); Peña-Mora, Han, Lee, and Park (2008)					5						
Swinerd and McNaught (2012)	1				5						11
Venkateswaran and Son (2005)					5						11
Wakeland, Martin, and Raffo (2004)					5				9	10	
Heath et al. (2011)					5		7		9	10	11
Rabelo et al. (2007)					5				9		11
Zulkepli, Eldabi, and Mustafee (2012); Lee, Cho, and Kim (2002)					5				9	10	11
Hester and Tolk (2010)									9	10	11
Lättilä, Hilletofth, and Lin (2010); Lorenz and Jost (2006)			3						9	10	11
Kotiadis and Mingers (2006)	1		3						9	10	11
Behdani (2012)									9	10	

Table 1: (continued)

Author(s)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Zeigler, Praehofer, and Kim (2000)				4				8			
Fishwick (1995)				4					9		
Holm, Dahl, and Barra (2012)	1										11
Borshchev (2013)		2	3						9	10	
Mingers (2000)	1	2							9	10	11
Baskent and Keles (2005)					5				9	10	
D'Ambrosio (1988); Donzelli and Iazeolla (2001); Birle, Hussein, and Becker (2013)					5				9		
Mustafee and Bischoff (2011)									9		
Sokolowski and Banks (2009)						6			9	10	11
Tolk (2010)									9		11
Tolk, Diallo, et al. (2013)			3							10	
Crespo and Ruiz (2012)			3		5					10	
Vangheluwe, De Lara, and Mosterman (2002)			3								

REFERENCES

Balaban, M., and P. Hester. 2013. "Exploration of purpose for multi-method simulation in the context of social phenomena representation." In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill and M. E. Kuhl, 1661-1672. Piscataway, New Jersey: IEEE.

Baoding, L., and L. Yian-Kui. 2002. "Expected value of fuzzy variable and fuzzy expected value models." *IEEE Transactions on Fuzzy Systems* no. 10 (4):445-450.

Baskent, E. Z., and S. Keles. 2005. "Spatial forest planning: A review." *Ecological Modelling* no. 188 (2–4):145-173.

Behdani, B. 2012. "Evaluation of paradigms for modeling supply chains as complex sociotechnical systems." In *Proceedings of the 2012 Winter Simulation Conference* edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose and A. M. Uhrmacher, 3794-3808. Piscataway, New Jersey: IEEE.

Birle, S., M. A. Hussein, and T. Becker. 2013. "Fuzzy logic control and soft sensing applications in food and beverage processes." *Food Control* no. 29 (1):254-269.

Borshchev, A. 2013. *The Big Book of Simulation Modeling*: AnyLogic North America.

Chahal, K. 2010. "A generic framework for hybrid simulation in healthcare." Ph.D. thesis, Department of Computing and Mathematics, Brunel University, West London.

Checkland, P. 1981. *Systems thinking, systems practice*. New York: John Wiley & Sons.

Choi, KS., DH. Bae, and TG. Kim. 2006. "An approach to a hybrid software process simulation using the DEVS formalism." *Software Process: Improvement & Practice* no. 11 (4):373-383.

Crespo, D., and M. Ruiz. 2012. "Decision making support in cmmi process areas using multiparadigm simulation modeling." In *Proceedings of the 2012 Winter Simulation Conference.*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose and A. M. Uhrmacher, 3634-3645. Piscataway, New Jersey: IEEE.

D'Ambrosio, B. 1988. "A hybrid approach to reasoning under uncertainty." *International Journal of Approximate Reasoning* no. 2 (1):29-45.

Donzelli, P., and G. Iazeolla. 2001. "A hybrid software process simulation model." *Software Process: Improvement & Practice* no. 6 (2):97-109.

Fahrland, D. A. 1970. "Combined discrete event continuous systems simulation." *SIMULATION* no. 14 (2):61-72.

Fetters, M. D., L. A. Curry, and J. W. Creswell. 2013. "Achieving Integration in Mixed Methods Designs-Principles and Practices." *Health Services Research* no. 48 (6pt2):2134-2156.

Fishwick, P. A. 1995. *Simulation model design and execution: building digital worlds*. Upper Saddle River, New Jersey: Prentice Hall.

Glazner, C. 2009. "Understanding Enterprise Behavior Using Hybrid Simulation of Enterprise Architecture." Ph.D. thesis, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Greene, J. C. 2007. *Mixed methods in social inquiry*. San Francisco, California: Jossey-Bass.

Greene, J. C., V. J. Caracelli, and W. F. Graham. 1989. "Toward a conceptual framework for mixed-method evaluation designs." *Educational Evaluation and Policy Analysis* no. 11 (3):255-274.

Heath, S. K., S. C. Brailsford, A. Buss, and C. M. Macal. 2011. "Cross-Paradigm Simulation Modeling: Challenges And Successes." In *Proceedings of the 2011 Winter Simulation Conference*, edited by S. Jain, R.R. Creasey, J. Himmelspach, K.P. White and M. Fu, 2788-2802. Piscataway, New Jersey: IEEE.

