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A Proposal for Production Control of Legacy Flexible Manufacturing Systems using Asset Administration Shell and Digital Twin

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Abstract

Industry 4.0 has revolutionized the way in which we relate to the industrial assets and production relationships. Focused on adapting technologies towards a digital transformation, its implementation brought several competitive leaps into product customization. The Digital Twin is a very powerful toll of this implementation, being able to simulate in real-time and make decisions based on real-world information as well as AI and business rules. However, and especially in developing countries, there are still barriers to establish Industry 4.0 both from a technical and an administrative standpoint. Interoperability of Legacy Systems and the investments needed for upgrades can make the reality of Industry 4.0 a distant future. To change that paradigm, research in Asset Administration Shell and the necessary adaptations of Legacy Systems is crucial to allow them the advantages of Digital Twins and the many features that can be implemented to enhance productivity and gain competitive advantages in a globalized scenario. This paper will focus on proposing a model based on AAS and other technologies from RAMI 4.0 that can be adapted to work not only with state-of-the-art equipment but with legacy systems as well. This model should work with future research to develop a solution to implement Digital Twin in Legacy Systems.

Keywords
Industrial Automation, Industry 4.0, AAS, OPC-UA, Legacy Systems

1. Introduction

The growth and advance of industry automation to enhance productivity and capability of the industrial process has become a constant in our current time, as such improvements brought less costs and waste, increase in quality, decrease in hard-labor and a better and healthier environment with robots helping now with ergonomics situation. The number of work-related accidents has also diminished with machines performing the most energy consuming and hard labor without increasing the overall unemployment, as the need for more technical staff has increase in management, monitoring, control and maintenance (Xavier et al., 2023)

The changes from the fourth industrial revolution – or Industry 4.0 – is now a reality is most countries, including emerging countries. One of the greatest advances was the large-scale implementation of Digital Twins (DT´s) due to the Cyber Physical Systems (CPS) capable of representing with high fidelity what is happening on the real manufacturing systems. It is important to notice that a "banalization" of the term Digital Twin was noticeable early, as due to commercial purposes the term gained a lot attention (Macchi et al., 2018). A classification was proposed that would differ the three main versions present in digital transformation: the Digital Shadows, the Digital Twin and the Digital Model (Kritzinger et al., 2018).

The implementation of Digital Twins is not only for production control and management purposes, but it allows for several additional tools to be integrated on the simulation side (Singh et al., 2021). Maintenance (Caldana et al., 2021; Liu et al., 2024), Integrated Manufacturing Execution Systems (MES) (Stolze et al., 2024; Ullah & Younas, 2024; Vyskočil et al., 2023), Error Detection (Negri et al., 2020), Bottleneck Predictions (Mahmoodi et al., 2022; Ragazzini et al., 2024) and Digital Commissioning (Florescu, 2024) are just a few examples of what this digital transformation has enabled in our current day-to-day operations. However current Legacy Systems do not possess the characteristics neither the adaptability to be introduced in Industry 4.0, especially when considering the Digital Twins many advantages listed here (Bitsch et al., 2023).

The implementation of the Digital Twin, and Industry 4.0 as a hole, in developing countries has had both technical and administrative obstacles due to mainly the large Legacy System Industrial scenario of those countries. Interoperability, i.e., having systems communicate with each other, is the main technical obstacle as Legacy System often rely on proprietary protocols and software for programming. Investments in equipment and scheduling are the main administrative obstacles, as implementing Digital Twins normally means replacing the whole production line. (Bajic et al., 2021; Rikalovic et al., 2022)

Since the 3rd industrial revolution interoperability has been an issue, and with the advances of Industry 4.0 and, more recently, the digital transformation and the integration of multiple systems from different suppliers and manufactures to incorporate complex Digital Twins solutions and the many features they allow the hardware installed at production plants aren´t able to share information in a standardized manner. For that purpose, interoperability has been a field of concern in industry for some time as uniting protocols and programming languages would solve the main technical obstacle in adopting Industry 4.0. The Reference Architectural Model Industry 4.0 (RAMI 4.0) standardized most of the aspects (ZVEI, 2015).

RAMI has a three-dimensional model that takes into consideration Hierarchy, Life Cycle & Value Stream and the different Layers - from Asset to Business. RAMI standards suggest the use of open technologies and protocols such as Open Platform Communications – Unified Architecture (OPC UA) (Mahnke et al., 2009) and Asset Administration Shell (AAS) (ZVEI, 2016) as an information model thus allowing all systems to have the same language and eliminating the interoperability issue. (Inigo et al., 2020).

