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ABSTRACT:

Modeling and Simulation (M&S) has been a staple for military training, education, reducing operational costs, and increasing force readiness. The power of evaluating “what-ifs” and experimenting under complex or dangerous conditions will keep it relevant. However, M&S is at a critical point where it either gets invigorated by enhancements brought from domains such as AI, big data, quantum computing, digital twins/synthetic environments, or it gets diluted by them. This report explores these technologies and provides insights about current state of the art, and potential future, where M&S is combined with, or has built-in capabilities from, AI, big data, and quantum computing so efforts like digital twins, and synthetic environments can be better executed. We argue, among other topics, the development of military-specific language models that can facilitate the creation of models by modelers with the participation of subject-matter experts. In addition, considering these language models as reference models, activities such as conceptual modeling, composition, and interoperation should be facilitated.

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The views expressed in this report are those of the authors and do not necessarily reflect those of NATO.

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EXECUTIVE SUMMARY

Advances in computational technologies have prompted the need to assess their impact on M&S (and vice versa). Research on artificial intelligence (AI), big data, quantum computing, digital twins, and synthetic environments has grown exponentially in the past ten years, leading to questions of how it will impact the M&S community. M&S is inextricably connected with the future of AI, big data, quantum computing, digital twins, and synthetic environments. Currently, these technologies operate in tandem—sometimes two or three at a time—but the future demands their unification into more powerful systems that help us to monitor and evaluate our complex world.

This report explores changes in each of these fields at their intersection with M&S. Commissioned by members of the NATO M&S community, this report also focuses on the potential implications for NATO partner countries and allies, particularly as it relates to the NATO M&S Master Plan. While many of the technologies supporting full integration of M&S and each these emergent technologies are still fairly young, the ideas are not. Decades ago, despite M&S subject matter experts recognizing their importance and relevance to M&S, computing power and developments in those areas limited what was possible. Today, that equation has changed including the countries and organizations playing a role.

In several cases, China remains the foremost funder of published research at the intersection of these technologies. Increasingly, industry is also funding research in areas such as digital twins. The growing investment in novel, budding fields such as quantum computing and simulation is gradually resulting in an expansion of application areas, from biology to climate to transportation. Bibliometric analysis of published literature on these topics suggests that M&S is not currently playing a premier role in scientific advancement of these fields, but rather is a supporting actor in many of the cutting-edge research. This is a critical time for the M&S community to experiment with these technologies and become familiar with ways in which M&S can, and will, increasingly play a frontline role in the advancement of these evolving technologies.

We outline here the implications of these studies for NATO, as well as provide a theoretical military exercise vignette to illustrate the potential injection of AI, big data, and quantum computing into the M&S lifecycle. Below is a summary of key recommendations generated from our research, which are expanded upon in the report.

- AI should facilitate the reconceptualization of what conceptual modeling and interoperability means and how model documentation can facilitate this process.
- Investment in research and development for natural language models that can increase accessibility to all parts of the M&S lifecycle are critical for engaging nontechnical users.
- Though quantum computing is in its infancy, now is the time to begin experimenting with quantum algorithms to understand what problems it might be best suited to solve.

- AI will be valuable for collecting, cleaning, and integrating various data sources (qualitative and quantitative) into the modeling process, as well as automatically documenting model specifications and outcomes.

- Personnel must be trained to interact with AI, and this includes non-technical personnel who can use increasingly conversational interfaces to engage with models and data.

- Monitor the extension of digital twins applications outside of industry domains to begin to conceptualize how it can be used in NATO training, decision making, and experimentation as computing power and technologies advance.

INTRODUCTION

Advances in computing are drastically changing the face of many fields, including modeling and simulation. In 2010, NATO published the "Guide to M&S for NATO Network-Enabled Capability (NNEC)" that provided evidence for how Modeling and Simulation (M&S)[1] could enhance diverse aspects of strategic development, from training and exercises to acquisitions and operations (NATO 2010). Since that time, the NATO Modelling and Simulation Group has managed and maintained the NATO M&S Master Plan, and annual reports for the NATO M&S Center of Excellence have documented the evolving integration of M&S with international strategic operations (NATO M&S COE 2023). Table 1 highlights some of the activities within the four core areas of NATO M&S capabilities:

Each of the four core areas of the NATO M&S Centre of Excellence mission above is fertile ground for innovation. Some of those innovations will come from emergent technologies, such as AI and quantum computing, and how they are leveraged to build and use models. This will be the subject of much of this paper.

The idea on the need to combine M&S with disciplines like AI is not new; it has been around for decades (O'Keefe and Roach 1987, Widman and Loparo 1990). However, over the last few years, rapid advances in Artificial Intelligence and Data Science have opened the door to the how: breakthroughs on hardware and software to recognize patterns in numbers, text, sound, images, and videos, to mention a few, out of ever larger multifaceted datasets. In fact, research on the topic areas of artificial intelligence (AI),

Education and Training	Knowledge Management/Lessons Learned	Support to Concept Development and Experimentation	Doctrine Development, Standards and Interoperability
• Coordinate Training • Organize M&S courses • M&S Support to NATO operations and training • Interact with M&S entities	• Support development and management of repositories of models, simulations, data, etc. • Support and integrate repositories of best practices • Support verification of M&S architectures	• Contribute to the development of concepts and conduct experimentation • Simulation Based Acquisition • Support the development of capabilities	• M&S system integration and interoperability • Contribute to the linking of real world and simulation systems • Provide M&S system assistance to NATO • Provide proposals for the transformation of the field of M&S

Table 1. NATO M&S Core Capabilities

[1] Throughout this report, we use the American English spelling of "modeling" and conform to American English conventions.

big data, and closely related areas such as natural language processing (NLP) and machine learning (ML), have outpaced that of purely M&S research. M&S shares common roots with other computational modeling approaches, and thus what we may be witnessing is an increasingly blurred line between traditionally M&S research and these emerging and evolving ways to mine, model, and analyze data.

This report highlights some of the changes in the field of M&S given the emergence of cutting-edge computational and algorithmic advances. The following sections reflect on the current state-of-the-art of M&S relative to these emerging fields, and then proceeds to summarize what the future of M&S holds when considering artificial intelligence, big data, quantum computing, and digital twins.

A. On Modeling and Simulation

While Modeling and Simulation has two components (modeling and simulation), simulation is often the focus of the two. This is potentially to the detriment of modeling, which is "the part that makes M&S unique from other software engineering influenced disciplines" (Tolk 2010).

Modeling—the construction of a "logical representation of a system, entity, phenomenon, or process (NATO/OTAN)"—could be characterized as the "art" of M&S; simulation—or "the execution of a model over time (NATO/OTAN)"—represents the engineering, method of scientific inquiry, or technical side of the two. M&S, as a research methodology, could be considered a "third way of doing science" that is a combination of inductive and deductive processes of inquiry (Axelrod 1997). As such, simulations provide a powerful way of experimenting, aiding understanding, exploring, and predicting based on abstractions of systems that may otherwise be difficult to study. For instance, M&S is well suited to those problems that have too many parameters or too few; involve phenomena that are difficult to understand or scope; or require data collection and/or experimentation that is too dangerous or unethical.

Simulations are essential for training as they have proven to be effective and more economical than conducting real-life exercises (NATO Modelling & Simulation Group 2012). The challenge, however, is that training simulations are labor intensive for both development and validation. Major efforts have gone into reusing or combining simulations to address this challenge. Yet, reuse and simulation interoperation bring a new set of challenges, chief among them that those source/initial simulations were developed with a different purpose than the reused or interoperated ones are trying to address.

The "art" of M&S, specifically modeling, has not been as widely discussed. Different phases and practices of modeling include representation, reference modeling, and conceptual modeling. Some have provided insights about the value and process of conceptual modeling (Robinson 2008, Balci and Ormsby 2007, Tolk et al. 2013). Much less has been discussed about efforts to standardize and develop conceptual models and modeling practices, and in particular communicating about conceptual models with subject matter experts. Efforts towards using ontologies for conceptual modeling, languages such as UML or frameworks such as OPM have been proposed but not widely used. Padilla et al. (2018) argue that conceptual modeling is still the "art" of M&S based on the fact that a portion of professionals still use pen and paper to develop conceptual models, or they bypass the process of conceptual modeling and go straight to simulation development.

Even though Modeling and Simulation can be broken down and explored as separate concepts, this study focuses on M&S as a topic area that is intersecting with an increasingly diverse and technologically advanced set of concepts and tools. We look at how emerging technologies such as Artificial Intelligence (AI) and quantum computing may change M&S in both positive and negative ways.

B. On Artificial Intelligence

AI is a field that has gone through a renaissance over the last decade not only in terms of technological advancements, but more importantly in terms of accessibility to the masses. In a US government report about the future of AI the authors noted, "an explosion of interest in AI began in 2010 due to the convergence of three enabling developments: the availability of big data sources, improvements to machine learning approaches, and increases in computer processing power" (Hoadley and Lucas 2018). Major advancements in computing have allowed AI to accelerate in areas such as image recognition and natural language processing.

AI has many definitions but a singular definition is a nontrivial task (Abbass 2021). These challenges are often derived from defining intelligence, what encompasses intelligence, or how to measure it. Different people have defined AI in ways that commonly center around intelligent computer programs and systems (McCarthy 2007), where some highlight the roots of AI in biology (Gumbs et al. 2021) and others emphasize the mathematical and algorithmic backbone of intelligence (Marr 1977). For this paper, we are interested in some of the implementations of AI that attempt to replicate human intelligence towards identifying patterns, predicting outcomes, automating processes, or entertaining users.

AI is built on a programmed "model" of how humans represent knowledge, process data, and take actions to generate new insights from which humans or computers inform/derive decisions. Many of the goals of AI are founded on the very same goals of M&S: knowledge representation, prediction, understanding, or decision making. While there is much advancement necessary to truly understand the "how" of bringing AI and M&S together, the shared foundational goals and questions make them mutually compatible and reinforcing companions moving into the future.

We focus on two subfields of AI: machine learning (ML) and natural language processing (NLP), with considerations for big data. ML provides the basis for systems to learn from data and experience, while NLP provides basis for systems to learn human language. The balance of quantitative (ML) and qualitative (NLP) is important to consider, as M&S relies on both types of data and associated methods.[2] Big data, as a term, comes from the need to analyze available and ever-growing massive data sets. It is important to note that NLP is considered a subset of ML focused on analyzing human language and both are subsets of AI.

According to the NSTC Subcommittee on Machine Learning and Artificial Intelligence (2016), "machine learning is one of the most important technical approaches to AI and the basis of many recent advances and commercial applications of AI." Machine learning consists of algorithms that learn from regularities and patterns in datasets to perform specific tasks. This contrasts with practices such as developing smart systems via rule sets (as in some M&S approaches). Algorithms trained on data will inductively identify patterns from the data they trained on, whereas those trained with rule sets will deductively infer new rules. As such, the latter will not be able to extrapolate outside the rules from which is it was programmed, while the former will.

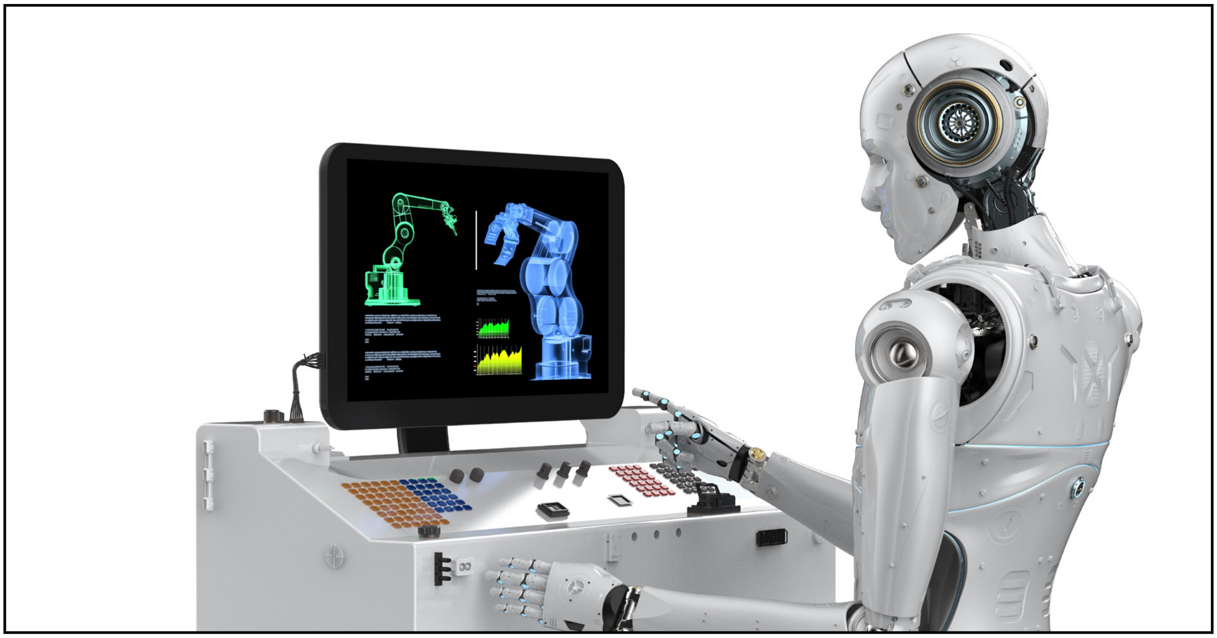
Natural language processing (NLP) focuses on the development of algorithms and computational techniques that allow computers to process and understand human language. It involves training machine learning algorithms on large datasets of natural language text to enable the algorithms to perform tasks such as language translation, text classification, and text generation. The transformer architecture, which was introduced by Vaswani et al. (2017) in the paper "Attention Is All You Need," has had a significant impact on the field of NLP by widening the scalability of language models to train on massive amounts of data and perform increasingly human-like computations and interactions. The use of ML and NLP to process big data is extensive, and the implications for and integration with M&S are many and varied. We will expand on these in the discussion section as areas where AI and M&S are currently applied.