Helal, M. 2008. "A hybrid system dynamics-discrete event simulation approach to simulating the manufacturing enterprise." Master's thesis, Department of Industrial Engineering and Management Systems, University of Central Florida, Orlando, Florida.

Henzinger, T. A. 2000. "The theory of hybrid automata." *Verification of Digital and Hybrid Systems* no. 170:265-292.

Hester, P. T., and A. Tolk. 2010. "Applying methods of the M&S spectrum for complex systems engineering." In *Proceedings of the 2010 Spring Simulation Multiconference*, edited by R. M. McGraw, E. S. Imsand and M. J. Chinni. San Diego, California: Society for Computer Simulation International.

Hofmann, Marko. 2013. "Ontologies in Modeling and Simulation: An Epistemological Perspective." In *Ontology, Epistemology, and Teleology for Modeling and Simulation*, edited by A. Tolk, 59-87. Springer.

Holm, L. B., F. A. Dahl, and M. Barra. 2012. "Towards a multimethodology in health care–synergies between Soft Systems Methodology and Discrete Event Simulation." *Health Systems* no. 2 (1):11-23.

Honderich, T. 1995. *The Oxford companion to philosophy*. Edited by T. Honderich. Oxford, New York: Oxford University Press.

Kotiadis, K., and J. Mingers. 2006. "Combining PSMs with Hard OR Methods: The Philosophical and Practical Challenges." *The Journal of the Operational Research Society* no. 57 (7):856-867.

Lättilä, L., P. Hilletofth, and B. Lin. 2010. "Hybrid simulation models – When, Why, How?" *Expert Systems with Applications* no. 37 (12):7969-7975.

Lee, YH., MK. Cho, and YB. Kim. 2002. "A Discrete-Continuous Combined Modeling Approach for Supply Chain Simulation." *SIMULATION* no. 78 (5):321-329.

Levin, T., and I. Levin. 2003. "Integrating hybrid modelling with system dynamics." In *Proceedings of the 21st System Dynamics Society International Conference*, edited by R. L. Eberlein: System Dynamics Society.

Lorenz, T., and A. Jost. 2006. "Towards an orientation framework in multi-paradigm modeling." In *Proceedings of the 2006 International Conference of the System Dynamics Society*, edited by A. Globler, E. A. J. A. Rouwette , R. S. Langer , J. I. Rowe and J. M. Yanni. Nijmegen, 23-27. The Netherlands.

Martin, R. H., and D. Raffo. 2000. "A model of the software development process using both continuous and discrete models." *Software Process: Improvement & Practice* no. 5 (2/3):147-157.

Mingers, J. 2000. "Variety is the spice of life: combining soft and hard OR/MS methods." *International Transactions in Operational Research* no. 7 (6):673-691.

Mingers, J. 2001. "Combining IS Research Methods: Towards a Pluralist Methodology." *Information Systems Research* no. 12 (3):240.

Mustafee, N., and E. E. Bischoff. 2011. "A multi-methodology agent-based approach for container loading." In *Proceedings of the 2011 Winter Simulation Conference*, edited by S. Jain, R. R. Creasey, J. Himmelspach, K. P. White and M. Fu, 234-245. Piscataway, New Jersey: IEEE.

Osgood, N. 2007. "Using traditional and agent based toolsets for system dynamics: present tradeoffs and future evolution." *Proceedings of the 25th International Conference of the System Dynamics Society*.

Partridge, C., A. Mitchell, and S. de Cesare. 2013. "Guidelines for developing ontological architectures in modelling and simulation." In *Ontology, Epistemology, and Teleology for Modeling and Simulation*, edited by A. Tolk, 27-57. Springer.

Peña-Mora, F., S. Han, SH. Lee, and M. Park. 2008. "Strategic-Operational Construction Management: Hybrid System Dynamics and Discrete Event Approach." *Journal of Construction Engineering & Management* no. 134 (9):701-710.

Rabelo, L., H. Eskandari, T. Shaalan, and M. Helal. 2007. "Value chain analysis using hybrid simulation and AHP." *International Journal of Production Economics* no. 105 (2):536-547.

Rabelo, L., M. Helal, A. Jones, and H. S. Min. 2005. "Enterprise simulation: a hybrid system approach." *International Journal of Computer Integrated Manufacturing* no. 18 (6):498-508.

Rabelo, L., M. Helal, A. Jones, J. Min, Y. J. Son, and A. Deshmukh. 2003. "A hybrid approach to manufacturing enterprise simulation." In *Proceedings of the 2011 Winter Simulation Conference.*, edited by S. Chick, P. J. Sánchez, D. Ferrin and D. J. Morrice, 1125-1133. Piscataway, New Jersey: IEEE.

Robinson, S. 2007. "Conceptual modelling for simulation Part I: definition and requirements." *Journal of the Operational Research Society* no. 59 (3):278-290.

Setamanit, S., W. W. Wakeland, and D. Raffo. 2007. "Using simulation to evaluate global software development task allocation strategies." *Software Process: Improvement & Practice* no. 12 (5):491-503.

Sokolowski, J. A., and C. M. Banks. 2009. *Modeling and simulation for analyzing global events*. Hoboken, New Jersey: Wiley.

