Design of Digital Twins for Optimization of a Water Bottling Plant

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***Abstract*— The advent of Industry 4.0 has resulted in a paradigm shift in the role of assembly lines in a manufacturing system. Previously, assembly lines were the central component in bringing about mass production. However, the shift in focus from mass production to mass customization has resulted in several changes to the traditional assembly line. A notable change is the need to create a Digital Twin, which can replicate physical assets, processes and systems that fulfill the various processes in a real world plant. This paper looks at creating a Digital Twin for the optimization of a water bottling plant in a production line. The Digital Twin utilizes an Open Platform Communication server to collect sensor information from the production line through a PLC. Once the Digital Twin has processed the information, the applied solution can then be sent back to the Open Platform Communication server and read in by the individual PLC's to reduce bottlenecks and production delays. This is accomplished by setting up a Digital Twin with three SMART Manufacturing Units that are tasked with the production of 500ml water bottles. Here premade 500ml bottles are fed into the system, filled by the first SMART Manufacturing Unit, capped by the second and thirdly packaged to order. The Digital Twin will be used to analyze the performance of the SMART Manufacturing Units connected in a production line. This performance can then be used as an estimation of how well the physical production line can hope to perform and give an indication of time to market.**

Keywords—Digital Twin, SMART Manufacturing Units, Optimization, Production Line, MATLAB, OPC, Industry 4.0

I. Introduction

The need for water management has seen a large increase in awareness due to the prolonged drought experienced in Southern Africa. [1] This has resulted in the need to have greater management of water bottling plants in recent years. Digital Twins (DT) are able to give estimations of how a system will perform under production and can easily identify efficiency enhancements.

DT [2] are mainly used in the early stages of development and design. It models accurately how certain systems and subsystem will perform. Progressing to the implementation of the physical system, a DT is then used to run in congruently with the physical system.

This congruency can be used to measure the accuracy [3] of the physical system in comparison to the theoretical concept. If a purely data analytic approach is taken, whereby the software system reads in physical data from the physical system and reports back in a digital representation [4], then the system is known as a DT. If the software system however has a direct feedback loop that control a physical process, then this is known as a cyber-physical system.

Digital Twins can also be deployed during production for analytical measurements of productions data. This will assist in achieving a decreased Time to Market [5] and reduce the number of products lost or destroyed between shipments from the plant to the warehouse. Digitization, through DT's footprints, of factory systems has proven to be an effective response to increase production efficiency and maintenance, both before and after project deployment.

This paper firstly revises the relevant literature, focusing on SMART Manufacturing, SMART Manufacturing Unit's (SMU's), Digital Twins (DT's) and finally Open Platform Communication (OPC). The paper then explains the methodology of utilizing an OPC server, to collect, analyze and archive data for processing through a DT. The paper is concluded by examining the simulated results, which provide an early indication of the DT as well as the response of the OPC server to DT's. This paper then contests the claim that OPC can be used within DT and SMART Manufacturing communication from the OPC's ability to be fully integrated while being able to transmit messages with low transit times and reduced latency in communication through machines. This paper investigates the usefulness of OPC's used with DT and SMART Manufacturing when relied on for real-time communication.

II. Literature Review

A. SMART Manufacturing

SMART Manufacturing [6] is one of the four main pillars of Industry 4.0, shown in Fig 1. SMART manufacturing is further split into Composability, Contextual Awareness, Data Analytics and Interoperability to name a few. The main characteristic focus of SMART Manufacturing in this study is Context awareness.

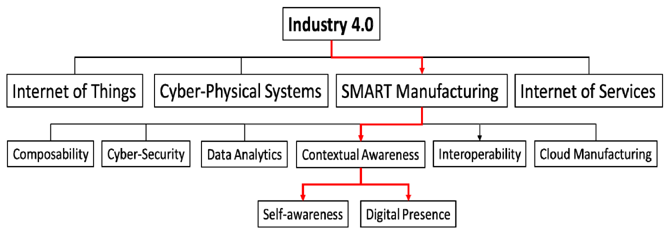

Figure 1: Contextual Awareness in Industry 4.0

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Digital Twins of the machines are designed within the Context Awareness characteristic to provide digital presence and self-awareness, making Digital Twins a part of SMART Manufacturing but not part of the physical unit, the SMART Manufacturing Units, itself but rather a software clone of the Unit.