The feasibility of upgrading and retrofitting Legacy Systems to enable them to use OPC UA has been proven by Sousa et al. (2024), as well as the implementation of AAS on Legacy Systems as shown in Barbosa (2024). AAS has also being linked to be the solution of the interoperability constrain according to Quadrini et al. (2023) showing that the solution to the interoperability issue can be found in integrating all this previous research to construct a complete Digital Twin.

1.1. Objectives

The objective of this paper is to propose a production control architecture to upgrade Legacy System, by incorporating an information model (AAS) in the main Integration Layer between the Legacy Systems and Industry 4.0. By adapting and upgrading the Legacy systems, enabling them to use the technologies suggested by RAMI (OPC UA and AAS) integrated with a MES we will have a scenario in which a full Digital Twin can be implemented in the future on the Legacy Systems.

The proposal of a production control architecture using AAS as the information model in Legacy Systems will allow the implementation of the Digital Twin and solve the interoperability issue. This is a valid contribution to the general AAS research, that is still under way, as it tackles an existing problem in many developing countries.

2. Literature Review

In this section the relevant review on the three main aspects of this proposal: Manufacturing Execution System (MES), Digital Twins (DT) and Asset Administration Shell (AAS). The MES is a fundamental part of solution as it is the part responsible for the "feedback" to the production line and what will give the Digital Twin the ability to infer changes on the real-life system. The Digital Twin itself needs to be studied to determine not only its main characteristics but also what modules and features can be implemented as shown in the introduction. Finally, AAS is the information model in which all be contained, ensuring interoperability.

2.1. Manufacturing Execution System

The Enterprise Information Systems (EIS) can be divided into six great areas as demonstrated in Figure 1 below. They are: 1. Enterprise Resource Planning (ERP), 2. Supply Chain Management (SCM), 3. Manufacturing Execution System (MES), 4. Client Relationship Management (CRM), 5. Product Life-cycle Management (PLM) and 6. Business Intelligence (BI). Amongst those, MES are responsible for the communication between all of the strategic models with the real-world factory equipment and assets, especially in Industry 4.0 and its evolutions that require the constant communication with sensors and other information from the factory floor to make business decisions in real time. (Mantravadi & Møller, 2019)

Most MES systems (MESA, 1997) started to be developed during the 1970´s to server as an online management system for the production lines. Their function was simply connect the ERP´s to the control systems (PLC´s and sensors) and collect information of the manufacturing process (such as equipment, assets and orders) to help guide the production process. (Shojaeinasab et al., 2022). Nowadays MES systems have much more complexity, especially after the introduction of FMS that can adapt to customers' needs on-line (sometimes even during the production of the part) (Ullah & Younas, 2024). Also, MES are a key component of the Digital Twin´s structure as a Twin must be able to infer change on the real-world assets and that happens via the MES. Without connection to a MES system a Digital Twin is basically a Digital Shadow or a Digital Model.

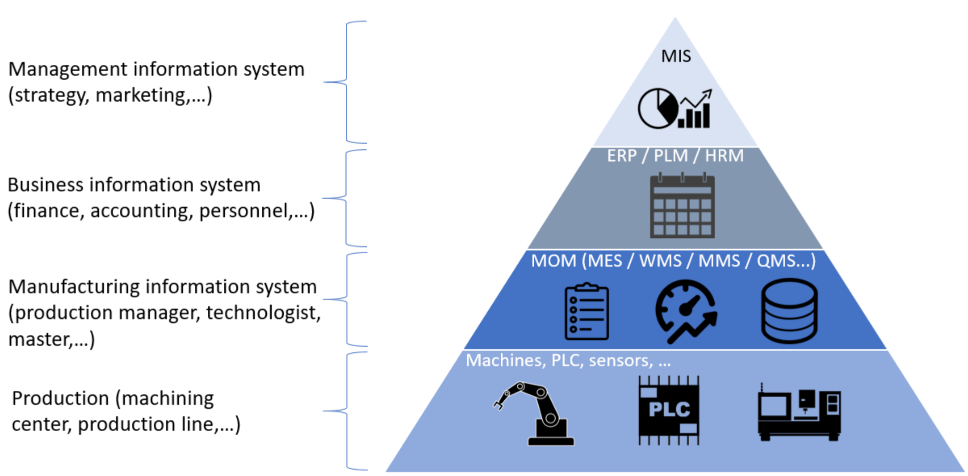

Figure 1. Enterprise Information Systems

2.2. Digital Twin

The first definition of the Digital Twin was made in 2002 by Michael Grieves, followed by a more current view by Glaessgen and Stragel in 2012 that states: *"digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc. to mirror the life of its corresponding twin"*. (Kritzinger et al., 2018). In the manufacturing scenario, there is a more detailed explanation provided by Garetti et al.: *"the DT consists of a virtual representation of a production system that is able to run different simulation disciplines that is characterized by the synchronization between the virtual and the real system, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration. The topical role within Industry 4.0 manufacturing systems is to exploit these features to forecast and optimize the behavior of the production system at each life cycle phase in real time".* (Negri et al., 2017). It is important to notice that despite its commercial use that banalized the term "Digital Twin", the level of integration is what defines and differentiates the three types: Digital Model, Digital Shadow and Digital Twin and will be detailed in the sub-sections below.