Swinerd, C., and K. R. McNaught. 2012. "Design classes for hybrid simulations involving agent-based and system dynamics models." *Simulation Modelling Practice and Theory* no. 25:118-133.

Tashakkori, A., and C. Teddlie. 1998. *Mixed methodology: Combining qualitative and quantitative approaches*. Vol. 46. Thousand Oaks: Sage Publications, Inc.

Tolk, A. 2010. "M&S Body of Knowledge: Progress Report and Look Ahead." *SCS M&S Magazine* no. 1 (4).

Tolk, A. 2013. "Truth, Trust, and Turing – Implications for Modeling and Simulation." In *Ontology, Epistemology, and Teleology for Modeling and Simulation*, edited by A. Tolk, 1-26. Springer Berlin Heidelberg.

Tolk, A., S.Y. Diallo, J. Padilla, and H. Herencia-Zapana. 2013. "Reference modelling in support of M&S—foundations and applications." *Journal of Simulation* no. 7 (2):69-82.

Tolk, A., B. Heath, M. Ihrig, J. Padilla, E. Page, E. Suarez, C. Szabo, P. Weirich, and L. Yilmaz. 2013. "Epistemology of Modeling and Simulation." In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill and M. E. Kuhl, 1152-1166. Piscataway, New Jersey: IEEE.

Turing, A. 2004. "Intelligent machinery (1948)." In *The Essential Turning: Seminal Writings in Computing, Logic, Philosophy, Artificial Intelligence, and Artificial Life: Plus The Secrets of Enigma*, edited by B. J. Copeland, 395-432. New York: Oxford University Press.

Vangheluwe, H., J. De Lara, and P. J. Mosterman. 2002. “An introduction to multi-paradigm modelling and simulation.” In *Proceedings of the 2002 AI, Simulation and Planning*, edited by F. Barros and N. Giambiasi, 9-20. Lisbon.

Venkateswaran, J., and Y. J. Son. 2005. "Hybrid system dynamic—discrete event simulation-based architecture for hierarchical production planning." *International Journal of Production Research* no. 43 (20):4397-4429.

Wahyuni, D. 2012. "The Research Design Maze: Understanding Paradigms, Cases, Methods and Methodologies." *Journal of Applied Management Accounting Research* no. 10 (1):69-80.

Wakeland, W. W., R. H. Martin, and D. Raffo. 2004. "Using design of experiments, sensitivity analysis, and hybrid simulation to evaluate changes to a software development process: a case study." *Software Process: Improvement & Practice* no. 9 (2):107-119.

Weisel, E..W., M..D. Petty, and R..R. Mielke. 2005. A comparison of DEVS and semantic composability theory. In *Proceedings of the Spring 2005 Simulation Interoperability Workshop*. San Diego CA.

Weisel, Eric W, Mikel D Petty, and Roland R Mielke. 2003. Validity of models and classes of models in semantic composability. In *Proceedings of the Fall 2003 Simulation Interoperability Workshop*.

Zeigler, B.P., H. Praehofer, and T. G. Kim. 2000. *Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems*. San Diego, California: Academic Press.

Zulkepli, J., T. Eldabi, and N. Mustafee. 2012. “Hybrid simulation for modeling large systems: an example of integrated care model.” In *Proceedings of the 2012 Winter Simulation Conference*, edited by C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose and A. M. Uhrmacher, 758-769. Piscataway, New Jersey: IEEE.

AUTHOR BIOGRAPHIES

MARIUSZ BALABAN received his two Masters in Mechanical Engineering from Lublin Technical University, Poland. He is currently pursuing a Ph.D. in Modeling and Simulation (M&S) at the ODU. He is M&S Engineer/Analyst at MYMIC. His research interests are R&D governance, innovation, evaluation methods, global events modeling, social systems, maritime systems, healthcare, and applied and methodological aspects related to M&S. His email addresses is mariusz.balaban@mymic.net.

DR. PATRICK T. HESTER is an Associate Professor of Engineering Management and Systems Engineering at ODU. He received a Ph.D. in Risk and Reliability Engineering from Vanderbilt University. His research interests include systemic thinking, stakeholder analysis, enterprise performance measurement and management, and multi-criteria decision analysis, and he is a member of the IIE, Performance Management Association, and International Society on Multiple Criteria Decision Making. His research has been published in *Systems Engineering*, *International Journal of Operations Research*, *International Journal of Critical Infrastructures*, *Journal of Defense Modeling and Simulation*, and *International Journal of System of Systems Engineering*, among others. His email address is pthester@odu.edu.

DR. SAIKOU Y. DIALLO is Research Assistant Professor with the Virginia Modeling, Analysis and Simulation Center (VMASC) at Old Dominion University. He holds a Ph.D. in Modeling and Simulation from Old Dominion University. Dr. Diallo has studied the concepts of interoperability of simulations and composability of models for the last six years. He developed a formal theory of interoperability and is currently extending it using Model Theory. He is currently conducting research into the design of infrastructures to integrate command and control systems (C2) with simulations or robotics. His email address is sdiallo@odu.edu.