C. On Quantum Computing

While quantum computing is still not widely accessible to the masses, its paradigm shattering potential—ranging from chemistry (e.g., drug discovery and development; development of new materials) to cybersecurity (breaking/improving encryptions)—makes it one of the most promising technologies today. As such, industry and governments are in a technological race, with financial and national security implications.

To start, a simple definition of quantum computing describes it as: "the use of quantum-mechanical phenomena to generate and manipulate quantum bits, or qubits. Qubits can be subatomic particles such as electrons or photons, or sufficiently small

[2]For a more comprehensive summary of AI and AI subfields and trends, see: Stone et al. (2016), Antebi (2021), and Hoadley and Lucas (2018)



structures such as superconducting loops on the nanometer scale" (Keshian and Wymer 2020). To understand quantum computing at a basic level, there are four concepts we need to consider.

The first concept is the physics of the very small. Recall that particles (atoms and subatomic particles) behave differently than large bodies. For instance, in classical mechanics, objects follow predictable trajectories or properties such as momentum and position that can be measured simultaneously. In quantum mechanics particles do not follow predictable trajectories, and properties such as momentum and position cannot be measured simultaneously. Quantum computing attempts to capture the behavior of the very small to take advantage of some of its properties.

This brings us to the second concept: superposition. Superposition, according to Gamble (2019), is "the counterintuitive ability of a quantum object, like an electron, to simultaneously exists in multiple 'states.' With an electron, one of these states may be the lowest energy level in an atom while another may be the first excited level." This ability to simultaneously exist in multiple states differentiates quantum computing from traditional computing. While the latter's computations are based on 1s and 0s, the former's computations are based on 1s, 0s, or both. Kanamori et al. (2006) describe this improved computational benefit as allowing one to perform four operations with one computational step, rather than having to do four separate computations.

The third concept is entanglement. According to Claudino (2022), "while superposition can be observed in a single qubit, entanglement is a collective characteristic of quantum entities." Simply put, two particles are entangled when their states are "connected" such that when the state of one is identified, the state of the second is also identified, despite their distance. The Caltech Science Exchange site provides an analogy: "When hundreds of particles become entangled, they still act as one unified object. Like a flock of birds, the particles become a whole entity unto itself without being in direct contact with one another" (Caltech 2022). This property allows quantum computers to perform faster and potentially safer operations (Jozsa and Linden 2003), since they can be treated as one entity. For instance, the Quantum Key Distribution (QKD) would potentially allow for the safe sharing of secret keys across long distances by entangling particles (Yin et al. 2020, Neumann et al. 2022).

The last concept is execution. To calculate the probabilities of superposition and guarantee entanglement requires a choreography of activities for computing to take place. To start, quantum computers are very susceptible to conditions like temperatures or interference by the environment. Even radiation from outside the solar system can impact the functioning of quantum computers (Witt 2022). As such, some of the challenges of quantum computing that make it particularly labor intensive and expensive include reducing error conditions; temperature regulation; limiting interference from the environment; and identifying problems suited for quantum computers.

Ultimately, the science is not there yet for the engineers to build quantum computers at scale. Companies like IBM, NTT Research, and Google, among others, are on the race to advance science and engineering to make quantum computing accessible. Quantum computers promise a new paradigm of computation, the extent of which most of us cannot yet imagine. It will work most effectively on certain types of problems, such as optimization; but, at least for the near future, we will likely require hybrid systems (traditional and quantum) where quantum computers address the most difficult computational portions of the problem (Hu 2022).

D. On Digital Twins and Synthetic Environments

The advances in quantum computing, AI, ML, NLP, and even big data are allowing an ever-widening potential for improving and integrating more complex, detailed, and large-scale M&S advances than ever before. Synthetic environments (SE) and digital twins (DT) are not new concepts and have pushed the boundaries of complexity of what can be modeled and simulated.

SE can be defined broadly as any environment driven by/enabling a 3D visualization that is interactive in nature (Fahlén et al. , Ladner, Abdelguerfi, and Shaw 2000, Menendez and Bernard 2000). Virtual Reality is a good example of synthetic environments. What makes SE and DT new are the same drivers we have discussed so far: rapid advancements in technology over the last decade in terms of computing powers, sensors, and large data processing.

In the context of this paper, SEs and DTs strive for a common major milestone: the creation of simulations that are as identical as possible to systems of interests. Their main difference is that a digital twin is coupled with the physical system allowing for direct monitoring and, ideally, auto correcting the functioning of the physical system if needed. They also differ in the primary industry usages, where military uses them for training and focuses on SE and industry focuses on managing product life cycle with an emphasis on DTs.

According to Budning, Wilner, and Cote (2022), synthetic environments take "the power of computing, digital processing, artificial intelligence, extended reality technology, and other advancements borrowed from the gaming industry to create a computer simulation with near-perfect levels of realism." This definition seems to build on that of Harper (2016) that defines synthetic training environment (STE) as one that "would harness new gaming and augmented reality technologies to improve war simulations that take place in the live, virtual, and constructive realm."

Digital Twins, according to the person who coined the term, maintain a data transfer link "between the physical and virtual worlds" and are distinctly different, but complementary, to simulations (Grieves 2022). In this separation of concepts, he suggests that simulations are useful for using the data and informing research and development and that, when combined, "they create immense value compared with the traditional physical-based ways of creating, testing, and operating products" (Grieves 2022). According to one characterization, DTs have three main elements: a "digital model" that is mediated by the design and software available to the modeler; a "shadow" that represents communication between the physical and digital systems and can suffer from challenges with how often and what kinds of data to transfer; and a "thread" that is a history of all the data exchanged (Saracco 2019). Further, some contexts are using "extended digital twins" where the virtual can influence and sometimes control the physical system (Saracco 2019). While much of these are used in industry settings, there is also growth in healthcare and even education and knowledge production applications (Saracco 2019). Given the immense data needs and evolving application areas of digital twins, the integration with innovative M&S techniques and intersection with quantum computing (eventually) and AI are necessary to advance this domain.

THE STATE OF THE ART IN CONTEXT

To empirically ground an investigation of their trajectories and potential overlap, we looked at each of the topics in the previous section in relation to M&S using the Web of Science[3] database to map out the current academic peer-reviewed, published literature. This is one way to observe the evolution and intersection of M&S with changing and emerging computational approaches, techniques, and advances.

It is important to note that Web of Science does not capture all publications, nor does it cover gray literature or publications that are not printed in English. Data was retrieved between 2 – 23

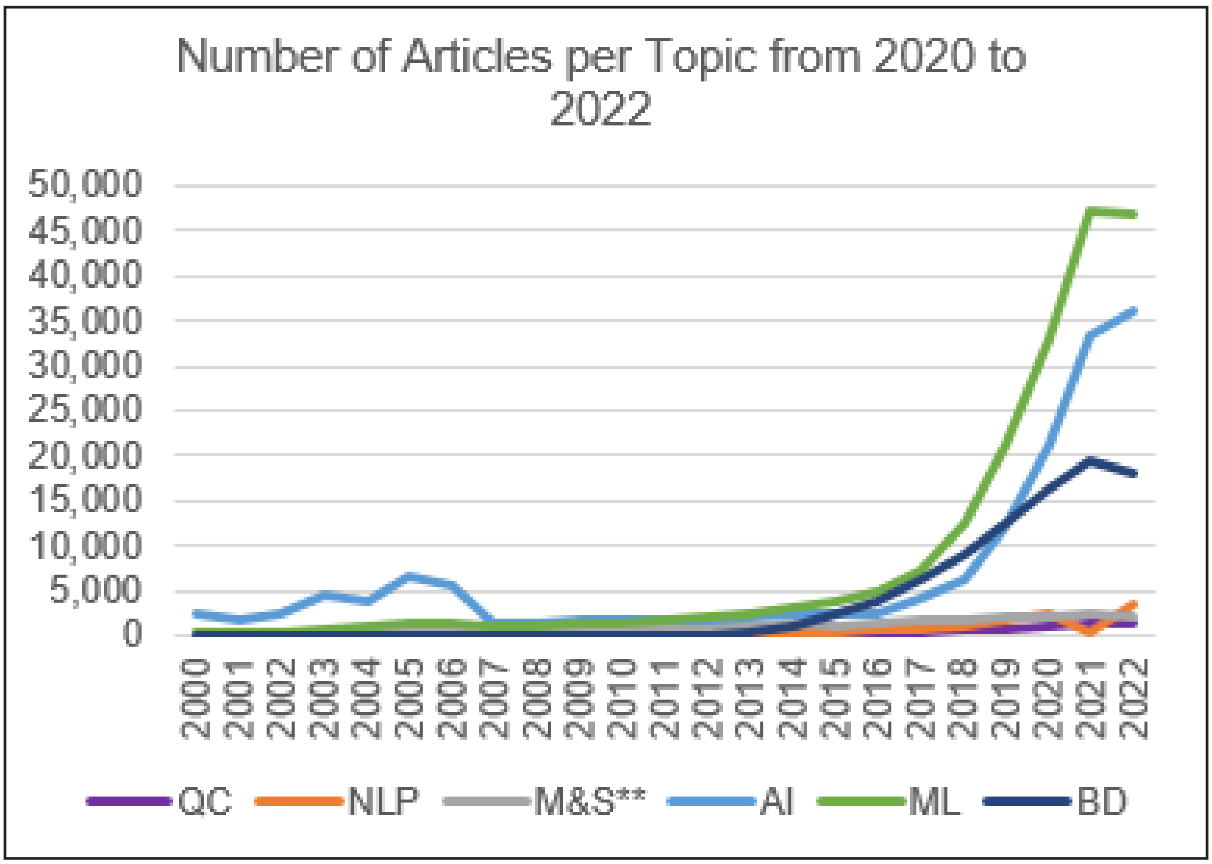


Figure 1. Number of articles per queried topic using Web of Science (2000-2022)

[3]*Web of Science indexes journals, conference proceedings, and other materials across areas of study.*
[4]*Keywords: quantum computing (QC), natural language processing (NLP), modeling and simulation (M&S), artificial intelligence (AI), machine learning (ML), and big data (BD).*

December 2022, with minor updates in January 2023.

Figure 1 represents the volume of published scientific articles[4] on the topics of Quantum Computing (QC), Natural Language Processing (NLP), Modeling and Simulation (M&S), Artificial Intelligence (AI), Machine Learning (ML), and Big Data (BD). While publications using "modeling and simulation" as a term (M&S[5]) are relatively small by comparison, Machine Learning, AI, and Big Data have seen a massive rise in recent years. NLP and quantum computing have yet to see such a dramatic increase; recent advances and investments will likely propel them into a similar trajectory.

M&S has maintained a steadily increasing presence in scientific publication across a diverse range of scientific disciplines, from physics to social sciences and humanities. Coverage by scientists working on Machine Learning (ML), Artificial Intelligence (AI), and Big Data (BD) has been exponential. But, there is significant overlap between the fields of ML, AI, and BD, so it is difficult to extract their separate influences. For instance, machine learning is widely used in big data analyses, where it is often conflated with data mining (Mannila 1996), and is an integral part of artificial intelligence (Michalski, Carbonell, and Mitchell 1986).

Figure 2 shows the same data from Figure 1 in a semi-log plot to highlight the rate of increase of each respective topic area. Given the wide range of values on the number of articles per topic, the plot highlights the rapid growth of big data (BD) over the last 12 years. Again, such growth is partly gained through the intersection of big data with the other areas because these emerging algorithms allowed for processing more data faster, as well as other technological advances in areas such as cloud computing and accessibility to platforms and software that facilitated processing capabilities.

