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A SIMULATOR TESTBED FOR MT-CONNECT BASED MACHINES IN A SCALABLE AND FEDERATED MULTI-ENTERPRISE ENVIRONMENT

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ABSTRACT

The emergence and steady adoption of machine communication protocols like the MTConnect are steering the manufacturing sector towards greater machine interoperability, higher operational productivity, substantial cost savings with advanced decision-making capabilities at the shop-floor level. MTConnect GitHub repository and NIST Smart Manufacturing Systems (SMS) Test Bed are two major resources for collecting data from CNC machines. However, these tools would be insufficient and protractive in Modeling & Simulation (M&S) scenarios where spawning hundreds of MTConnect agents and thousands of adapters with real-time virtual machining is necessary for advancing research in the digital supply chain. This paper introduces a flexible simulator testbed of multiple MTConnect agents and adapters for simulating Levels 0 & 1 of the ISA-95 framework and help support R&D activities in complex multi-enterprise supply chain scenarios. To the best knowledge of the authors, there is no publicly accessible multi-enterprise MTConnect testbed yet.

1 INTRODUCTION

The term 'Smart Manufacturing' is characterized by the presence of an integrated and synergized system of hardware, software, and information operating to improve production efficiency and responding to dynamic changes through data-driven intelligent decision making. Producers are adopting smart manufacturing technologies to be profitable in the competitive global market and to support sustainability, reduce running-costs and perform basic machine monitoring at the shop floor (Shao et al. 2010; Lynn et al. 2017; Flum et al. 2019). Methods like On-Machine Measurements (OMM) can be deployed on legacy equipment and assembly lines to monitor critical interfaces of a process (Lei et al. 2017) and support digital twin applications. Manufacturing Data Analytics (MDA), low-cost Internet of things (IOT) devices, advances in computational resources and global competitiveness are some of the key enablers of this newly founded intelligence colloquially referred to as 'Industry 4.0'.

Digital Twin is one of the trending concepts in smart manufacturing (Garner-Trends 2018) and is projected to be omnipresent in future factories. It is a virtual representation of the physical process mimicking behavior in near real-time and has a multitude of applications in quality control, automation, design simulations, troubleshooting, manufacturing traceability and dynamic assessment across the product life cycle (PLC) (Parrott 2017). Thus, analysts can recognize actionable insights from enormous streams of shop floor data using advanced algorithms and domain knowledge (Brodsky et al. 2017).

Modeling and Simulation (M&S) concepts are extensively leveraged for understanding, analyzing and optimizing dynamic manufacturing systems (Negahban and Smith 2013). The biggest drawback with M&S is that 31% of time and resources are lost in gathering, processing and extracting suitable data (Bengtsson, 2009). Research and development of smart manufacturing applications catering to multi-enterprise level problems are impeded by the unavailability of simulation resources, multiple testbeds, robust architectures, and public-access shop-floor data repositories. For instance, a simulation experiment involving 100 virtual factories each with a separate MTConnect agent and multiple machines would be very costly to manually implement and time intensive to execute. As demonstrated by (Edstrom, 2017), connecting just 8 simulators to one MTConnect agent can take about 5 minutes in configuration files setup and adjustments. Beyond just setup time, M&S scenarios require that machine behavior be modeling into the virtual machines to simulate shop-floor conditions.

In this paper, we introduce the architecture of a fully-automated system capable of generating and sustaining real-time MTConnect agent simulators rapidly (MTConnect Standard, 2018). To the best knowledge of the authors, there is no open-source or commercial grade MTConnect multi-agent, multi-adaptor simulation platform yet. The focus of this paper is the overall architecture framework for creating a multi-enterprise simulated environment. This framework will help researchers in getting access to MTConnect compliant streams of data from multiple simulator agents in an efficient manner. This simulates the Level 0 and Level 1 operations specified in the ISA-95 standard for the integration of enterprise and control systems (ISA, 2017). The motivation behind choosing the MTConnect protocol is its steadily rising popularity (Figure 1), read-only-access nature and well-defined semantics implementable across a variety of industrial machines. This platform is an effort to support R&D applications in areas such as decentralized manufacturing (Angrish et al. 2018), integration of virtual machining models (Shin et al. 2016), crowdsourcing models on a high-level scale (Jain et al. 2015), simulating cyber-physical production systems (CPPS) (Kang and Lee 2018) , predictive maintenance (Vogl et al. 2016) with federated learning and M&S use-cases in planning & scheduling (Negahban and Smith 2013) .

2 LITERATURE REVIEW

2.1 Modeling & Simulation

Modeling & Simulation (M&S) saves considerable costs and time by substituting the physical process with a mathematical model running on a computing device. Furthermore, M&S can be executed at an accelerated rate and conditions which may be impossible or even unethical to test in the real-world. In a fast-paced industry like manufacturing, M&S has immense value in territories like design, planning, hazard analysis, engineering, production, and training.

A study of 290 papers by (Negahban and Smith 2013) explores M&S opportunities and research in manufacturing system design, production system operations and simulation language/package development. The paper mentions the need for generic simulation modelling for facilitating reusability and interoperability between different industries. It also highlights contributions by the National Institute of Standards and Technology (NIST) researchers in creating generic manufacturing shop and virtual factories.

Some of the biggest requirements and challenges in implementing digital twins have been explained by (Shao and Deogratias 2018). Their study points out the hurdles in the development of digital manufacturing technologies and describes the relationships between IOT, Artificial intelligence, and digital threads. A prototype of the NC machining process with life cycle assessment was done in a simulated environment to achieve sustainable manufacturing (Shao et al. 2011). In other works, (Jain et al. 2015) proposed a standard based automatic generation of a virtual factory using a hybrid simulation approach.