1) SMART Manufacturing Units

SMART Manufacturing Units (SMU's) are part [7] of the growing industrial revolution, which are concerned with [8] the ability of making intelligent decisions during the production process, in real time. One key characteristics of SMU's is that of digital footprints [9].

Digital footprints are established by collecting the information gathered from the SMU's with devices on a network. This information is used for the optimization and analysis of a system, often with no human input, as some SMU's are sought after for the self-correcting features and early detection of faults.

These features only become available when the performance of the units are compared to a benchmark or reference point. If SMU's evaluate themselves on their own hardware, then this is known as self-awareness [10], however if separate hardware on a network, has a digital model of the hardware and information of a SMU, then the evaluation is known as part of the Digital Twin.

Creating a Digital Twin for a SMU is beneficial to simulate and evaluate the performance of machines on a production line while not needing to interact with the physical production line itself. The DT used in this paper will be designed to reside above the production line and have access to the OPC server, as depicted in Fig 2.

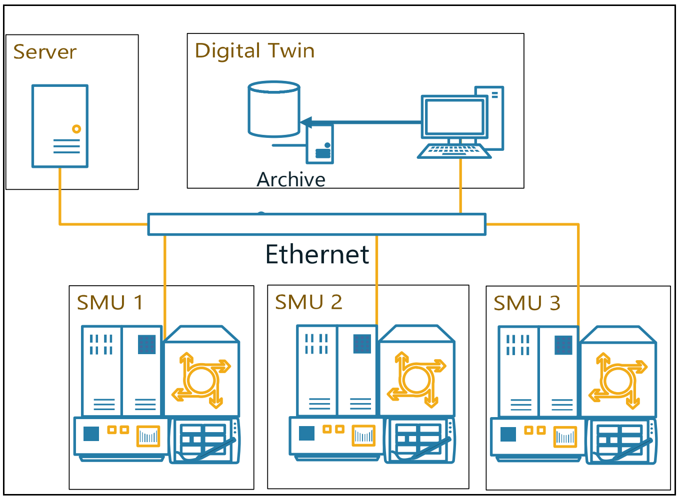

Figure 2: Digital Twin Setup

2) Digital Twin

Digital Twins are used predominantly in creating a virtual representation of a physical system, normally for the use of simulation or prediction. However DT's can be also be used in parallel with the physical system during operation to predict maintenance and be useful in data analytics.

A Digital Twin can be used to estimate the cost implications and resources required [11] for a project to succeed, before the physical system is built. Later on, once the physical system is implemented the DT can be used to see optimal working conditions and used as a benchmark of the physical system for maintenance of efficiency, fault detection and production management.

The functional extent of a Digital Twin is measured based on how it is able to handle ***Identity***, ***Location***, ***Status*** and ***Time*** [12] of the data. DT's can be used to measure forces, time, transactions temperature control and so on, with the limitation being on the accuracy of design and computational power of the DT. During production, SMU's will all have individual tasks and the ability to distinguish between each unit is of importance to production both inform a hardware and software stand point.

Each SMU, both in the physical and digital space will need its own unique identifier. This allows each SMU to have their own ***Identity***. This will allow machines and users to distinguish between machines for better and easier flow of communication and maintenance. Since no two machines can exactly operate in the exact physical space, no two machines can occupy the same software space and/or identity.

With products often having a range of production changes, occurring at different machines, often the physical ***Location*** is off importance, but the flow of a program can be dependent of this location. Location can also be broken into separate layers of each machine that specify where certain components and equipment may lie, or if multiple processors exist in a machine, then to which processor the relevant data is sent.

The ***Status*** of the machine can be used to describe the present state of a machine. This is useful to know which process a certain unit is currently implementing and the duration of the process. Multiple status indication can exist within a machine to indicate individual components and sensors workings and full operations. An overall status indication can then be made up if one or more faults occur or if production cannot continue.

The ***Time*** of a SMU also needs to be included as many processes include timely procedures or, in other cases, local time might need to be included. The timing of Digital Twins can also be extended to communication and processing completion, giving indication of if back logs and bottle necks occur in the system.