In this graph, we can see that M&S has slowed its

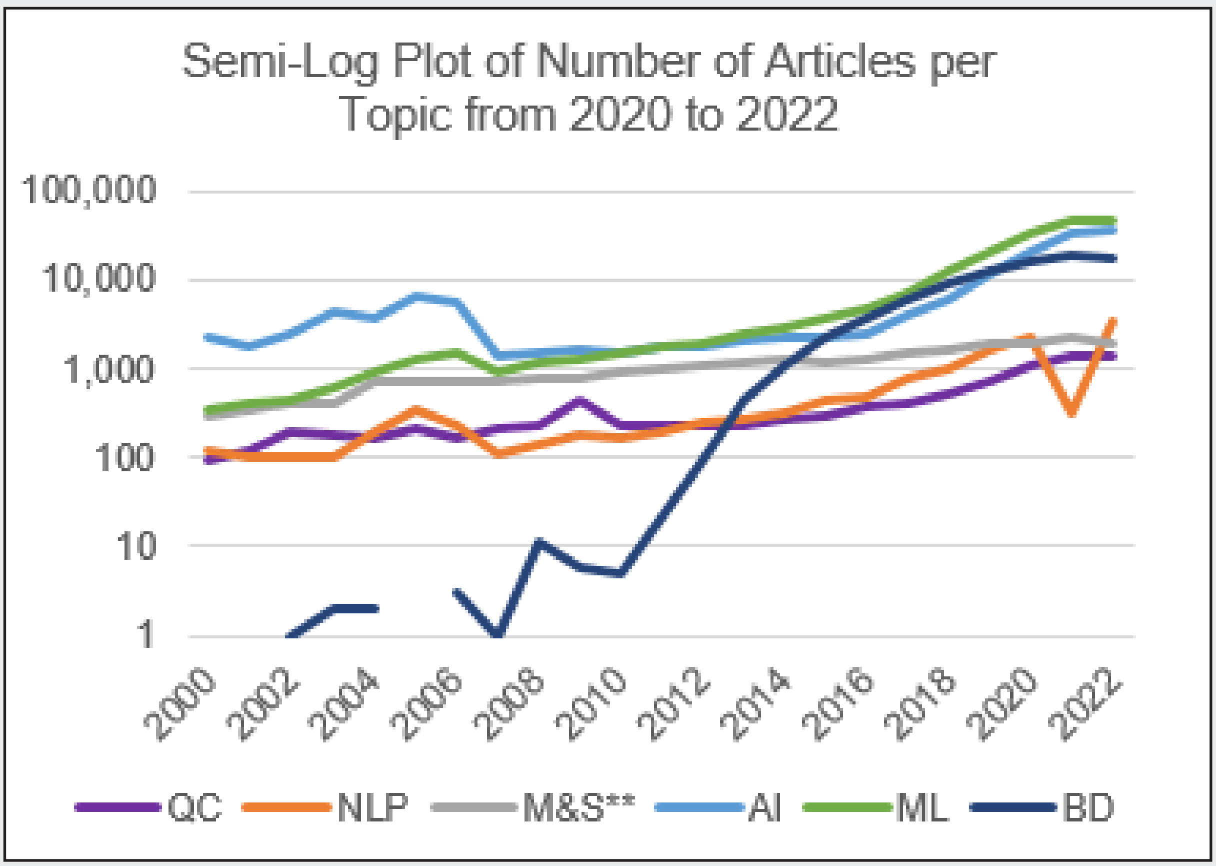


Figure 2. Semi-log plot of number of articles per queried topic using Web of Science (2000-2022)

[5]It is important to differentiate between M&S as an area of study (or community) that develops and applies simulation methods for varied purposes and other areas, such as biology, that develop simulation methods for specific purposes. We assume that the query M&S will draw papers related to the area of M&S. Conversely, we use the term "simulation" to capture papers used by the large scientific and engineering communities.

rate of growth since 2006, leading to a potential argument that there are no major companies driving the development of new M&S-only technologies, or that M&S has reached a point of maturity as an independent scientific discipline or community.

However, in the following sections we will observe that simulations are key to the advancement of science and engineering for the same reasons they have been valuable so far: less expensive and intrusive than life experiments (in some contexts); to train for facing complex and/or dangerous scenarios; when the technology is "not there;" to generate data for machine learning algorithms; to explore "what-ifs," despite the abundance of data; to experiment when new situations arise and we do not have data to make assessments; or to gain understanding under uncertain conditions. What these emergent technologies bring to the M&S picture is the potential re-formulation of how to build and compose models and execute and interoperate simulations. They are multiplying factors bringing enough momentum to evolve how we do modeling and simulating today, from modeling question formulation to simulation validation and accreditation.

A. Simulation + Artificial Intelligence (AI)

Given their shared computational roots, it is a natural evolution of science that simulation development and use will overlap with other fields, including ML and big data. Just looking at M&S and these topics in Web of Science, simulation seems to be an integral part of the exponential growth in computational and algorithmic advances since around 2016-2017. Figure 3 illustrates growth in interest across these topic areas.[6]

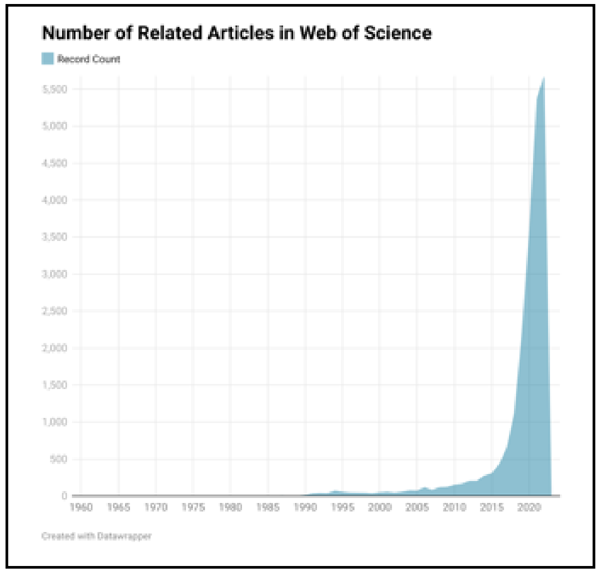


Figure 3. Simulation + (NLP, AI, ML) Publication Volume

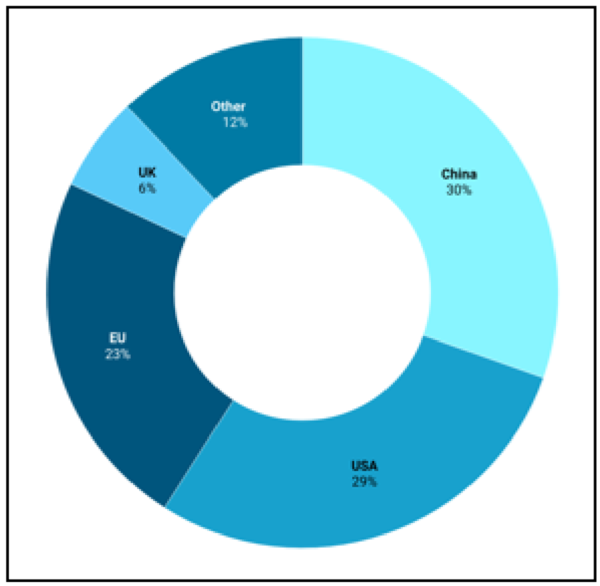


Figure 4. Country Source of Scientific Funding

Further breakdown of the articles by funding shows the countries leading the knowledge creation at the intersection of simulations and other computational fields (Figure 4). In AI, China holds a slight lead over the US and European Countries, with the National Natural Science Foundation of China (NSFC) funding 14.3% of all published papers in Web of Science that use simulations and AI, ML, or NLP. That is followed by the US National Science Foundation (NSF) at 6.5% and the European Commission at 3.8%. Other key countries that appear in the top 25 funding agencies of publications in our query include Germany, Canada, Korea, Japan, Brazil, Spain, and Switzerland.

Dividing up the publications into two categories—before the apparent boom around 2017 and after—there is very little change in the areas in which these studies take place (engineering, physics, telecommunications, computer science, chemistry, and some engineering multidisciplinary studies). Prior to the boom in 2017, Operations Research

[6] *Topic Search Query: simulation AND ("artificial intelligence" OR "machine learning" OR "natural language processing"), generated 21,735 results.*

Management Science featured a prominent role in the topical representation (around 6%) but became more obscure after the boom.

We performed a thematic analysis using network diagrams of the co-occurrence of terms in titles, abstracts, and references for each of the 21,735 articles that were categorized as M&S and "artificial intelligence" or "machine learning" or "natural language processing."

Figure A10 in Appendix A shows the major themes identified from 2017 and earlier. There are four major interconnected clusters:

- Intelligence (Red), which includes smaller nodes about multi-agent systems, robots, reasoning, and communication.
- Data (Green), with dataset and support vector machine as the most important nodes, but also including data analysis techniques and machine learning algorithms like Random Forrest models.
- Learning (Blue), with artificial neural network as its most important node, and including other concepts about fuzzy cognition and swarm optimization.
- Biological (Yellow), with molecular dynamics and protein as some of the most important nodes.

The red cluster captures terms found in simulation, both simulation and AI, or simulation with AI terminology. Terms such agent, robot, logic, and decision support system are some of the salient concepts that reappear together and most frequently across the academic published literature. The green cluster captures terms found mostly in machine learning literature. Terms such as support vector machine, dataset, random forest, and regression relate to the "simulation study" node. The blue cluster captures terms related to artificial neural networks (ANN). ANNs are used to perform classification and pattern recognition. As such, they are a type of machine learning. The yellow cluster focuses on terms related to molecular dynamics. Molecular Dynamics is a simulation-based field that uses M&S to simulate protein flexibility, for instance.

How simulation intersects with AI after 2018 in the Web of Science database provides a much different picture (Figure A11). In this period, the semi-cohesive network morphed into one where simulations seem to be embedded in major,

unconnected (or barely connected) clusters. There are four major clusters where simulations are combined with AI:

- Technology (Red), which focuses on internet/cybersecurity and cloud computing.
- Physics and Biology (Green)
- Chemistry (Yellow)
- Climate/Weather (Blue)

The technology cluster contains terminology used in network systems and the simulation of network systems, especially when considering cybersecurity. Network systems terms include intrusion detection, routing protocol, network performance, and attacker (internet). The Physics and Biology cluster overlaps considerably with the Chemistry cluster below. These topics rely heavily on simulation and AI to advance understanding of molecules and drug development. In addition, we see how this cluster captures simulation in context of quantum computing. Terms such as quantum system, quantum machine, quantum computer, quantum algorithm, and quantum circuits appear related to SARS-COV2 and "drug development" and "vaccine." The blue cluster captures a combination of hydrological/meteorological terms in what appears to be context related to water management and flooding prediction. Terms such as ANFIS (adaptive neural fuzzy inference system) and basin (water/river basin) take central roles.

This survey of the literature suggests that simulation continues to be one part of an ever-increasing computational toolkit that is available for research and practice. It is useful in the entire span of research design including data collection, analysis, and visualization, but never features prominently as a central node or even one that strongly links topics together. This suggests that while simulation is a fundamental part of technological development across many fields and academic disciplines, it is not seen, from this dataset, as a primary discipline unto itself.

B. Simulation + Big Data (BD)

Like in the previous section, we searched for the intersection of the terms simulation and "big data" in Web of Science. We separated the BD search to differentiate the nature of the approach (AI, ML) from their use in BD.[7] The result yielded 8,416

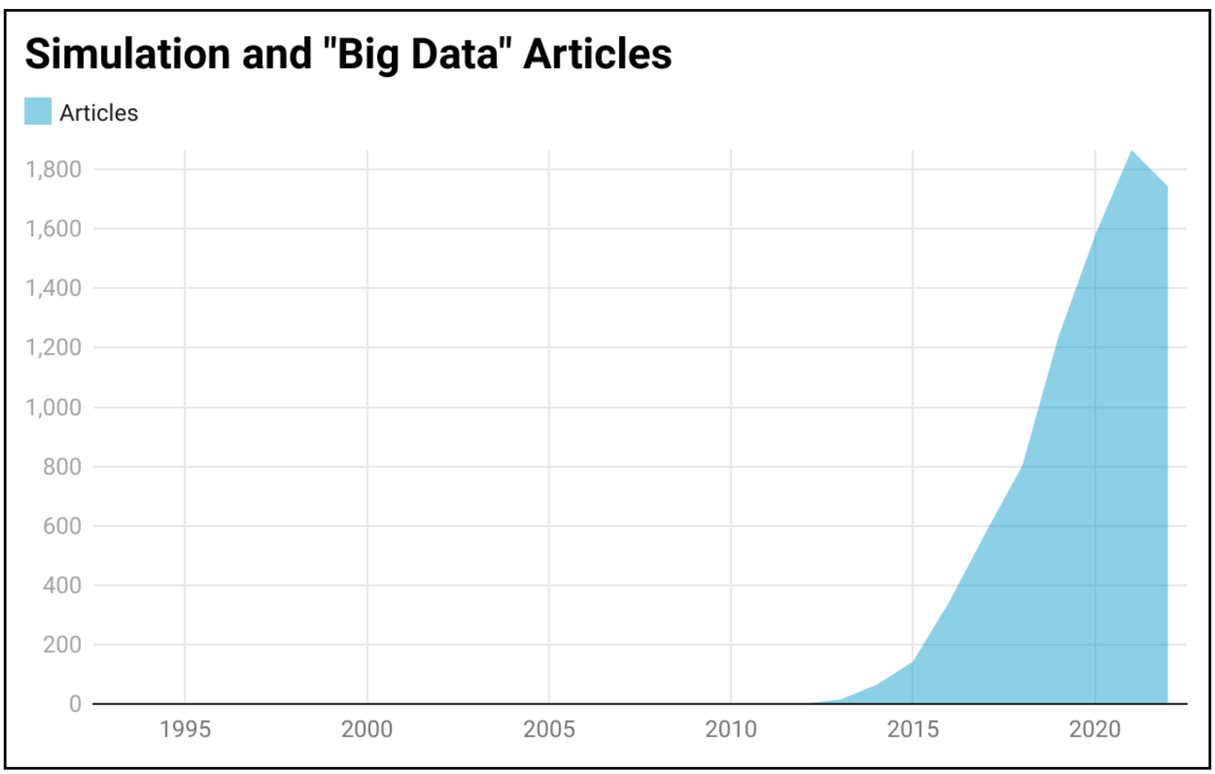


Figure 5. Simulation + 'Big Data' Publication Volume

[7]It is noted that researchers may have been using alternative terms like large data sets to denote big data. As such, publication records may be higher.

results with a large portion of that funding coming from agencies and programs in China (NSFC, National Key Research and Development Program of China, Fundamental Research Funds for The Central Universities, and China Postdoctoral Science Foundation); US NSF, NIH, and DHS, followed by the European Commission and the UK Research and Innovation (UKRI). Publication numbers also show a steep increase between 2017 and 2019 (Figure 5).