The research team (Kibira et al. 2015) introduced a systematic method to drive a simulator behavior only from the parameters most pertinent to the problem statement. (Jain et al. 2017) demonstrated the usage of M&S and Manufacturing Data Analytics (MDA) in decision support through predictive and prescriptive models on a complete factory level. Other research shows an organization and key structure of a reusable knowledge base consisting of atomic, composite performance models and analytical dashboards for creating decision support systems (Brodsky et al. 2017).

2.2 MTConnect Protocol

Two protocols that have gained immense popularity among manufacturing researchers over the last few years are 1) Object Linking and Embedding for Process Control Unified architecture (OPC UA) and 2) MTConnect. Both are open source, royalty-free, standards built on top of the Hyper Text Transfer Protocol (HTTP) layer and have their advantages and disadvantages. One notable difference is that MTConnect is a read-only protocol while OPC UA has read-write features and often used in conjecture with Programmable Logic Controllers (PLC). Another distinguishing feature of MTConnect is that it provides a dictionary of contextualized technical vocabulary for data communication between machines and different OEM's.

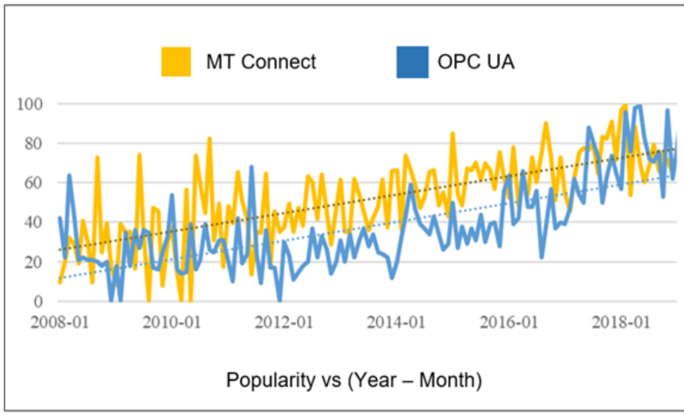


Figure 1: Google search volume for keywords "MTConnect" and "OPC UA" from 2008 – 2019.

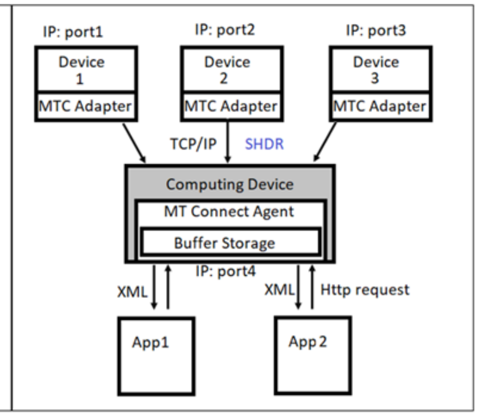


Figure 2: MTConnect Framework.

MTConnect plays a crucial role by smoothly connecting novel and legacy machines to software applications in a plug-n-play manner. For the uninitiated, MTConnect framework comprises of 3 central elements – (i) Adapter, (ii) Agent and (iii) Applications (Figure 2). An adapter is a software or hardware which extracts real-time, multi-type, signals at the device level and relays it over TCP/IP in Simple Hierarchical Data Representation (SHDR) format which is a time-stamped key-value pair delimited by the "|" symbol. An agent is a program that reads incoming SHDR data from the various adapter ports listed in its configuration file. It parses the incoming data, validates the MTConnect schema compliance and translates it into a unified Extensible Markup Language (XML) document retrievable over a web browser with HTTP requests. Users can build applications with functionalities ranging from basic time-series visualization for statistical process control (SPC) to complex cyber-physical production systems (CPPS) (Hedberg et al. 2019).

It is possible to run simulators mimicking machine behavior and interacting with the original MTConnect agent. For the advancement of smart manufacturing R&D, AMT offers public access to the C++ agent software, adapter simulator and schema files on the official GitHub library (AMT, Github MTConnect, 2018). Customized adaptors and simulators are also commercially available to users through 3rd party vendors and OEM's. Some of these simulators have advanced machining capabilities like generating feed path x,y,z, coordinates data from a STEP-NC program (Shin et al. 2016). It is highly improbable that any simulator will possess the exact features of a physical machine. Nevertheless, statistical and stochastic variation can be programmed into its behavior to closely replicate machine operation. Researchers have performed simulations at the machine level, process level and manufacturing-cell level using discrete event simulation (DES) techniques (Jain et al. 2015)

Several research projects have employed MTConnect framework for developing conventional and advance manufacturing technologies such as web-based machine monitoring (Edrington et al. 2014; Lynn et al. 2017), knowledge resource center (KRC) or data management algorithms (Kang and Lee 2018). Researchers have investigated concepts like Fog computing with MTConnect DAQ (Data acquisition) by conducting a high-frequency vibrational analysis of dynamic machine parts (Lynn et al. 2018). Many other research projects use MTConnect for creating factory-level data acquisition (Yu et al. 2018) and building efficient virtual factories for simulations. (Jain et al. 2015) .

2.3 Manufacturing Management and Analytics

The MTConnect standard which is analogous to Bluetooth protocol for consumer electronics was developed with a vision for plug-n-play interoperability between industrial machines and software (Albert , 2007). This potentially augments efficient automation systems and management of manufacturing shop floor activities. Manufacturing management means optimizing operations and resources with both technologies and methods. Intelligent methods like virtual sensing can be deployed to accurately predict the energy consumption of a device , its tool path or uptime (Gittler et al. 2018). Multi-level production planning through M&S and linear programming can be enhanced significantly by including dynamic factors like inventory buffering and real-time breakdown information (Kibira et al. 2016). Also, Artificial Intelligence techniques like reinforcement learning can be the cornerstone to novel methods like real-time batching of production orders (Zhang et al. 2018) and prognostic maintenance (Vogl et al. 2016).