The Digital Twin can be modeled within three areas of the production line being; *The device*, *the subsystem* and *the module*. These levels are detailed in Fig 3. [13] Typically in the device level, details will include the microchip's mathematical models of transistors. This allows for high accuracy timing and miniscule deviation in performance simulations. However, the complexity to fully design a system for the device level up is exponentially increased when compared to the starting stand point of the sub-system level.

The sub-system level design sees a reduced but largely usable area of accuracy timing, being in the region of microseconds. The Sub-system level design also sees a lower complexity of not only individual machines, but also overall as a whole when spate machines and products are designed separate and assembled into one larger simulation. The sub-system level design offers a much lower complexity while not sacrificing too much on a good accuracy timing and low deviation.

The module design does provide the lowest complexity, but with a huge range on margin errors and a higher risk of false promises and hidden hurdles, it is not commonly sort after for project planning. For this reason, the ideal level for a production line Digital Twin design lies within the Sub-System Level. The module level can be interpreted as s sum of the sub-system level, however some design neglect the communication between the sub-systems in a module design.

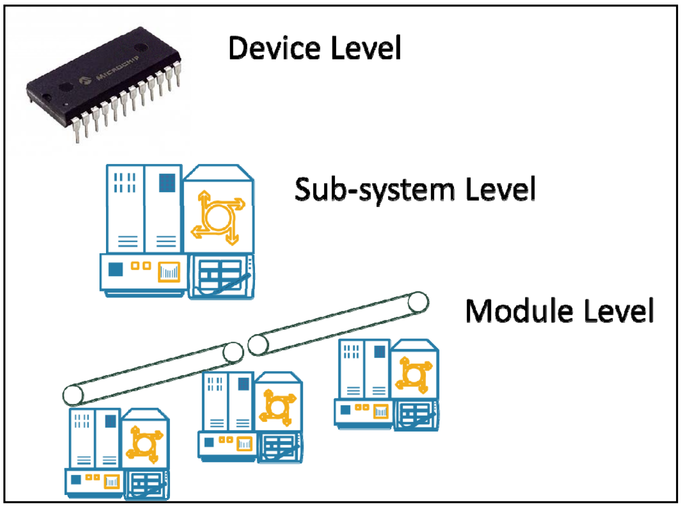

Figure 4: Level Modeling Design Levels

In order for a DT to be successful during production three main data steps need to be followed, namely *Data Collection*, *Data Analytics* and *Data Archiving* seen in Fig 4. [14] Convention will follow that on machines, such as those of SMU's, primary source of data collection is through attached sensors and network data of other machines sensor or production data. After this, analytics of the data can commence.

These analytical evaluations are usually done on two platforms [15]; the first being on a connection to a central server or of the attached machine. Information evaluated by the machine itself allows machines to form intelligent decisions of its own efficiency in a production line and can communicate its conclusions to surrounding machines so that they can take actions to increase efficiency. This is a decentralized approach of analytics and usually requires more resources to be added to each individual machine.

The second approach utilizes one large analytical computational unit located outside of the production system. This unit will collect all production and sensor information from the central server. This does see an increase in more network traffic to transmit the data, but requires less resources per machine for evaluating production data. Instead a single processor can analyze all production data and update tags for individual machines to set production rate and job activities.

After either data analytic methods are completed, the data is archived to be analyses by independent parties to evaluate the performance of production times, efficiency, job assignments and how well the analytical processor('s) performed.

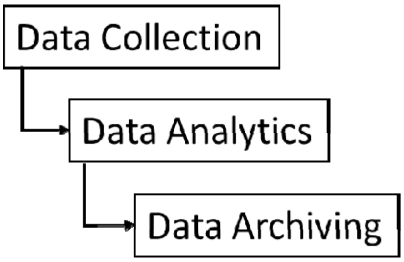

Figure 3: Data Control

B. Open Platform Communication –Unified Architecture (OPC-UA)

Open Platform Communication - Unified Architecture (OPC-UA) is a communication protocol used to facilitate the flow of information [16] from machine-to-machine [17]. OPC-UA allows for communication in heterogeneous environments through a central server connection. Depending on the type of OPC server, information can then be gathered, published and archived from each machine on the OPC server.

This allows for individual machines to post the sensor and production data on an OPC server and be analyzed by independent processors. After the analyzed data is read by the machines, the information can be archived and stored on the OPC server, allowing for data archiving and future analysis.