Figure A12 in the Appendix shows the network map for the bibliometric analysis. There are seven different clusters, making the combination of M&S and BD difficult to analyze.

- Mathematical (blue and purple), with and terms such as regression model, real data analysis, and numerical simulations.
- Biology (green), thematically covering topics related to molecular biology and the study of disease and infections.
- Supply Chain (yellow), including terms like "digital twin," industry, and data analytic
- Technology (Red), which focuses on internet/cybersecurity and cloud computing.

Two smaller and looser clusters are related to traffic modeling (orange) and communications (light blue). Both these clusters point to the combination of BD and M&S but suggests that the intersection of these topics is in its infancy (small cluster size). The biology cluster is consistent with a similar cluster in the AI literature, suggesting that M&S continues to be important and rapidly evolving with emergent technologies and algorithms in this field. The largest, tightest cluster is Technology, which echoes the literature in the AI and M&S section above.

C. Simulation + Quantum Computing (QC)

Like the evolution of AI and M&S, simulation and quantum computing have seen a rapid growth starting around 2017-2019. Despite the low number of articles (when compared to AI), the increase is notable (Figure 6). Advances in quantum computing, due to the potential for high impact on areas such as cybersecurity and drug development explain the surge in interest. However, quantum computing faces significant challenges as discussed above (such as limited access) compared to traditional computing.

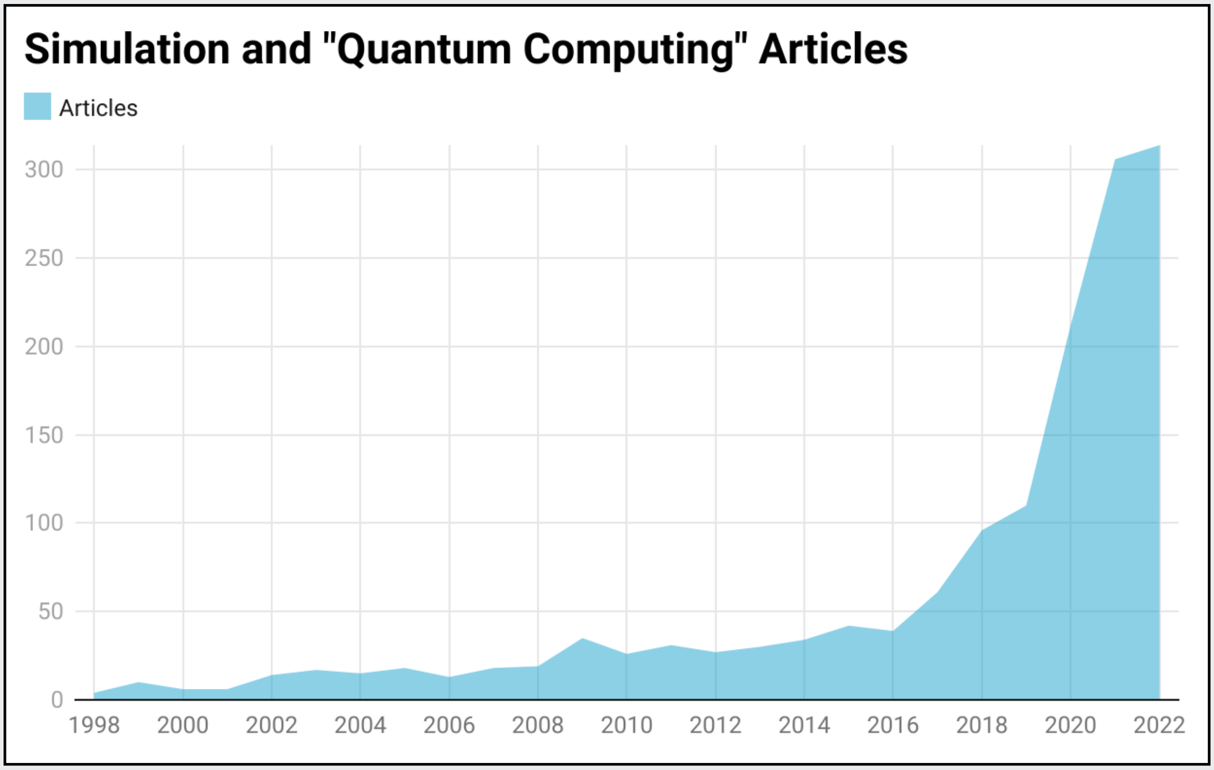


Figure 6. Simulation + 'Quantum Computing' Publication Volume

These challenges may explain the low volume of publications overall.

In the area of quantum computing, the United States is the leading funder. Among the 25 funding agencies with the largest share of published articles are: US Department of Energy (11.8% of all publications funded by DOE); National Science Foundation; US Department of Defense; and other US DOD agencies and research labs. As a single funding entity, the National Natural Science Foundation of China still funds the most publications (187, or 12.4%). Other top 25 funders also included Germany, Japan, Australia, Canada, and Spain. Additionally, and unlike the earlier summary of funders for M&S and AI, we see the emergence of the first industry donor. Samsung is one of the top funders in M&S and quantum computing, having funded 23 articles, or 1.5% of all publications in this topic area in Web of Science.

Using a bibliometric analysis from Web of Science based on the terms simulation AND "quantum computing," 1,505 published articles in the database create the network diagram in Figure A13 in Appendix A that illustrate the co-occurrence of words in the titles, abstracts, and references of the publications. We identified three clusters:

- Algorithms (Green), which focuses on quantum/algorithms and activities such as optimization.
- Application Areas (Blue), linked to topical applications of QC to areas like chemistry and the use of simulation (Hamiltonian)/ simulator. This cluster also contains topics related to molecular studies about advances in the use of qubits made of molecules, instead of electron/photon.
- Molecular Studies (Red), where publications capture information about quantum computing and quantum physics. Concepts like gate (quantum logic gate), coherence, and photon, are some that are easily identifiable.

Overall, the quantum computing literature is much more exploratory and not as grounded in real-world contexts as M&S literature tends to be. It also relies on specific implementations of M&S-related topic areas, relying on simulations to advance structures and algorithms in the quantum computing field. After more advances in QC, this topic should be reinvestigated to understand the future of M&S relative to quantum computers as they become available.

D. Simulation + Digital Twin

Looking at the Web of Science, publications with the digital twin (DT) term had a slow take off since 2014, despite the term introduction in 2003. The use of the term accelerated around 2020 with a total number of 1,363 records as of January 10, 2023 (Figure 7). Top funding countries are China (45%) followed by the EU (13%), UK (11%), and the US (8%) covering topics ranging from Engineering Manufacturing to Operations Research. The context is mostly industrial.

Figure A14 in Appendix A shows the network map for the bibliometric analysis.

We identified three major clusters:

- System Integration (Blue), which covers topics related to functionality and productivity. Other key nodes are architecture and production which refer to manufacturing and physical systems.
- Industry (Green), containing topics related to the application of DT in decision-making, management, and "life cycle."
- Experimentation (Red), highlighting central terms such as algorithm, prediction, accuracy, structure, and condition. Terms in this cluster are related to measurement including reliability, computation, stability, and experiment.

True to its roots in industry, the Digital Twin literature focuses predominantly on the physical and computational aspects of DT, where simulation takes a back seat and only features as very small nodes, indicating that at least in the publication literature, M&S is not a primary concern in evolving DT research. Simulation, however, is poised to take DTs to the next level and will continue to be part of future DT research.

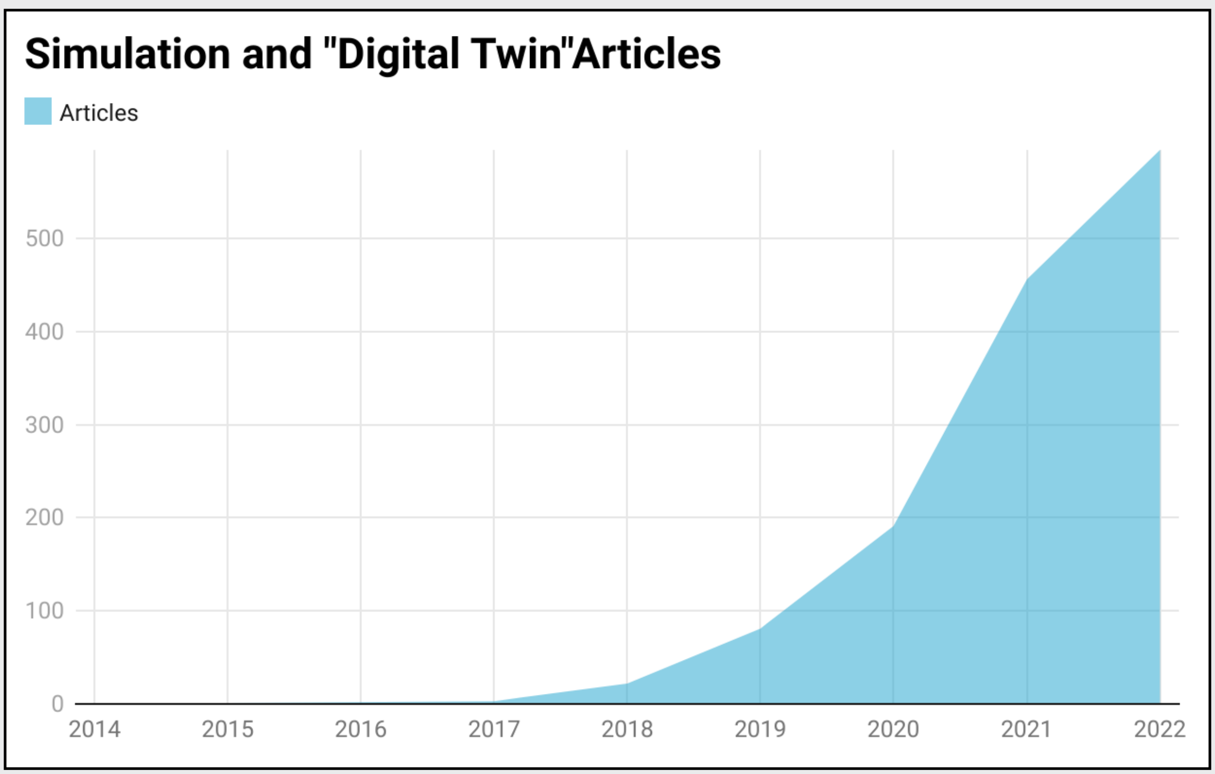


Figure 7. Simulation + Digital Twin Publication Volume

DISCUSSION

This section covers two parts: how we could leverage simulations with these emerging technologies and how the combination of them may be applicable to training and other activities relevant to NATO. This section will summarize the sections above and highlight some potential applications and implications for each. To supplement this discussion, we spoke with other simulation experts and include some of their thoughts here based on their own expertise and observations of the evolution of M&S.