There are several applications of Digital Twin and they depend mostly on the specific needs of the industrial process that is being controlled. The applications can vary from the production process, production scheduling and order management, logistics and etc., all with the end goal to increase efficiency and productivity. The correct implementation of a Digital Twin system allows for greater flexibility, adaptability and system predictability as it collects data from the real world, analyses the historical production data and gets data from possible simulation models to achieve the best practical result. Simulation data can also be used to determine which situations need to be avoided. (Lugaresi & Matta, 2021)

The solutions for Digital Twins that are present today in the market are manufacturer dependent and do not take into consideration open access protocols such as OPC UA and Node-RED or AAS as the information model. The solutions have little to none interoperability when adapting to legacy systems or other suppliers. Abdel-Aty et al. (2022) points to the need of research in adapting AAS to the Digital Twin scenario and many of the gaps that still exists in the area.

2.2.1. Digital Model

The digital model is a representation that does not use any kind of automated exchange of information and/or data between itself and the existing physical counterpart. It is possible for the Model to have data from the existing physical system, but this data exchange is done in a manual way. The most important factor is that a change is sensor data from the physical system has no direct effect on the model. (Kritzinger et al., 2018)

It runs independent from its physical counterpart and some of the applications are: a) simulation models of planned factories for commissioning purposes; b) mathematical models of new products to be tested on a digital production line before it reaches the physical counterpart; c) simulation models to change the order of stations in a flexible manufacturing line to increase production or tackle bottleneck problems; d) 3D simulations of the production process for operator training.

2.2.2. Digital Shadow

A digital shadow has a higher level of integration, allowing for constant and automated one-way data flow from the physical system to the digital counterpart. In this scenario a change in real live data will be reflected automatically in the digital shadow. There is, however, no direct interference of the digital shadow on the physical counterpart. (Kritzinger et al., 2018).

The Digital Shadows runs concomitantly to the physical counterpart and might include, but is not limited to: a) 3D visualization of the production run; b) real-time simulation for fault finding; c) real-time analysis of timed events and historical data for predictive maintenance purposes.

2.2.3. Digital Twin

In this level of integration there is a full duplex communication between the digital and the physical counterparts. The Digital Twin is often responsible for the controlling of the physical system, which happens typically via a MES. The Digital Twin and the Physical systems can be altered by other instances, however those changes are immediately updated on both (Kritzinger et al., 2018).

The Digital Twin runs simultaneous to the physical system and is often responsible for production logistics, order management and real-time response to unexpected events, amongst several other applications.

2.3. Asset Administration Shell

The idea of AAS came as a response to the necessity of standardization and interoperability within the context of Industry 4.0. With the advance of digital technologies and the digitalization of production lines that are continuously increasing in complexity it became evident that a new structure that could digitally represent physical assets in a uniform and scalable format. The German platform "Industrie 4.0", based on the needs of the industry for interoperability and RAMI, started thus developing the Asset Administration Shell (AAS), with the objective of describing physical Assets in a standardized digital format allowing diverse systems on the factory floor to communicate with each other. Because of the increasing complexity and the need for scalability, a single structure was not viable, and AAS turned to a digital submodel solution in which each set of aspects of the physical asset is represented by a digital counterpart following their specifications and standards. Several of this submodels and their respective guidelines are shown in Figure 2 below. (Inigo et al., 2020; Quadrini et al., 2023)

AAS supports industrial automation systems, industrial assets and CPS within the product lifecycle in an environment to facilitate Digital Twin implementation, the main objective of this proposal. The AAS file is divided into two parts: a header and an information field. The header contains a unique identifier that can identify the asset inside AAS while the information field has all the pertinent submodels that were included with embedded text, images and also files (if applicable). The information held can be accessed by both real-world and digital-world applications, making AAS a powerful toll for the implementation of Digital Twin (Marcon et al., 2018). Since it is not a fixed structure, new submodels can be implemented without disturbing or altering the information already contained inside the file, with examples available at Baron & Braune (2020) and Cainelli et al. (2022).