OPC compatible machines are manually added to a hosting server, where tags can be added and grouped. These can then be used by machines read or write multiple formats of data. When these tags are updated by the OPC protocol, near real time communication can take place between the different machines and the same OPC Server. This communication time [18] does effectively increase with the number of machines attached as well as each tag update sample time. This can push communication tags being update into the seconds range.

Although with a change in tag information appearing every second being acceptable for data analytics, missed updates could occur. Machine also acting solely on timing may also not be able to use the OPC server for communication to other machines, instead a more direct link may be preferred. However, the ability of the OPC protocol to manage a large number inputs with minimal drops in communication make it ideal for attached data analytics and Digital Twin to operate congruently with physical machines.

III. METHODOLOGY

The water bottling plant discussed in this study is tasked with the collecting of orders of customized number of water bottle orders with a variety of different bottles, namely 500ml and 300ml for this study. Customers are able to place orders online, where load balancing of the bottling plant orders takes place [18], before the order is sent to the production line to be filled, capped and packaged can take place. The objective in this study is to create a Digital Twin of the entire system that will oversee the production line during the three stages of filling, capping and packaging. A CAD drawing of SMU 1 can be seen in Fig 5. The DT is required to; monitor the amount of water left in the tank for filling bottles and warn users, through an OPC tag, when the water level is running low and an estimation of time at current production rate. The DT must also measure the rate of production through all three SMU's and balance the production rate equally throughout the system, to prevent bottles necks. The DT should also constantly monitor production rates of all individual SMU's to detect where specifically bottle necks are occurring. The DT also must be able to detect the available amount of bottles and caps available for production. Finally, the DT must be able to calculate the production rate, increase production rate to maximum efficiency and calculate the Time-To-Market of the proceeding bottles and entire orders.

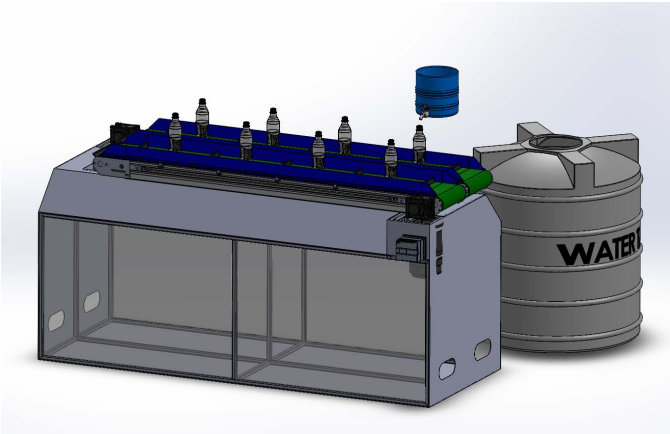

Figure 5: CAD of SMU 1

The role of the DT in this case is to evaluate the efficiency and production rate of a water bottling plant controlled by SMU's. The entire production line is connected by a central OPC server that collects data during production of bottled water orders, as depicted in Fig 2.

Optimization can then be evaluated on the production of orders and to view any potential bottle necks and communication latency. The production line includes three SMU's, where one task each exist to; *fill the water bottles*, *cap the water bottles* and *package the water bottles*. Two different types of water bottles are able to be produced from the production line, including; *500ml bottles* and *300ml bottles*, however this study is limited to the *500ml bottles*.

The SMU's have the ability to communicate to each other through the OPC server. The server posts information such as; total number of units produced at each stage, and the type produced. This information is then logged at timely intervals to evaluate the time of production.

Although each machine is able to read when the *unit bottle* is ready to move onto the next stage, each SMU has sensors attached to read in real time when a unit bottle has reached its station. In addition, each water bottle is attached with a SMART RFID tag and each station is attached with an RFID antenna.

This RFID extension allows each station to read in events of the product from previous machines in the production line. With this each station is able to decide for itself if the machine needs to increase or decrease production rate to keep a uniform production system throughout the system. This is needed in systems where, certain sub-systems need longer amounts of time than other sub-systems to complete their entire actions, creating a uniform production rate without bottle necks.

These tags and information cohesion from the OPC server gives contextual awareness to the machines in of surroundings, allowing them to generate intelligent decisions for themselves and prove its networkability. Although each machine is directly attached to the central server and allows for each machine to have access to every others machine sensor data and have communication between machines there could exist latency problems with the central server and the overwhelming traffic.