A. Implications for M&S

The emergent technologies discussed in this paper—AI, big data, quantum computing, synthetic environments, and digital twins—are either still in their relative infancy, or are going through a rebirth, catalyzed by (or catalyzing) increases in computing capabilities. Their integration with M&S is still very novel. What is clear is that their futures are deeply interconnected. As the bibliometric analyses of each topic area suggested, the lines between each, particularly as they relate to M&S, are becoming increasingly blurry. It is difficult to see a future where we don't need at least two or more of these computational approaches to address real world problems. What is not clear is how independently M&S will continue to exist as its own unique discipline as the lines between computational methods and technologies blur and integrate.

In fact, M&S has become such a multidisciplinary field, it may be difficult to identify its contributions as a discipline, as a practice, or as a technology set that augment or support other disciplines. This may raise an alarm in terms of what the M&S community brings to the Body of Knowledge. There are problems, like interoperation, that have been the purview of this community to meet training or experimenting needs. On the other hand, if the M&S community relinquishes this role, other communities, like those pushing these emergent technologies, will promptly fill the gap to meet those needs.

A.1. THE FUTURE OF M&S WITH AI AND BIG DATA

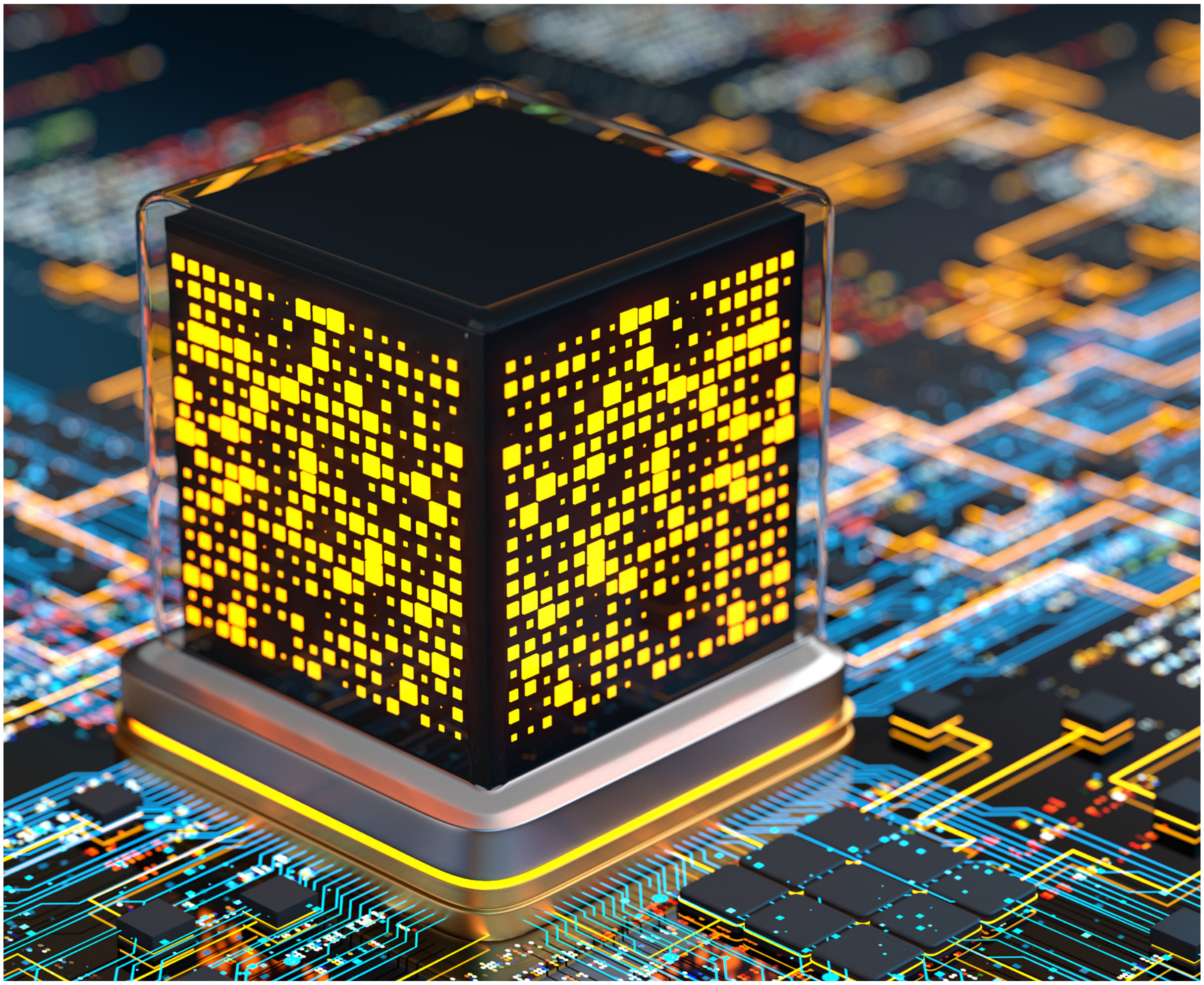
The main AI fields of Machine Learning (ML) and Natural Language Processing (NLP) are already propelling M&S into the future, and they are integrally connected with advances in big data. These fields share mutually compatible and reinforcing goals such as knowledge representation, prediction, understanding, and decision-making. Like M&S, AI fields are making advances to incorporate a wide range of data types, from qualitative to quantitative, and rely on increasingly large datasets (big data) as both inputs and outputs. The difference is in the how.

This is where AI can augment M&S: by facilitating processes that are either labor intensive and are human centric (problem formulation, conceptual modeling, simulation specification) or by automating process that are data centric (analysis of results, pattern identification); or a combination of both (simulation development, simulation interoperation). Academic publications on M&S and AI subdomains have seen an exponential rise in recent years as computational

advances create more opportunities for innovation and development. These publications were originally centered around topics of intelligence of systems (e.g., agents and robots), data analysis, learning (e.g., artificial neural networks and fuzzy cognition), and molecular biology studies. In more recent years, the focus has shifted towards technology and cyber security, broader application areas in physics, biology, and chemistry, and even a growing usage in climate and weather research. In these studies, the use of M&S and AI go mostly hand-in-hand, with simulations informing research and development of AI, and AI informing advanced applications of simulations. Each approach—AI, ML, and M&S—can solve a different part of the problem in complementary (but nontrivial) ways (Giabbanelli 2019).

The implications for data usage—both input and output/analysis—are straightforward; however, cutting-edge research is probing the integration of AI at every phase of the modeling and simulation development process, from conceptual modeling to calibration, verification and validation, initialization, and output analysis. Using techniques developed for big data, ML can expedite some of these processes. For instance, Kavak (2019) embedded agents in an agent-based model with ML capabilities trained with large datasets instead of relying on a qualitatively specified rule set. This attempt to embed agents with intelligence has been explored over the past two decades (Russell and Norvig 2016, Negahban 2017), and recent advances in AI technologies and methodologies continue to advance what is possible.

Another emerging area of development is the use of natural language processing (NLP) in its potential to make M&S more accessible to subject matter experts. NLP could make accessible the design and development of M&S, but also aid in understanding conceptual models or simulation results. Padilla, Shuttleworth, and O'Brien (2019), for instance, explored how NLP applied to written narratives could facilitate the conceptualization and specification of agent-based models. On the other end of that process, Shrestha et al. (2022) explored the premise of using natural language generation (NLG) to generate text out of conceptual models in order to make them more accessible and understandable to a range of stakeholders and subject matter experts who may be participating in the modeling process.



Both NLP and NLG open the door to change the way we abstract a problem and conceptualize it in a model, regardless of application area. Given that this abstraction and conceptualization is fundamental in M&S, improving these processes to include a wider range of participants is essential for identifying and developing new methods for activities such as composition or interoperation.

Inconsistent semantics lead to issues such as polymorphisms or encapsulation—problems related to simulations interpreting differently or hiding information, respectively—when composing models or interoperating simulations (Diallo, Padilla, and Tolk 2010, Lynch and Diallo 2015). AI may aid this process by using natural language models to process the semantics of the input text and generate an interpretable prompt that confirms the user's intended meaning and/or asks for clarification to resolve discrepancies. Tolk et al. (2012) posit that, "our approaches to M&S interoperability have been shaped by software engineering and computer engineering principles that are necessary, but not sufficient. The alignment of conceptual constraints is not supported enough by the current approaches and standards."

This alignment of conceptual constraints may be facilitated by fine-tuned language models—models that are trained to predict word sequences—that could address semantical challenges by acting as the "Übermodel from which all simulation representations can be derived by pruning or aggregating" (Tolk et al. 2012). In other words, if we consider language models fine-tuned with domain-specific knowledge, say military terminology/ontologies/lessons learned, challenges in composability and interoperability may be simplified or automatically engineered.
Simulations themselves do generate data and, in some cases, lots of it. As such, we need computer

[8] *https://qiskit.org*

(hardware) resources and ML to aid in the process of gaining insight from simulation-generated data. Simulation-generated data (i.e., synthetic data) can also be used to train or test ML, when data for training ML is scarce due to low quality data, ethical concerns, data privacy, or has a different data format/type than required, among others. In such contexts, synthetic data can be used instead of real-world data. This will likely play an increasingly large role in the development of AI models in the future (Andrews 2021). One simulation expert shared an example of this in the context of self-driving cars:

Computer vision models are being trained to detect and avoid pedestrians, in order to develop self-driving cars. But we don't have hundreds of self-driven cars going on real roads, occasionally running over people to learn that they should not do it next time. Hence, we have to create virtual environments that provide salient characteristics of the real-world. It is thus already a reality that simulations provide controlled datasets in supplement of 'little data' problem -- the small amounts of data available are used to check the adequacy of the simulated environment. (Giabbanelli, P., Email correspondence with authors, November 29, 2022)

As an example of researchers using small datasets to create generalizable model rule sets, Yoshizawa et al. (2016) used very small sample sizes (N=18 participants) to generate qualitative rules about distracted driving with an ML support vector machine. The combination of M&S, AI, and big data is just beginning, and it will most certainly be part of the future of M&S.

A.2. THE FUTURE OF M&S WITH QUANTUM COMPUTING

Quantum computing stands to change the face of science across many academic disciplines. Currently, quantum computing is not broadly accessible to the average researcher. Significant challenges exist with quantum computing, everything from temperature regulation to environmental interference to understanding for what problems quantum computers are best suited. The science and engineering are not quite advanced enough to make QC accessible and usable to where we might be able to know how it will affect M&S. However, M&S practices play a supporting role in the technological race that will make quantum computing more accessible by aiding in the design and experimentation of new ways of making these computations (i.e., alternative molecule configurations). Since 2017, the quantity of research using M&S and quantum computing has gone up dramatically. In this area, simulations—particularly physics and chemistry uses—are playing a major role in helping to propel advancements in quantum computing algorithms and molecular studies to create more robust and usable iterations of quantum computing (Trabesinger 2012).

Quantum computing researchers often quote Richard Feynman to emphasize the foundational importance of simulation in quantum computing when he said,

…And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look easy." (Feynman 1982)

Simulation and optimization are at the very core of the complex problems for which quantum computers may perform best. The major challenges, as mentioned before, are identifying the problems suitable for superposition and entanglement, the development of algorithms that take advantage of these properties, and accessibility to the hardware capable of running those algorithms. Cloud Quantum Computing has been made accessible to users to test and explore the benefits of QC. IBM, for instance, provides the Qiskit SDK (software development kit) so people interested in QC get to know "quantum computers at the level of pulses, circuits, and application modules."[8]

Quantum computing is a particularly steep technological to climb. The fact that there are, although limited, ways of familiarizing oneself with the technology, actual usage of QC requires a major step forward in technological advancements. The opportunity of combining quantum and traditional computing to identify and explore solutions potentially puts M&S at a point of major breakthroughs (after AI). We could use QC, for instance, to identify optimal solutions while traditional computing can be used to experiment with variations of those solutions. Recall that QC

[8] *https://qiskit.org*

will not replace traditional computing. It is a different technology that will facilitate the development of new solutions to problems that can take advantage of superposition and entanglement. The identification of those problems is the first major challenge for the M&S community.

A.3. THE FUTURE OF M&S WITH DIGITAL TWINS

Digital Twins is perhaps the key emerging technology that is actively highlighting the combination between AI, simulations, and big data, and could reap the benefits of quantum computing in the future. Digital Twin research and development relies on the integration of M&S with AI in order to develop solutions and advance understandings and application areas of this paradigm. To illustrate that connection, a simulation expert at the 2022 Winter Simulation Conference pointed us to Formula One, as it is relatable for non-technical audiences (author conversation with Dr. Joshua Ignatius, December 2022 – citation references added by authors):

Formula One cars generate large amounts of data. The "combustion engine alone houses between 40 and 50 sensors that analyze all of the critical parameters, from instantaneous temperatures, pressure, rotational speed in revolutions per minute, engine status and many more" (MAPFRE 2020). The volumes of data create massive datasets and require increasing computing capacity and data analysis techniques. This information needs to be processed in real time to generate insight that can be relayed immediately to the driver. Further, this information is fed to simulations that lead to decisions that affect race results (Newcomb 2022). The Mercedes Benz Team, for instance, capture racetracks that they use with a virtual car simulator for the driver to practice before a race. Few virtual race simulations lead to running thousands of constructive simulations generating large amounts of data that allow them to tailor car and driver performance to a specific track (Mercedes-AMB Petronas Formula One Team 2020).