3 SYSTEM ARCHITECTURE

The purpose of a multiple enterprise MTConnect simulator is to enable R&D and M&S in digital manufacturing technologies flexibly and efficiently. All the components of this simulator including the MTConnect agents are written in Python as it is one of the fastest growing programming languages (Spectrum, 2018). With a Flask micro-framework, the simulator has been converted into an intuitive web app. The system architecture and sub-systems are depicted in (Figure 3) and explained in the following.

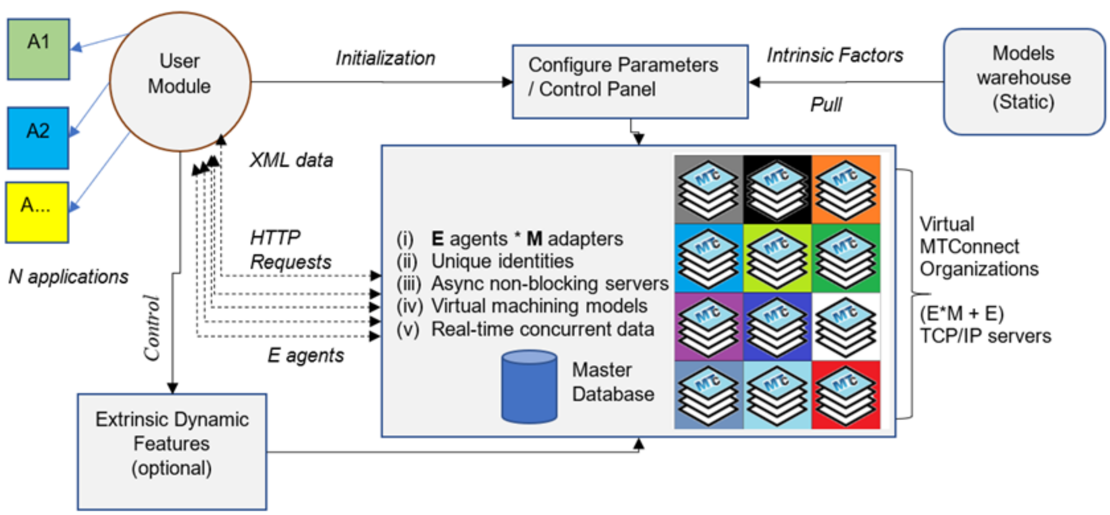


Figure 3: Simulation platform architecture.

3.1 Virtual Organizations

Every colored box in Figure 3 represents a unique virtual factory (manufacturing cell) having a random number of machines/digital twins and individual properties. Just like a physical factory, each virtual factory has a geographical location and metadata sampled through a database of cities. The top layer of the virtual factory is an MTConnect agent that assimilates real-time data from virtual machine adapters. A holistic view of 60 different virtual factories is shown in Figure 4, where red markers denote a non-operating enterprise, green markers with a star represent those running at full-capacity and so on. Clicking a marker pops up the dashboard of the corresponding manufacturing enterprise and displays Organization ID, Agent

Port number, URL Links to MTConnect agent and probe, number of virtual machines and a metric of capacity utilization.

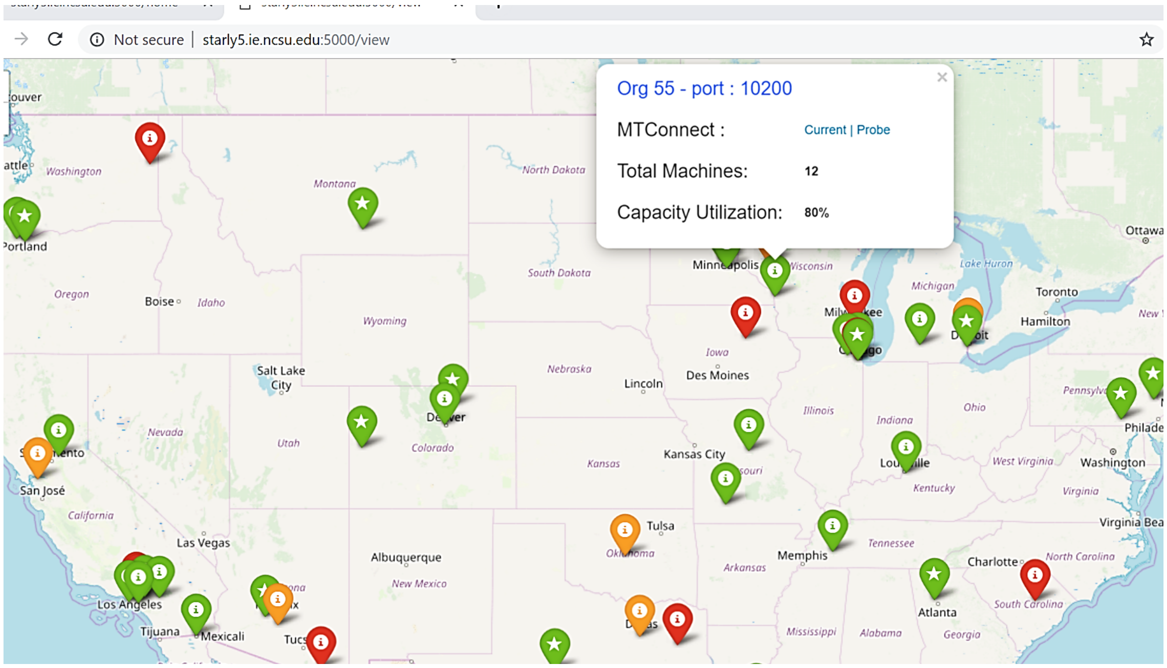


Figure 4: Federated view of 60 enterprises and respective MTConnect agents.