With evaluation needing to be done of production efficiency, Time-To-Market (TTM) of the products and identification of potential bottle necks, the Digital Twin will be designed per subsystem of the entire production line. This leads to three existing subsystems, representing the individual SMU's, seen in Fig. 6.

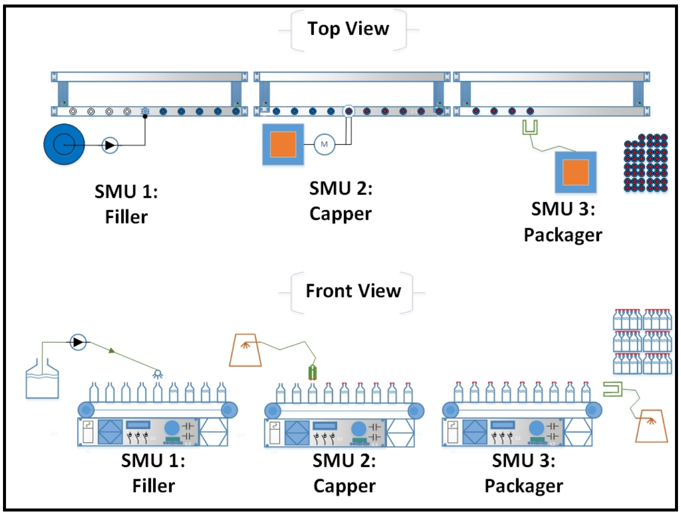

Figure 6: SMU Layout

The Digital Twin of each SMU is designed in MATLAB-Simulink in the Sub-System Level where:

- The first SMU is tasked with filling the water bottles and monitors the remaining amount of water in the filling tank.
- The second SMU is tasked with capping the water bottles and monitors the amount of caps that is left.
- The third SMU is tasked with packaging the amount of water bottles per order and writes a

complete tag on the OPC server when a production is ready.

Fig 7 shows the Simulink code used to communicate to the OPC sever as well as the separate SMU Digital Twin, representing the DT in Fig 2. The OPC is used to house the data from each SMU, which is done by writing the sensor data to OPC tags in near real time. This allows for each SMU to read in data of the production line and make informed intelligent decisions if production can be completed.

The SMU's are digitally created in MATLAB Simulink to simulate the estimated production and identify any potential bottle necks. The Digital Twin then used to mark off all aspects of data control by collecting sensor data, updating the OPC server, calculating the production line efficiency and finally storing the number completed orders.

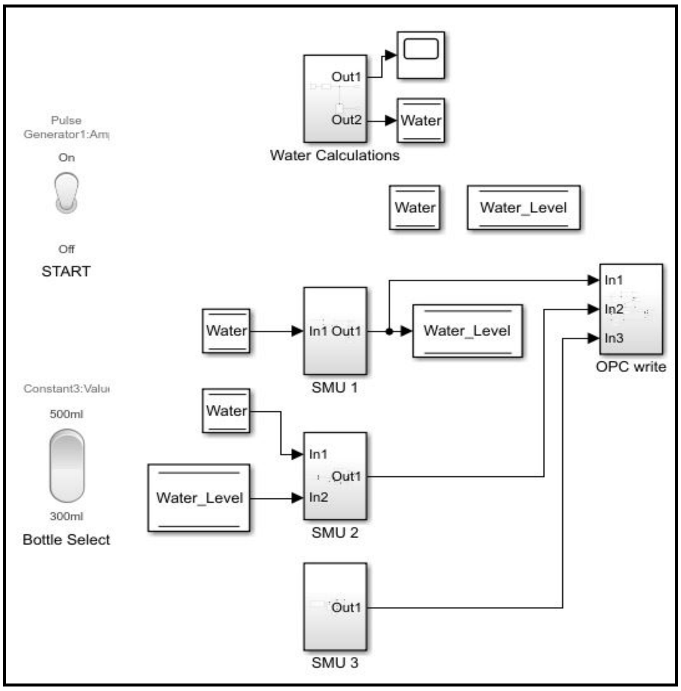

Figure 7: Simulink Code

IV. Results

It is important to note that each physical SMU only communicates through the OPC server, where if any sensor data needs to be read in from other machines, this is down through OPC. However, information is locally cached and compared to the OPC upload and refresh rates. The Digital Twin constantly monitors if the water in the fill tank is sufficient to continue with orders. Once the water in the tank empty's, the simulation stops.