For now, published literature suggests that digital twin and synthetic environments research uses M&S in some ways, but that the potential integration and mutual benefit may be increasing. Advances in each of the computational approaches—AI, big data, and QC—discussed in this paper are constantly evolving, and therefore the integration with digital twins and synthetic environments evolves as well. Advances in the granularity of data able to be captured by the digital twin require increasingly advanced data analysis tools that will likely come from AI, as well as computational capacity (Amier et al. 2022). The ability to increase the fidelity of the digital twin and synthetic environments as computational capacities grow will continue to expand settings beyond industry and government in which these systems are used. One of the likely premier frontiers of this research will be in the study of Cyber Physical Systems (Steinmetz et al. 2018). Even now, researchers are beginning to talk about the potential for "quantum digital twins," which they describe thus:

We posit that the quantum (digital) twin concept is not a contradiction in terms - but instead describes a hybrid approach that can be implemented using the technologies available today and combines classical computing and digital twin concepts with quantum processing. As the quantum computing field evolves, quantum twins that use quantum-only approaches will likely become possible as well… As quantum processing power will increase, more realistic applications will be implemented, including complex "twin" simulations of real-world objects, processes and systems. (Amier et al. 2022)

It is certain that digital twins will be an increasing area of research, particularly related to industry, in the coming years and will most certainly benefit from advances in AI, but also in the long-term will benefit from quantum computing.

B. NATO/MILITARY IMPLICATIONS

The potential for AI, big data, quantum computing, digital twins, and synthetic environments to transform what we know about M&S and impact the way NATO and partner nation militaries fulfill their obligations to maintain global peace and security, is large. Given that these technologies are in their infancy in most cases, the future trajectory and integration with M&S is largely unknowable. Here, we use the structure of the NATO M&S Master Plan (NATO Modelling & Simulation Group 2012) to speculate on the impact of these technological advancements on NATO and partner countries' militaries.

B.1. TECHNICAL FRAMEWORK FOR INTEROPERABILITY

New language will be necessary to add to the common technical framework as advances in computation lead to new terminologies or the evolution of old terms to mean new things. M&S has always been multidisciplinary, but incorporating rapidly advancing technologies, data, and methodologies from disparate academic disciplines, industry, and other practical application areas will require revisiting the M&S Glossary of Terms. As of this writing, for instance, "big data" is not defined with relation to M&S in the NATO M&S glossary (NATO/OTAN). Generative pre-trained language models could be used to process and generate documentation of existing models across use cases and platforms used by NATO partners, as well as ingest conference papers, press releases, and other written materials to suggest the most commonly used vocabulary (and possibly even definitions) that circulate in various M&S communities.

What may have taken years before—the standardization of a technical lexicon—could be done quickly and iteratively using the very materials generated by M&S experts and stakeholders to ensure models and the terminologies they use are up-to-date with technological advances. These same technologies could also be trained to update existing training materials, classify models, documentation, and findings/outcomes in order to suggest new ways to measure compliance with standards (or updates to standards) and evaluate interoperability potential. Harnessing AI—machine learning, NLP, and other emerging technologies—would propel NATO efforts to standardize and advance the education on, use of, and development of M&S.

B.2. INCREASING COST EFFECTIVENESS THROUGH COORDINATION

Similar to the above use, AI would be an effective ally for documenting and educating about M&S in order to update advancements in the M&S Master Plan. Knowledge management of M&S resources could be dramatically shaped by AI and big data, potentially facilitating a restructure of how we, as humans, store, access, and update information. Above and beyond those tasks, these advances themselves might be able to generate entirely new advances—models and notions of interoperability that we haven't even thought of yet. For instance, as we move towards using AI to help generate—design, develop, test, and experiment with—models and simulations, what if a NATO-specific language models captured all papers associated with a NATO MSG? We could at least capture an AI-based lessons learned "repository" that could be queried using natural language towards generating new models and potential simulation implementations. ChatGPT,[9] for instance, has shown us what is possible when it comes to AI and human language. An equivalent infrastructure for the M&S community and for NATO is within reach. Soon, while these will not likely yield executable code in the near future, they could jumpstart a project and provide a framework for fast-tracking model specification and development.

B.3. DEVELOPING SIMULATIONS

In addition to the above future scenarios in which AI might assist with model specification and development, M&S with NLP built-in could facilitate tabletop exercises by letting the experts coming up with new ideas (without knowing the technical details of M&S) and develop models in near-real time to explore scenarios. Tabletop exercises do not currently take advantage of simulation models as most are focused on the discussion of evolving scenarios. NLP could change that. NATO's DTEX (Disruptive Technology Experiment), for instance, would be an ideal testing ground for M&S with NLP built in. DTEX is a "distributed simulated environment allowing new concepts and technologies to be tested within NATO operation scenarios. Its main advantages are to be very flexible, quick to deploy, and open to large and diverse audiences" (Innovation Hub 2023).

Capturing insights from DTEX tabletop participants and transitioning these to simple simulation models that then feed back into the exercises would play a key role in the evaluation of disruptive technologies and their social dynamics. It is important to note that DTEX participants are often military and civilians with no M&S expertise; with NLP advancements, however, technical expertise or even the skills to know how to frame a problem for a computer are unnecessary. In combination with the above implications of AI for M&S, large language models are making it possible for nontechnical interaction

[9] *A natural language interface for a Large Language Model developed by OpenAI: https://openai.com/blog/chatgpt*

with technical things, like computer code, models, and even big data (e.g., simulation results).

Quantum computing (eventually) could facilitate the optimization of models that accumulate increasing complexity from users during the exercise, as new requirements and requests are made to the AI to change, manipulate, augment, or reduce the simulation as it was at the start of the exercise. This creates significant future potential to make M&S accessible to a wider range of exercise participants and stakeholders, possibly even for capturing, evaluating, and communicating the outcomes and lessons learned from exercises. Additionally, like sections B.1 and B.2 above, these technologies could aid in documenting the simulation that was designed (in near-real-time), archiving that documentation following the established framework of requirements, and facilitating future interoperability. Ultimately, as AI becomes more robust in other languages, all of these materials could become instantly translatable into any partner nation language to facilitate communication and interoperability, as well as reuse for partner nations' specific context and use-case.

B.4. ENHANCE NATO MISSION EFFECTIVENESS

Synthetic Environments and Digital Twins need to find their way into improving military training and experimentation. A large portion of the literature on Digital Twins comes from the manufacturing domain. This makes sense as industry use-cases are relatively well-bounded, and the use of sensors is already part of the day-to-day process. The challenge lies in how to design training activities that warrant the use of digital twins and where to apply them. If we extrapolate the Formula 1 example to LVC simulations, data generated from live and virtual exercises can feed constructive simulations as agents/entities that are be embedded with troops' behaviors. Constructive simulations can then be used to explore different scenarios. Results from these constructive simulations can then be sent back to those in live and virtual simulations.

In terms supporting resources to operate simulations (NATO objective 4.2 from the M&S Master Plan), as in the earlier sections, AI can facilitate the interaction between non-technical, non-M&S expert personnel and the simulations through natural language engagement. This reduces the training and education required to operated simulations and make sense of the output, and allows personnel to focus on the mission, objectives, and outcome of the exercise. As above, they may even be able to change the model as their expertise or other input requires, and then ask the AI to generate documentation of the changes made to the simulation model. Additionally, AI may be able to help harness large amounts of data collected by NATO and/or partner nations that could be easily cleaned and formatted to feed directly into M&S and allow for models to be tailored to emerging security environments and situations.

B.5. INCORPORATE TECHNICAL ADVANCES

This goal of NATO's M&S Master Plan is the culmination of the discussion thus far. NATO and partner nation militaries stand to benefit from these potential methodological implications. How those translate to NATO can take different forms. In the future, trained AI models—NLP, ML, and whatever comes next—will likely be able to assist in all aspects of the M&S life cycle and reduce the cost and also the entry-level expertise to engage with and benefit from M&S. While we can imagine the implications for NATO and partner nations, we don't yet know what we don't know. As discussed above, nations outside of NATO are also using these advanced technologies in a technological race across all domains including cyber. The potential injections of these technologies in the M&S lifecycle are many and varied. Figure 8 below illustrates opportunities to inject AI, ML, NLP, big data, and quantum computing into the M&S lifecycle.

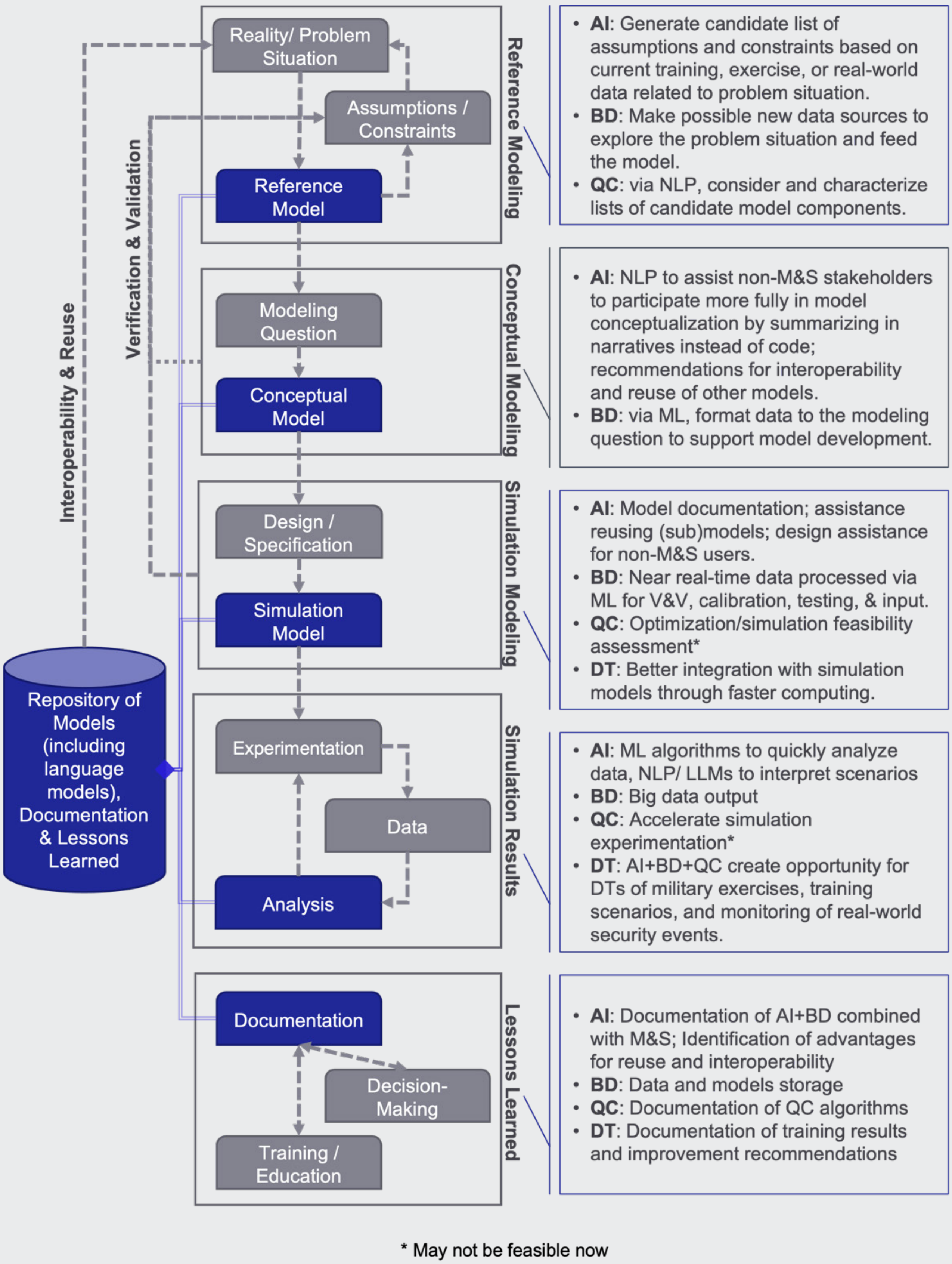


Figure 8. Opportunities for Technology Injects into M&S Lifecycle (Adapted from Tolk et al. (2013) and Balci (2012))

CONCLUSIONS: THE FUTURE OF M&S

A. The Road So Far

This paper explores a gathering body of evidence that M&S, artificial intelligence, big data, quantum computing, digital twins, and synthetic environments are all inextricably connected. As the previous section discussed, this presents opportunities that impact the entire lifecycle of M&S. It also creates challenges for keeping up with and driving the innovation that keeps M&S relevant and benefiting from technological advancements in disparate fields and application areas.