3.2 MTConnect Adapter

An Adapter is a piece of hardware or software that captures machine data through inbuilt machine sensors, external sensors or an application programming interface (API). An adapter may have “many-to-one”, “one-to-one” or “one-to-many” relationship with the devices. The collected data is streamed via TCP/IP (Transmission Control Protocol/Internet Protocol) based socket servers in a fixed format which is timestamped and delimited (SHDR format). Each Adapter is bonded to a unique port address and tags the data with contextual information like ‘EVENTS’, ‘CONDITION’, ‘FEEDRATE’.

3.3 MTConnect Agent

This is the heart of the MTConnect standard which iteratively listens to incoming data from adapters and performs parsing, mapping and buffer storage service. It responds to client Representational State Transfer (REST) calls by sending an XML document of the translated data in a federated, structured hierarchical format. An MTConnect agent can be accessed through its IP:port address and supports queries through /sample, /current, /probe, /asset requests.

- **Probe request**: MTConnect returns a static XML document containing data-items description for the connected device(s).
- **Current request**: It is a snapshot of the current values or states of available data-items in the device(s). MTConnect records change of state in data and has adjustable polling frequency rate.
- **Sample request**: Since polling the agent with requests for current data continuously may overburden the server, the agent has temporary buffer storage retrievable with sequence IDs.
- **Asset request**: An asset is an auxiliary device or tool connected to the main device and can be removed or replaced without affecting the main device.

3.4 User Module

This is an intuitive web-based interface with login authentication, control functions and input features for the simulator testbed. Model warehouse selection functions and probabilistic behaviors could be stated at this juncture. It is a gateway programmed on the Flask micro-framework to intuitively and effortlessly manage the complex interconnections and computations of thousands of real-time servers in the backend.

3.5 Control Panel

Once the environment is generated and initialized, the user gets a view panel that displays the virtual organizations and a dashboard of their properties (Figure 4). Users can STOP or RESET the environment through the control panel. Extrinsic properties or events can also be triggered through this module. Tasks like manually 'Shut down all factories in Ohio for 2 days' or 'Stop a particular virtual device' in a simulation testbed which has 600 adapters and 60 agents (E=60, M=10) can be easily automated.

3.6 Extrinsic Features

Real-world data APIs could be integrated with the simulator programmatically. Using Weather API and GPS location in the master database, virtual factories in a particular region can be shut down during a 'real world' hurricane. In other prospective simulation, news from Twitter feed API and traffic data from Google maps API can be made to change STATE of machines and impact the supply chain and production decisions. The extrinsic features module of the testbed provides limitless simulation possibilities impacting the real-time MTConnect data streams. A MongoDB database connects to the external API's and interacts with the MTConnect simulators.

3.7 Models Warehouse

During the generation process, the system pulls predefined properties, behaviors, and functions from the model warehouse. It is an essential element to this system bringing reusability, realism and integration to the virtual machines and respective organizations. Machine models and properties are stochastically distributed amongst the virtual factories, and can be reprogrammed as needed. For instance, the virtual factory size is assumed as directly proportional to the region population. Hence, the factories near New York city have more machines than the one near Raleigh city in North Carolina.

Similarly, virtual machines can generate data for cutting path with mathematical functions. Several mechanisms exist for generating and optimizing tool paths from STEP-NC files or G-Codes by performing simulations in multi-process manufacturing environments (Rauch et al. 2014)**.** Figure 5 (a) shows the tool path with **x = r*cos(t), y = r*sin(t)** at different **radius r** and **t**. Figure 5 (b) shows a linear cutting path. Real-time data functions will have interactions with overall machine operations like Planned Shutdowns and Breakdowns as shown in Figure 5 (c).

3.8 Master Database

Once the environment is generated, meta-data such as GPS coordinates, unique ports and machines of the virtual factories are saved in masterdb.csv file. It is useful for quick access to environment parameters and for creating a dashboard view in the user control panel. Static data about the organizations and virtual machines are stored in each run of the simulation testbed.

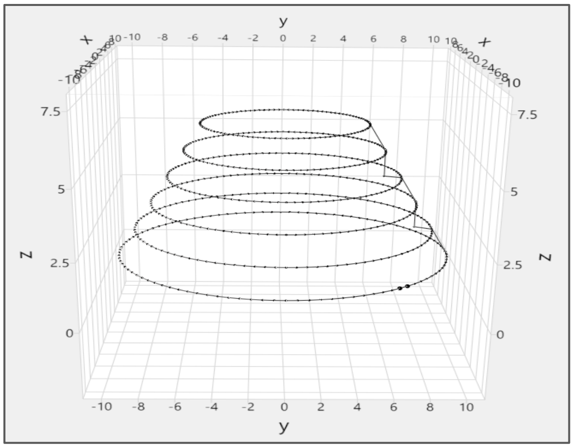


Figure 5(a): Tool-path of virtual machine 1.

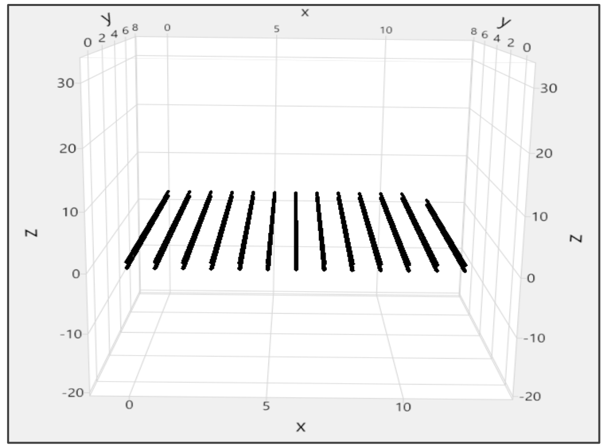


Figure 5(b): Tool-path of virtual machine 2.