Seen in Fig. 8 is the monitoring of the water level in the tank to fill water bottles. As seen that the cached memory of SMU 1 is in line with the data uploaded to the OPC server with no drift throughout the simulation.

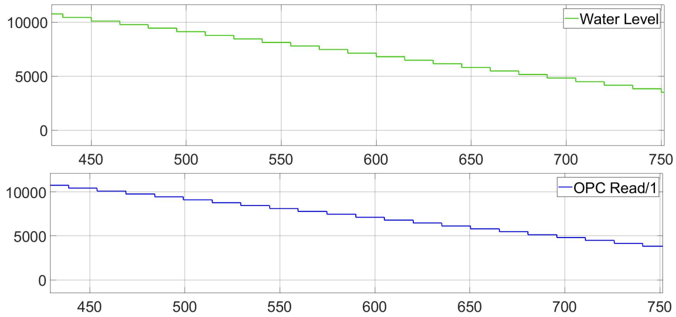

Figure 8: Water Level Monitoring

The water from each step taken out of the tank is used to fill water bottles as they arrive. Since this is the first stage of the production line no bottle neck can occur however the process may slow down due to availability of water.

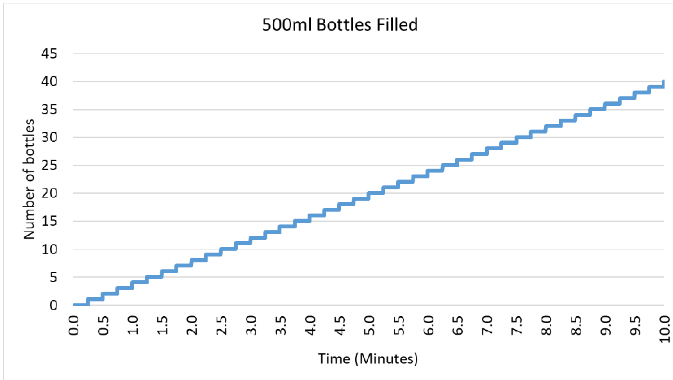

Figure 9: 500ml Bottles Filled

When a bottle is filled and move down the production line, the second SMU is able to read off the OPC server that a bottle is ready to be capped. Sensors attached to the SMU are then able to cap the bottle and write to a separate OPC tag that a bottle is capped. This sensor data is then fed into the monitoring system of the Digital Twin in Fig 9 through the OPC server.

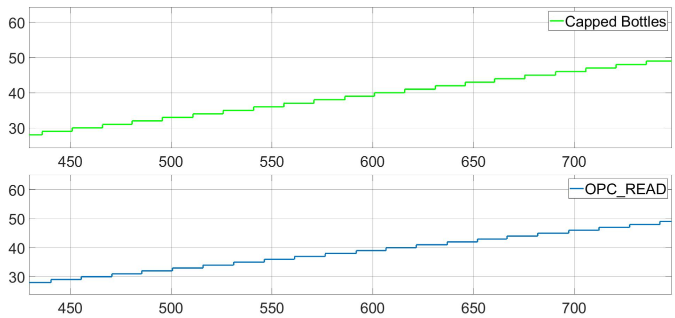

Figure 10: 500ml Capped Bottles

As seen in Fig. 10 the Digital Twin is able to read in the sensor data of each SMU through the OPC server tags, shown in Fig. 11 and no direct communication is down through the

SMU’s. These tags are used to indicate the input restraints, measurements of completed orders, TTM, production rate and indications of any bottlenecks.