A saying is going around social media: "AI will not replace humans, but humans with AI will replace humans without AI." AI is rapidly finding its way into how we feed data into our models and how we analyze the data coming out of them. M&S will not go away with AI. ML will not replace M&S and M&S will not replace ML. Each provides unique advantages over the other. The challenge is how to maximize their combined use. Simulations will provide the best way of training and experimenting, second only to live training and live experimenting. And it is this simulated experience that makes it invaluable. ML is about prediction while M&S captures facets in addition to prediction. Their use in tandem is the present. Their unification is the future. That unification will lead to new more ways of exploring problems of interest, new problems, or problems for which where was no solution using traditional computing.

M&S is at a crucial point where new ways of building models have arrived. Yet, some of this progress has been slow compared to the progress of the fields from which these technologies come. AI efforts to facilitate programming (e.g., "copilot") are already old news. However, while programming is necessary for M&S, it is not sufficient. AI efforts to develop models and simulations are needed so that activities like training, experimentation, and decision-making take priority over technical decisions on how simulations are executed or interoperated.

While some of these technologies are still in their relative infancy, it is already time to be thinking about how to integrate new kinds of data, new kinds of algorithms, and new kinds of computational resources. Tools that can take on the challenge of combining qualitative and quantitative data with AI and M&S are necessary, but these still require exploration. Some tools exist, like updates to AnyLogic that can support some use cases for the combination of M&S and AI. To move beyond that and into the future, it is important to create ways that these technologies can streamline and improve the M&S life cycle. For instance, research must support the development of NLP algorithms in the form of user-friendly tools that can assist in designing and developing models or quantifying qualitative data.

A "reference model," or collection of all knowledge and assumptions (even if contradictory) about a given modeling problem (Tolk et al. 2012, Tolk et al. 2013), could make use of a domain-specific fine-tuned language model from which we could derive conceptual models by choosing relevant factors and resolving conflicts between assumptions in order to derive simulation models. If built on the backbone of AI that knows NATO's model specifications and terminology, interoperability should be guaranteed as simulations conform to semantically consistent conceptualizations.

It may be time for a paradigmatic shift in thinking about how we make models, but also what they are for. Perhaps it is time to reconsider the idea of interoperating large models and instead focus on developing smaller and simpler models from a common conceptual model. These models may be helpful for generating thoughts and discussions—maybe even policy evaluations and actions—instead of identifying solutions. As AI matures, those small and simpler models will grow and the ability to compose them will be a reality. The "qualitative" solutions/discussions derived from people's participation in the modeling process (and in training/exercises) can still be captured via NLP and then modeled, or even used to adapt or augment existing models. What this adds is the study of social dynamics (science of teams) where AI can additionally play a role in identifying optimal team configuration by modeling how and in what ways people communicate around, about, and in response to models and simulations. In the meantime, large and complex models will still be required, yet their use should be limited to special cases that warrant their expense and labor commitment.

B. Where We Need to Go

There is much to explore as these emergent technologies change rapidly in response to advances in algorithms and computing. As such, M&S needs to be rethought, from how we conceptualize and execute our models and simulations, to how we use M&S to understand reality. This is also an opportunity for the M&S community to ensure that activities like training, experimenting, and decision-making have the benefit of AI and QC integrated in technologies like digital twins.

This combination, however, goes beyond the M&S community. It requires that the M&S community connects with other research and development communities (including academia and industry) that are also looking at these disruptive technologies, from philosophers and ethicists to social scientists and engineers. This interdisciplinary perspective will consider not only the technology, but more importantly its users and how we advance activities like decision-making with fast simulation prototyping.

Ultimately what technologies like AI bring to any endeavor is the potential to simplify processes that were once difficult and crucial but have now become secondary technologies. This could allow for more people to be involved in conceptualization, design, development, testing, evaluation, and usage of M&S, present opportunities for increased interoperability, more near-real-time insights and adaptation of models, and streamlining of documentation to increase reuse of models. It is a long road for M&S to get there, but it is just a matter of time. Figure 9 below presents a theoretical vignette of some steps of a military exercise with examples of how AI, big data, and quantum computing could be used to augment the process.

Figure 9. A Vignette of a Simulation Exercise with AI, big data, and quantum computing

Moving into the future, we suggest these recommendations for ensuring that M&S evolves hand-in-hand with advances in AI, big data, quantum computing, digital twins, and synthetic environments to take full advantage of the opportunities and possibilities that those offer:

- Reconceptualize what interoperability might mean, specifically what kinds of additional documentation (e.g., images, written narrative, exercise outcome data, or evaluations) could facilitate a fuller documentation that AI could use to identify how models might work together. This requires understanding how and for what purpose to train AI models that meet the specific needs of the M&S community. An AI Reference Model, for instance, could provide semantic consistency for derived conceptual models and for simulations derived from those conceptual models.
- Invest research and development in natural language models that can interact with model and simulation users in conversational form in order to change inputs, parameters, test, evaluate, and execute simulations in near-real time. These models should allow non-technical users to understand and operate models, as well as make use of large and small data that can tailor the simulation to the specific operational environment or challenge at hand.

- Begin experimenting with cloud quantum computing to explore what might be possible in the near future in terms of the identification of NATO problems that could take advantage of such technology and how to move forward considering existing limitations.
- Invest in research and development in machine learning that can import, clean, and inject qualitative and quantitative data into models, as well as quickly output insights from simulations (including tabletop exercises).
- Begin training individuals to interact with AI in both technical and nontechnical interfaces so they can train to explore the potential for M&S across the full spectrum of the modeling lifecycle.
- Monitor and explore research on the use of digital twins in contexts outside of industry that are increasingly emerging to strategize on how these advances can change the ways that training, education, and real-world peacekeeping and military contexts are modeled, as well as the kinds of decision-making support that will become available as quantum computing aids in the speed of data generation and analysis.

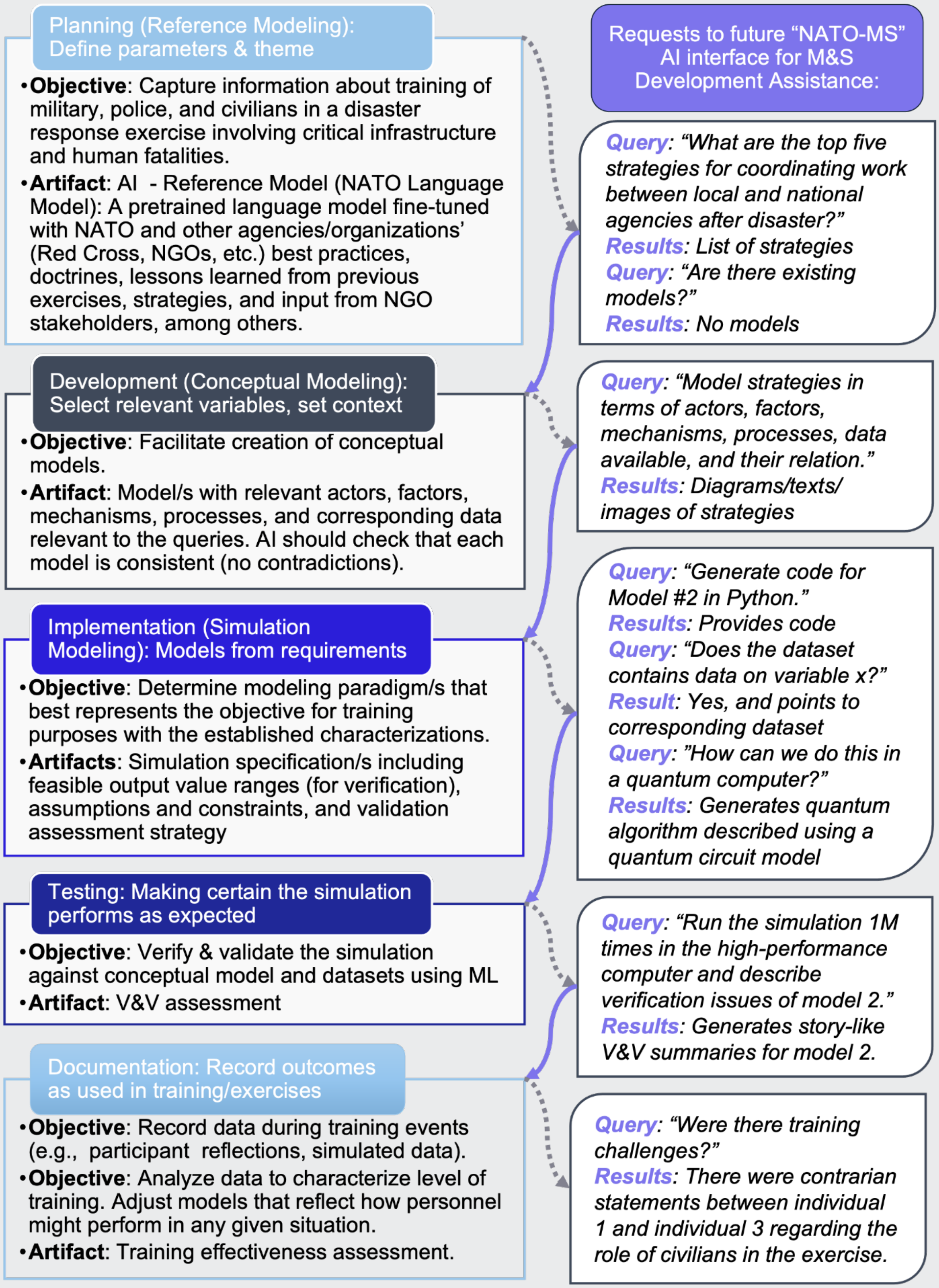


Figure 9. A Vignette of a Simulation Exercise with AI, big data, and quantum computing

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APPENDIX A - NETWORK DIAGRAMS