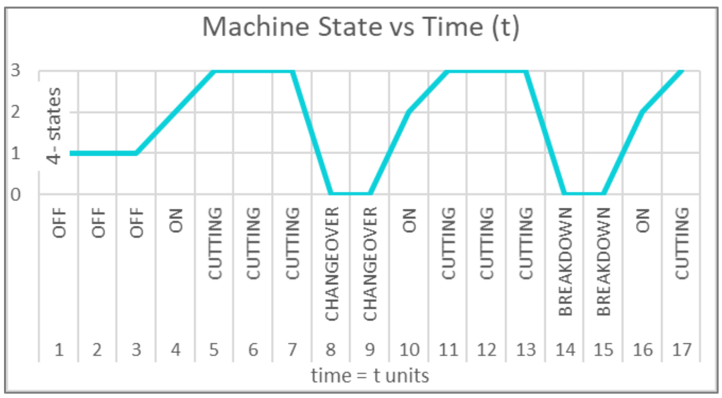


Figure 5(c): Device STATE change at time "t".

3.9 Client Applications

Although not an internal feature of the system, the real-time MTConnect data generated from the virtual factories is ingested by applications and processed accordingly. This simulation testbed current handles 3 main client requests – Sample, Current and Probe.

4 PROCESS FLOW

The backend mechanism and overall process flow (Table 1) in the simulation platform is described briefly in the next section.

Table 1: Various steps in the process are enumerated below.

Step Name	Stage	Description
Input Parameters	Generate	User enters parameters like number of organizations (Figure 6 a)
Allocation	Generate	Auto-allocate metadata like Longitude-Latitude for organizations.
Pull Models	Generate	Assign properties from the model warehouse to the virtual entities.
Auto Coding	Generate	The assigned models merge with template source code and replicates subdirectories containing files for agent, adapters, XML docs, etc.

Create View	Initialize	Interactive map dashboard built using Folium package (Figure 4).
Start	Initialize	Sequentially execute server files of MTConnect agents and adapters. Real-time data communication takes place in an asynchronous and non-blocking manner. Asyncio network programming library drives high-performance web-servers and event looping on agents essential for large volume data management.
Agents XML Response	Simulate	Respond to MTConnect requests by returning devices.xml, current.xml and sample.xml files to the client (Figures 7a and 7b). ElementTree library with XPath referencing achieves high-speed processing of data and saves a buffer.txt file in a last-in-first-out (LIFO) style.
Events	Simulate	The system performs discrete event simulation in the virtual organizations according to the stochastic behavior defined by the user in master template files and influence of extrinsic factors
Control	Simulate	Sustain system control features like 'START', 'STOP' (Figure 6 b).

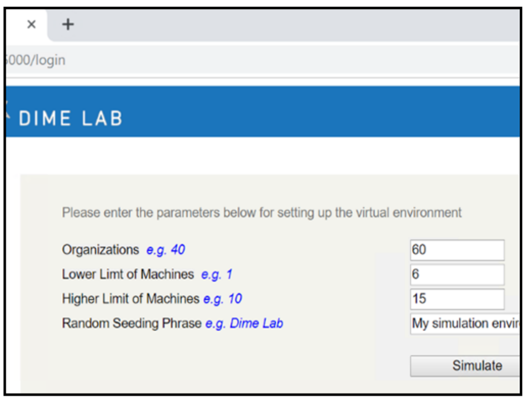


Figure 6 (a): Configuration page.

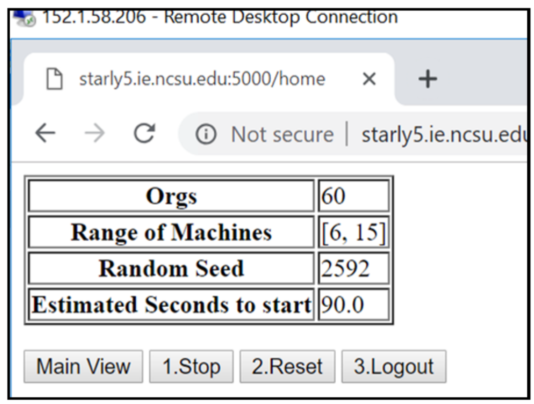


Figure 6 (b): Control page.

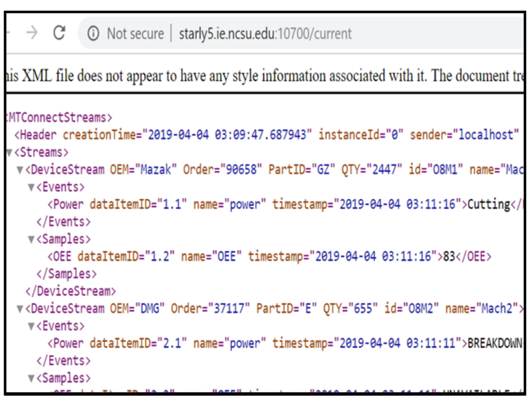


Figure 7 (a): /CURRENT request.

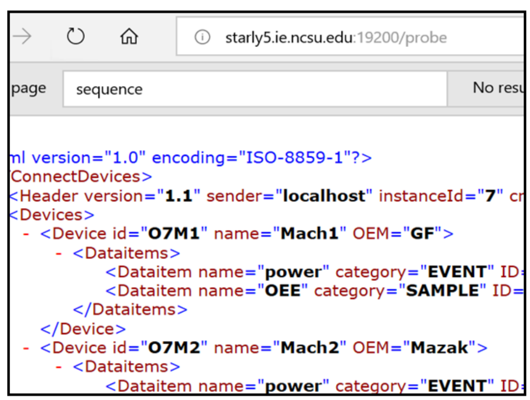


Figure 7 (b): /PROBE request.