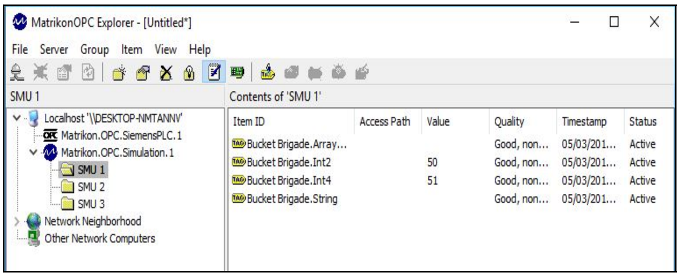

Figure 11: OPC tags

Since the Digital Twin is tasked with performance evaluation of the production line, the DT is to be able to; perform load balancing and correct production time delivery, monitor TTM, monitor restraints in inputs, measure products completed and balance production rates through the system. At this stage the system is able to evaluate a lag/bottleneck in production. If the capping of the bottles falls below a set rate, then the speed at which SMU 2 operates increases. Seen in Fig. 12, the starting if the first bottle capping is low, due to the initialization of the OPC server and startup of the SMU’s. After bottle 6 a slower rate is observed from the SMU and an increase in production speed is set to prevent any bottles necks.

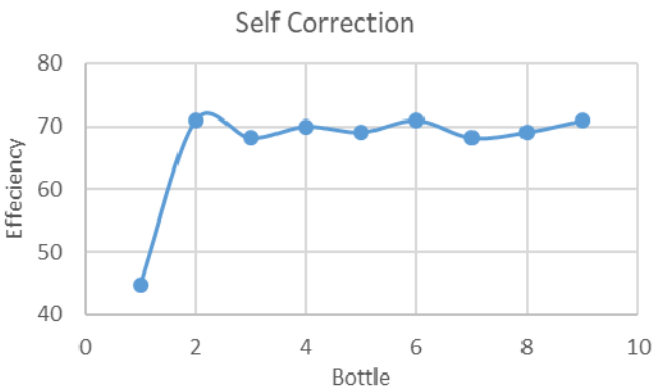

Figure 12: Production Rate of SMU 2

So as every machine is able to read the sensor data of other machines through OPC communication can take place weather to increase or decrease production speed. However, seen in Fig. 13 is the latency for the OPC server to read state changes of tags. The OPC server is much dependent on hardware resources of the server and network itself and even in high industrial equipment a latency of >0.5s and an accuracy bit issue is experienced.

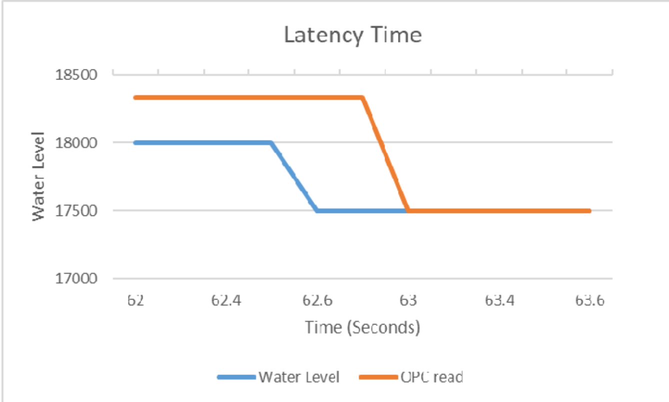

Figure 13: Latency Time

V. Conclusion

The use of Digital Twins sets out to evaluate performance and efficiency of systems in early development and future deployment. Early predictions of efficiency and production rates can be made with beforehand development of physical systems. In this paper a DT of a water bottling plant was designed in the subsystem level to evaluate the efficiency, latency of communication and production rate of 500ml water bottles.

The Digital Twin is also able to give indications of production times and performance by reading OPC tags and performing critical analysis on these tags. Drops in production rates and indication of where possible bottle necks may occur can be identified and self-corrected using DT’s. Once deployed alongside the actual factory machines, the DT can help indicate where faults may lie, minimizing the maintenance time. With proper design of DT’s becoming essential in Industry 4.0 to evaluate the performance of a system [20], this paper suggest that similar approaches in designing DT’s be used alongside physical machines [21].

However, the machines are not able to rely directly on an OPC server in terms of communication and timing. This is due to the large latency time, ranging from 100ms to 500ms and an average of 200ms latency an OPC server might experience with an increase number of connections and update of tags. This will have a direct impact on purely timing systems. SMU’s will therefore need a faster means of communication between each other for timely production needs.

This section has reviewed the literature review defining the needs of communication in DT’s and SMART Manufacturing, with a special focus on real-time communication, as well as examined the results of the Water Bottling DT. This section then concludes that with the OPC slacking in real-time communication, when a scaled project is in use, future DT’s and SMART Manufacturing applications might benefit from faster peer-to-peer communication standards.

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