A. AI BIBLIOMETRIC MAPS

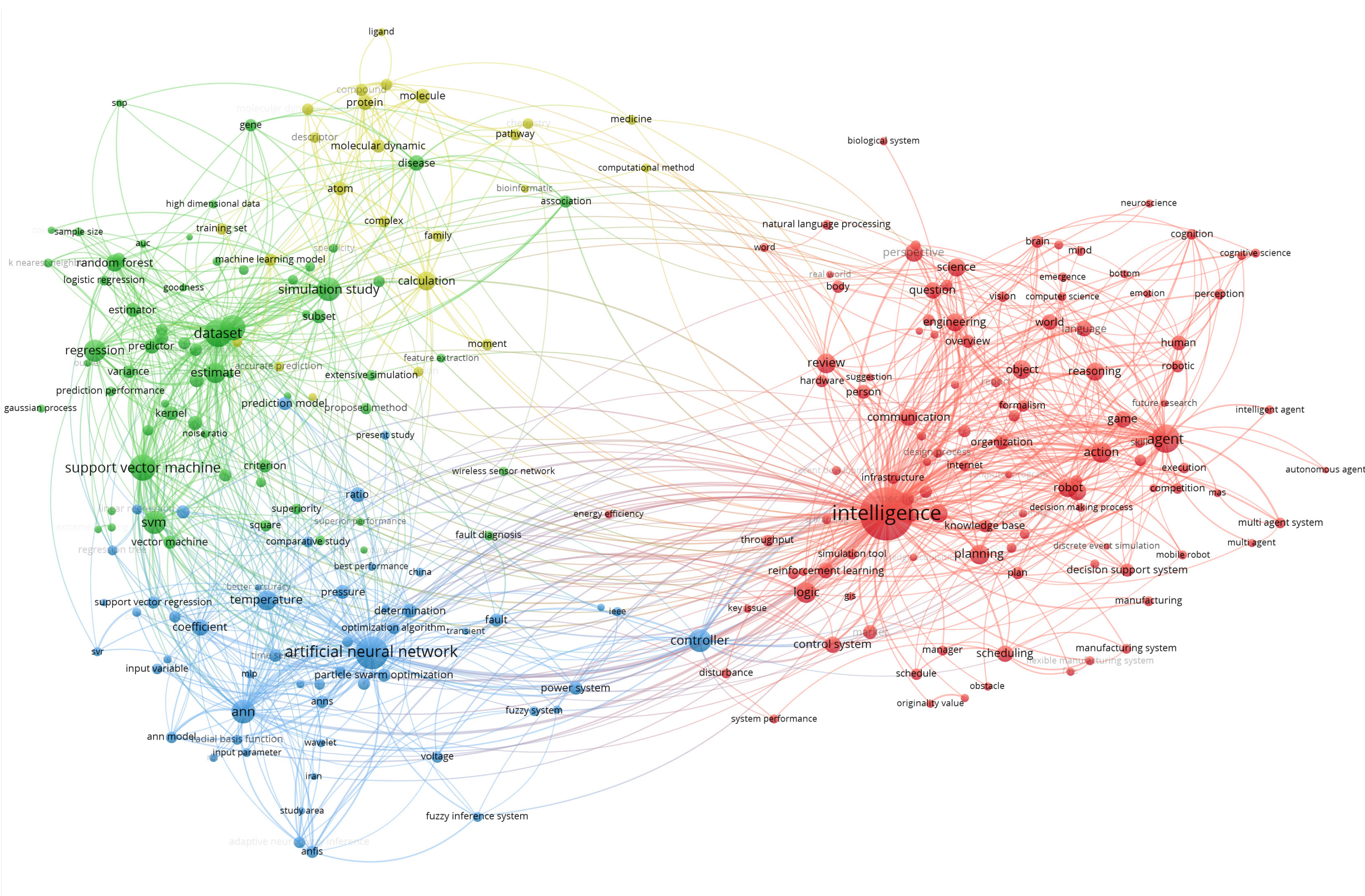

Figure A10. Topical Map of Simulation and AI, from 1960 - 2017

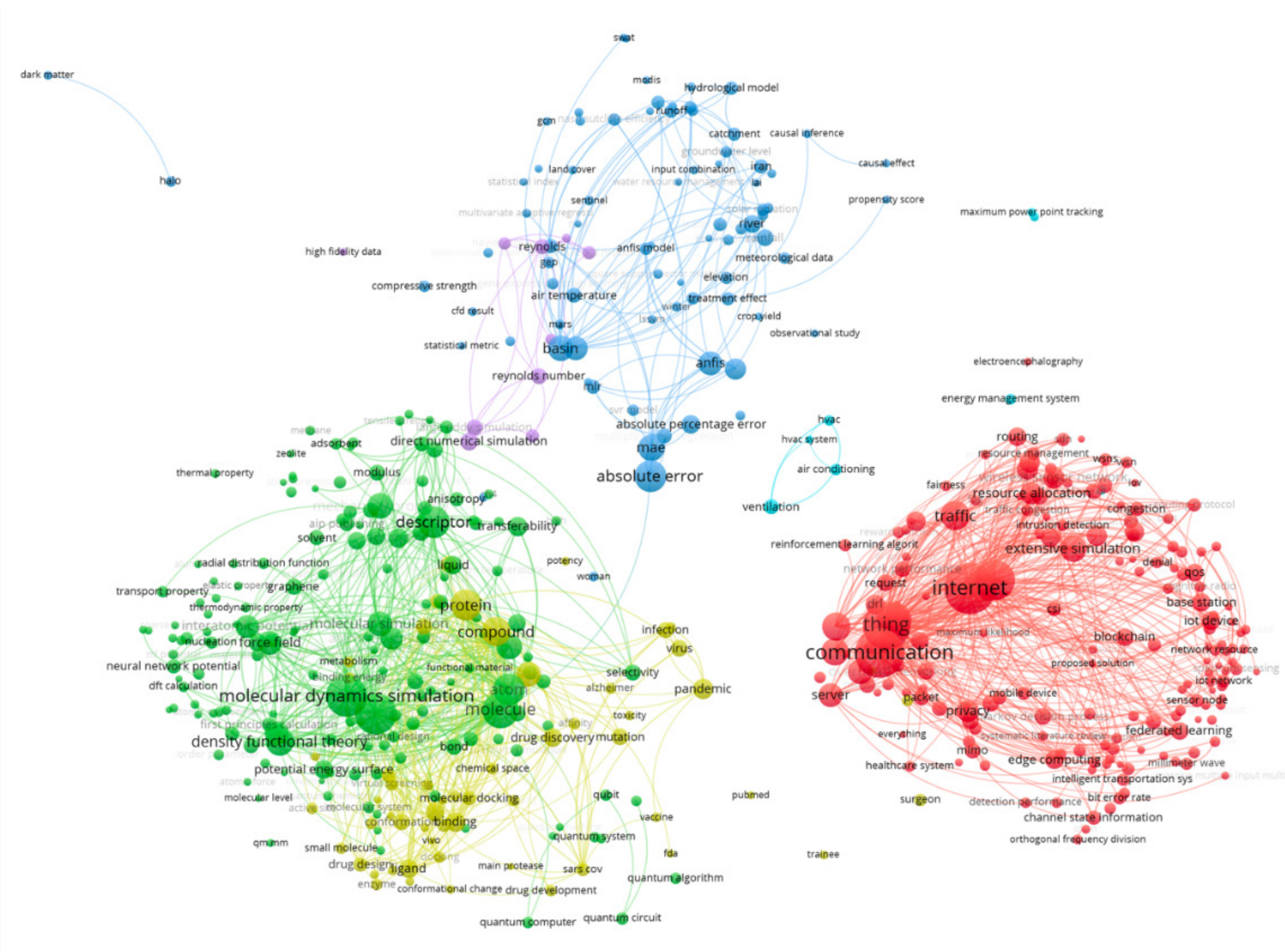

Figure A11. Topical Map of Simulation and AI, from 2018 - 2022

B. BIG DATA BIBLIOMETRIC MAP

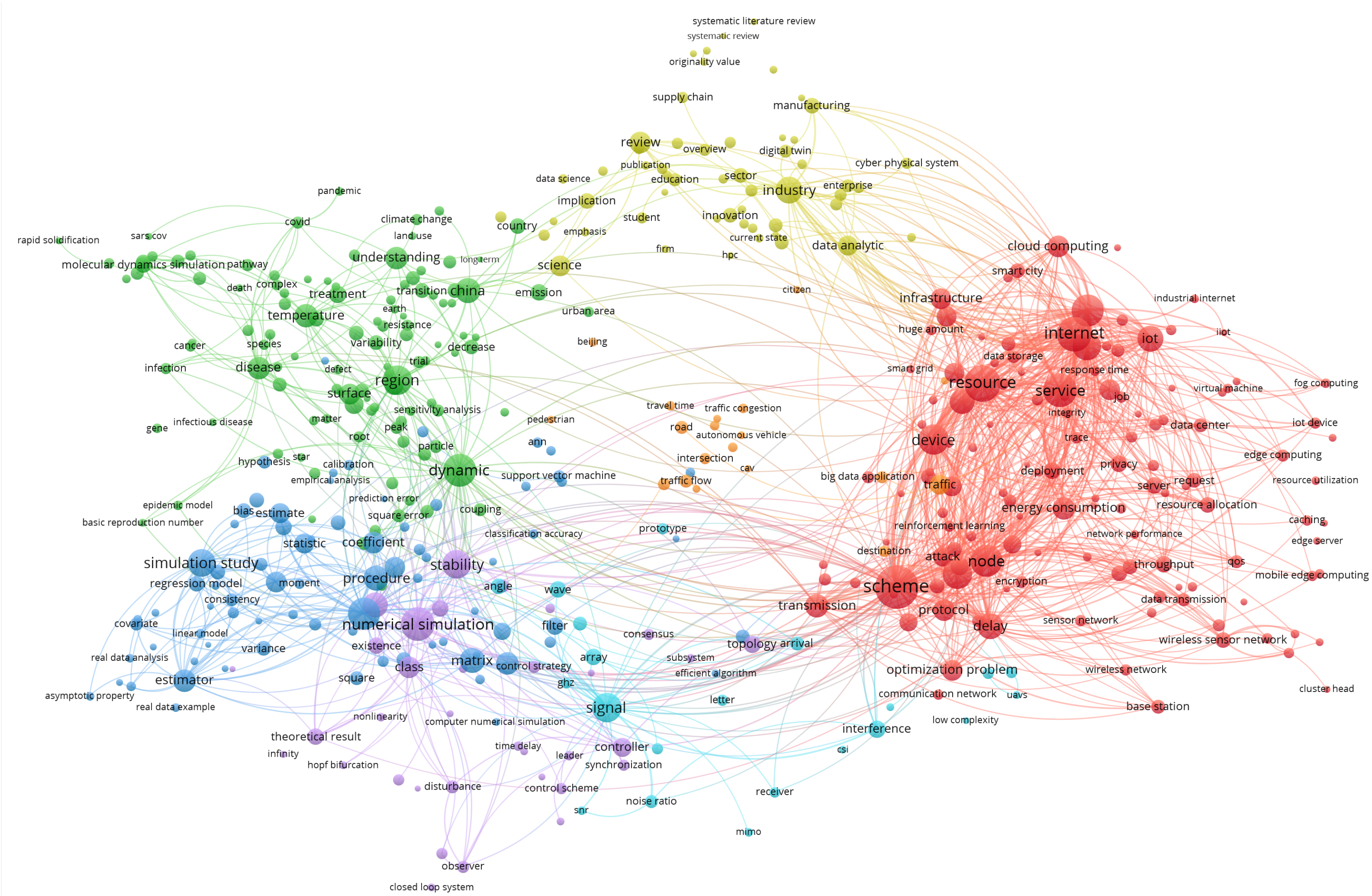

Figure A12. Topical Map of Simulation and "Big Data"

C. QUANTUM COMPUTING BIBLIOMETRIC MAP

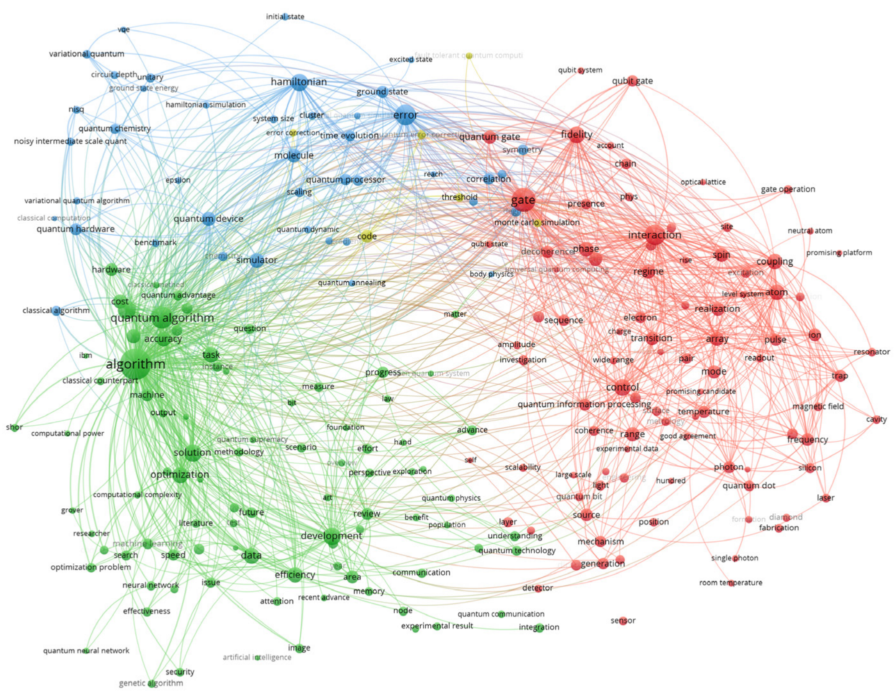

Figure A13. Topical Map of Simulation and “Quantum Computing”

D. DIGITAL TWIN AND SIMULATED ENVIRONMENTS BIBLIOMETRIC MAP

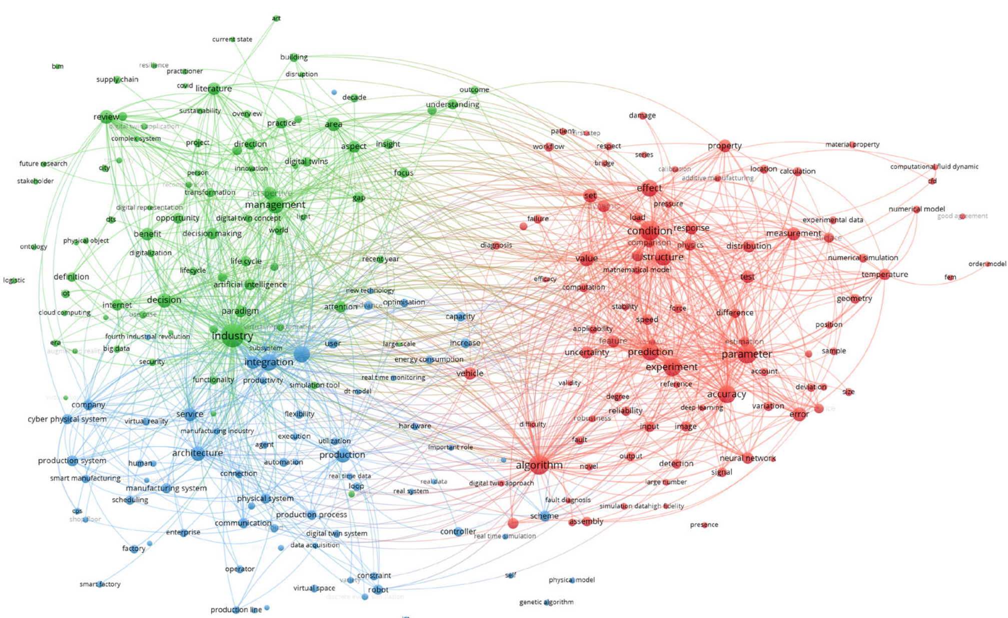

Figure A14. Topical Map of Simulation and “Digital Twin”

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