5 USE-CASES

In the following sections, some use cases for the multi-enterprise MTConnect simulation testbed are briefly described. Since this paper's primary goal is introducing MTConnect testbed simulation tool, therefore the dynamisms, fidelity and standards pertaining to higher control levels have been assumed negligible. For a small-sized manufacturing company or individual manufacturer, this assumption is pragmatic and reasonable.

5.1 Artificial Intelligence for Breakdown Prediction

Bill, a researcher at DIME Lab wants to design a breakdown prediction model for CNC machines using deep learning techniques that could be readily deployed in a real-world MTConnect compliant shop floor. He doesn't have enough data, multiple physical machines or MTConnect agents access from manufacturers. Using this testbed, he simulates multiple virtual machines with breakdown models in the warehouse. He trains a deep learning algorithm on "A" set of virtual CNC machines and tests it on the "B" set using XML data fetched from /SAMPLE request.

5.2 Client Application Testing

A software developing firm wants to demonstrate a real-time multi-facility OEE monitoring application to the CEO of a large manufacturing group. This simulator helps them design, build and test the intended dashboard which pulls XML data from the MTConnect agents of different manufacturing units and computes the necessary KPIs.

5.3 Combinatorial Optimization

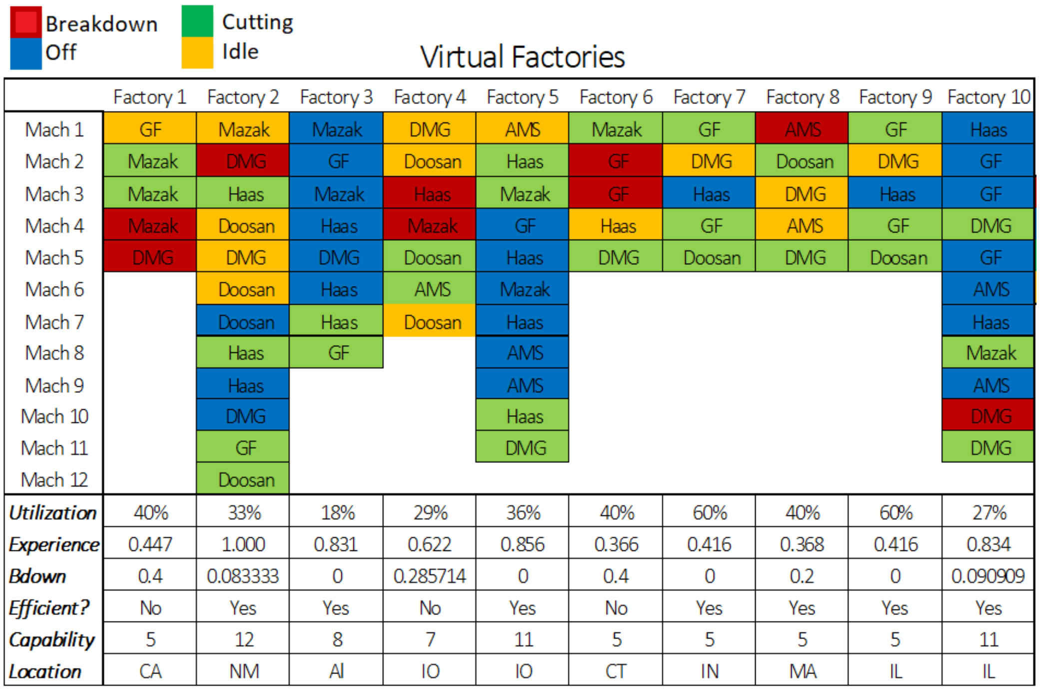
The procurement team at an Auto-Parts company is designing a system to save logistics costs and negotiate the price with suppliers through delivery time and urgency. They have access to MTConnect agents of supplier shop floors but can't vary the actual physical conditions needed to design, build and test their optimization model. Hence, they use this simulation testbed and validate their application before testing on the real agents.

5.4 Case Study

Group of manufacturing companies "A" in Connecticut city have frequent emergency shutdowns due to "forest fires" in the region. They cause unforeseen production order delays and customer attrition. The company owners in the region want to develop an automated system that subcontracts immediate pending orders to similar manufacturers "B" in other cities at an optimal cost. This would save their reputation, mitigate losses and keep future schedules on track. We shall assume that "A" companies can do 'Best Selection', 'Price negotiation' and 'fast decision making' by checking the real-time capacity utilizations and capabilities of prospective subcontracting manufacturers.

For an order requirement of Type = F, Quantity = 150, Machine = GF, Customer Location = Connecticut (CT),we simulate 10 virtual factories each having a random number of machines in the range (5-12). The multi-enterprise MTConnect simulator testbed will stream real-time machine data of the 10 virtual factories and is executing on a computer Xeon(R) CPU 3.50 GHz, x64 with 128 GB RAM. An optimization application running on a laptop Intel(R) i5 1.6 GHz represents the manufacturers "A".

The search app queries the 10 MTConnect agents at ports 19200, 17500, 10700, 19000, 14200, 18900, 13100, 14100, 13100, 11700 and receives relevant real-time data of devices from virtual factories plotted in (Figure 8).



	Factory 1	Factory 2	Factory 3	Factory 4	Factory 5	Factory 6	Factory 7	Factory 8	Factory 9	Factory 10
Mach 1	GF	Mazak	Mazak	DMG	AMS	Mazak	GF	AMS	GF	Haas
Mach 2	Mazak	DMG	GF	Doosan	Haas	GF	DMG	Doosan	DMG	GF
Mach 3	Mazak	Haas	Mazak	Haas	Mazak	GF	Haas	DMG	Haas	GF
Mach 4	Mazak	Doosan	Haas	Mazak	GF	Haas	GF	AMS	GF	DMG
Mach 5	DMG	DMG	DMG	Doosan	Haas	DMG	Doosan	DMG	Doosan	GF
Mach 6		Doosan	Haas	AMS	Mazak					AMS
Mach 7		Doosan	Haas	Doosan	Haas					Haas
Mach 8		Haas	GF		AMS					Mazak
Mach 9		Haas			AMS					AMS
Mach 10		DMG			Haas					DMG
Mach 11		GF			DMG					DMG
Mach 12		Doosan								
Utilization	40%	33%	18%	29%	36%	40%	60%	40%	60%	27%
Experience	0.447	1.000	0.831	0.622	0.856	0.366	0.416	0.368	0.416	0.834
Bdown	0.4	0.083333	0	0.285714	0	0.4	0	0.2	0	0.090909
Efficient?	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Capability	5	12	8	7	11	5	5	5	5	11
Location	CA	NM	AI	IO	IO	CT	IN	MA	IL	IL

Figure 8: KPI's computed from MTConnect data of virtual factories in real-time through the testbed.

The algorithm computes KPI's and ranks the top 3 organizations (Table 2). Then it minimizes the costs by assuming uniform weights and selecting **Factory 10** as the best available subcontractor in the current time. The simulation was possible due to the availability of MTConnect data stream from the supplier's machines revealing their current operational states. Hence, with the help of this simulator testbed, we successfully created this basic yet practical and useful application to test our algorithm with realtime MTConnect datastreams.

Table 2 : Top 3 Organizations ranked on different criterion.

Rank	**Distance**	**Experience**	**Capability**	**Availability**
1	Org 7	Org 2	Org 10	Org 10
2	Org 10	Org 10	Org 7	Org 3
3	Org 9	Org 3	Org 9	Org 5

6 CONCLUSION AND FUTURE WORK

This paper introduces a unique simulator testbed for MTConnect based machines in a multi-enterprise environment. As demonstrated above, the architecture can instantiate multiple virtual MTConnect agents and adapter enabling R&D and M&S of digital supply chain technologies. Some of the future work is to enhance the simulator's error handling capability, integrate broad MTConnect schema validation and optimize memory management and computing resources. Our research is also directed towards building virtual models' warehouse, MTConnect based predictive maintenance applications and to develop reliable device authentication methods. Future work encompasses the integration of other machine communication protocols like OPC/UA on this testbed and features to connect physical sensing devices for data gathering.

REFERENCES

Albert, M. 2007. *Thinking About Shopfloor Interoperability-And Making It Happen.* Article, Modern Machine Shop. https://www.mmsonline.com/articles/thinking-about-shopfloor-interoperability-and-making-it-happen , accessed 24th April 2019.

Sobel, W. 2018. "MTConnect ® Standard". Technical Standard version 1.4.0, MTConnect institute, Association for Manufacturing Technology, McLean, Virginia.

Angrish, A., B. Craver, M. Hasan, and B. Starly. 2018. "A Case Study for Blockchain in Manufacturing - 'FabRec': A Prototype for Peer-to-Peer Network of Manufacturing Nodes". In *Proceedings of the 46th SME North American Manufacturing Research Conference NAMRC 46th,* edited by L. Wang, 1180-1192, Texas: Elsevier.

Bengtsson, N. E., G. Shao, Y.T. Lee, S. Leong, and C. McLean. 2009. "Input Data Management Methodology For Discrete Event Simulation". In *Proceedings of the 2009 Winter Simulation Conference*, edited by M. D. Rossetti, R. R. Hill, B. Johansson, A. Dunkin and R. G. Ingalls, 1335–1344, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. .

Brodsky, A., G. Shao, M. Krishnamoorthy, A. Narayanan, D. Menascé, and R. Ak. 2017. "Analysis And Optimization Based On Reusable Knowledge Base Of Process Performance Models". *The International Journal of Advanced Manufacturing Technology* 88(1–4):337–357.

Edrington, B., B. Zhao, A. Hansel, M. Mori, and M. Fujishima. 2014. "Machine Monitoring System Based On MTConnect Technology". In *Proceedings of the 3rd International Conference in Through-life Engineering Services*, edited by R. Roy, T. Tomiyama, A. Tiwari, K. Tracht, E. Shahab and A. Shaw, 92-97. Cranfield: Elsevier Procedia.

Edstrom, D. 2017. Running Eight MTConnect Simulators To One MTConnect Agent. Tutorial Blogpost, http://photonsandelectrons.blogspot.com/2017/08/how-to-demonstrate-eight-mtconnect.html, accessed 29th April 2019.

Flum D., J. Sossenheimer, C. Stück, and E. Abele. 2019. "Towards Energy-Efficient Machine Tools Through the Development of the Twin-Control Energy Efficiency Module". In: *Twin-Control: A Digital Twin Approach to Improve Machine Tools Lifecycle*, edited by M. Armendia , M. Ghassempouri, E. Ozturk and F. Peysson, 95-110. Cham : Springer.

Panetta K. 2018. Gartner Top 10 Strategic Technology Trends for 2019. https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019, accessed 24th April 2019.

Gittler, T., A. Gontarz, L. Weiss, and K. Wegener. 2018. "A Fundamental Approach For Data Acquisition On Machine Tools As Enabler For Analytical Industrie 4.0 Applications". In *Proceedings of the 12th CIRP Conference on Intelligent Computation in Manufacturing Engineering*, edited by R. Teti and D.M. D'Addona, 586-591, Naples: Elsevier.

Hedberg, T. D., M. E. Sharp, T. M. M. Maw, M. M. Rahman, S. Jadhav, J. J. Whicker, A. B. Feeney, and M. Helu. 2019. "Design, Manufacturing, and Inspection Data for a Three-Component Assembly". *Journal of Research of National Institute of Standards and Technology* 124(2019):124004.

Hu, L., N.T. Nguyen, W. Tao, M. C. Leu, X. F. Liu, M. R. Shahriar, and S.M.N.A Sunny. 2018. "Modeling Of Cloud-Based Digital Twins For Smart Manufacturing With Mtconnect". In *Proceedings of the 46th SME North American Manufacturing Research Conference NAMRC,* 46th edited by L. Wang, 1193-1203, Texas: Elsevier.

Jain, S., D. Lechevalier, J. Woo, and S-J. Shin. 2015. "Towards A Virtual Factory Prototype". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 2207-2218, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. .

Jain, S., G. Shao, and S-J. Shin. 2017. "Manufacturing Data Analytics Using A Virtual". *International Journal of Production Research* 55(18) : 5450-5464.

Kang, H. S. and J. Y. Lee. 2018. "A Realtime Cyber Modelling Approach In Mtconnect Based Cyber Physical Production Environment". In *Proceedings of the 51st CIRP Conference on Manufacturing Systems, Elsevier Procedia* ,edited by L. Wang, 462–467, New York: Curran Associates, Inc. .

Kibira, D., G. Shao, and B. Johansson. 2016. "Framework For Standardization Of Simulation Integrated Production Planning". In *Proceedings of the 2016 Winter Simulation Conference*, edited by T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, 1226-1237, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. .

Kibira, D., Q. Hatim,S. Kumara, and G. Shao. 2015. "Integrating Data Analytics And Simulation Methods To Support Manufacturing Decision Making". *In Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, 2100-2111, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. .

Lei, P., L. Zheng, L. Wang, Y. Wang, C. Li, and X. Li. 2017. "Mtconnect Compliant Monitoring For Finishing Assembly Interfaces Of Large-Scale Components: A Vertical Tail Section Application". *Journal of Manufacturing Systems* 45(2017):121-134.

Lynn, R., W. Louhichi, M. Parto, E. Wescoat, and T. Kurfess. 2017. "Rapidly Deployable MTConnect-Based Machine Tool Monitoring Systems". In *Proceedings of the 2017 Manufacturing Science and Engineering Conference*, July 17th -20th , Los Angeles, USA, 1-10.

Lynn, R., E. Wescoat, D. Han, and T. Kurfess. 2018. "Embedded Fog Computing For High-Frequency Mtconnect Data Analytics". *Manufacturing Letters* 15(B): 135 – 138.

Negahban, A. and J.S. Smith 2013. "Simulation For Manufacturing System Design And Operation: Literature Review And Analysis". *Journal of Manufacturing Systems* 33(2):241-261.

Parrott , A. and L.Warshaw. 2017. *Industry 4.0 And The Digital Twin : Manufacturing Meets Its Match.* https://www2.deloitte.com/insights/us/en/focus/industry-4-0/digital-twin-technology-smart-factory.html, accessed April 29th, 2019.

Rauch, M., R. Laguionie, and J. Hascoet. 2014. "A STEP-NC Approach For Multi-Process Manufacturing, Simulation And Optimisation". *International Journal of Product Development* 19(1/2/3):21 – 38.

Shao, G. and K. Deogratias. 2018. "Digital Manufacturing: Requirements And Challenges For Implementing Digital Surrogates". In *Proceedings of the 2018 Winter Simulation Conference*, edited by M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 1226-1237. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. .

Shao, G., N. Bengtsson, and B. Johansson. 2010. "Interoperability For Simulation Of Sustainable Manufacturing". In *Proceedings of the 2010 Spring Simulation Multiconference*, April 11th - 15th , Orlando, USA , 159-166.

Shao, G.,E. Chernow, D. Kibira, and K. Lyons. 2011. "A Prototype of Modeling and Simulation for Sustainable Machining". In *Proceedings of the IEEE International Symposium on Assembly and Manufacturing*, May 25th - 27th , Tampere, Finland.

Shin, S.-J., J. Woo, D.B. Kim, S. Kumaraguru, and S. Rachuri. 2016. "Developing A Virtual Machining Model To Generate Mtconnect Machine-Monitoring Data From STEP-NC". *International Journal of Production Research* 54(15): 4487-4505.

Cass S. and P. Bulusu. 2018. "Interactive: The Top Programming Languages 2018.Spectrum: Institute of Electrical and Electronics Engineers". https://spectrum.ieee.org/static/interactive-the-top-programming-languages-2018, accessed March 10th 2019.

Vogl, W., B. A.Weiss, and M. Helu. 2016. "A Review Of Diagnostic And Prognostic Capabilities And Best Practices For Manufacturing". *Journal of Intelligent Manufacturing* 30(1):79–95.

Hu, Y., L. Zheng, Y. Wang, and W. Fan. 2018. "Semantic Information Model And Mobile Smart Device Enabled Data Acquisition System For Manufacturing Workshop". In *Journal of Physics Conference Series*, edited by A. Ashton, S. Gill and K. Parsons, 449-455. Bristol, UK: IOP Publishing Ltd. .

Zhang, T., S. Xie, and O. Rose. 2018. "Real Time Batching In Job Shops Based On Simulation And Reinforcement Learning". In *Proceedings of the 2018 Winter Simulation Conference,* edited by M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, 3331-3339. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

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