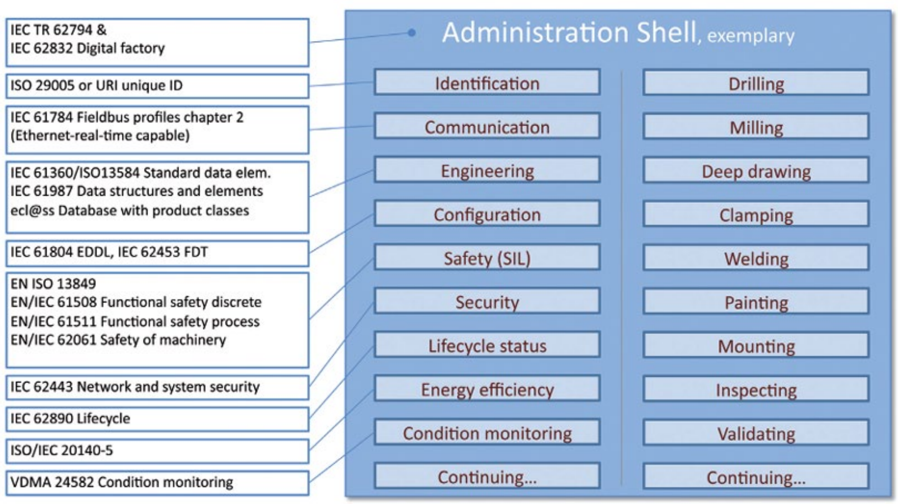

Figure 2 *AAS and some of its submodels (Barnstedt et al., 2018)*

AAS has three different types depending on the level of interaction between it. Type 1 – or passive AAS, includes information and their respective submodels that are fixed such as Manufacturer (info and logo), Order Number, Serial Number, Technical Specifications and etc.; Type 2 – or reactive AAS, comprises information and submodels that covers on-line and changeable information, such as sensors and machine and order status, in which access to the on-line servers and registry is provided through API´s; Type 3 – or proactive AAS is still under research and the final specifications have not yet been published by IDTA. The main feature of this type will be the ability to directly interact with other AAS, thus enabling a greater interaction. Type 3 will have an active and a passive portion, allowing it to be compatible with Types 1 and 2.. (Stolze et al., 2024).

Due to the flexibility of the information model, AAS can accommodate all the necessary features to implement a Digital Twin in a Legacy System. It has the capability of represent the assets with multiple submodels to represent each characteristic as well as specific submodels for the "digital transformation" part, such as Simulation Models that can house all the information regarding the model, the use and other relevant information. Since AAS is applicable in Legacy Systems, it solves the interoperability issue and it is still on the developing phase, it becomes an important area of research that this proposal will tend to.

3. Method, Materials and Development

As mentioned on the objectives, the goal of this study is to better understand how a full Industry 4.0 solution with AAS is implemented in State-of-the-art installations and how they can be adapted to the reality of the Legacy Systems. Understanding how this is done in high technology systems is an important factor to be able to adapt the existing structure for that end. In doing that, the advantages mentioned before will be reachable. For this purpose, two different FMS where selected: The "Legacy" FMS installed at UNESP Sorocaba in Brazil and the "State-of-the-art" FMS installed at Politécnica di Milano in Italy. The systems are detailed in the sub-sections below.

It is important to notice the systems are inherently different, not only in technology of their PLC´s but in terms of stations and products that can be manufactured. Even though this is a limitation of the application of the results, the difference in both systems may create a solution that can be largely adopted independently of the configuration of the production line, focusing not on the modeling of the stations but on the level of integration needed so that they can both work properly. There will still be some particularities that will need to be address for each case, as it is clear that the solution needs to be tailored to each FMS in regards of stations, but the structure and information model proposed will be similar to allow interoperability and is the main focus of this study.

3.1. Legacy FMS

The Legacy FMS system at UNESP Sorocaba, as seen on Figure 3 below, is used for teaching and research purposes. It is equipped with six production stops, each having one or two modules. All the different stations are connected by a conveyor system. It is possible to create several different production scenarios that can include the order each part stops at the stations or what is done inside each of them. The FMS is also equipped with an RFID system, composed of an INfinity 510 RFID reader and 4 RFID Antennas, installed at the stops a, b, d and e. The MES of the FMS is being implemented with these features in the design process. The stops are:

Figure 3. UNESP Sorocaba´s FMS (The Authors).

a) Distribution/Testing: Where parts are fed to the line and identified by color type. Production possibilities are single delivery, specific amount delivery or continuous delivery. It is also possible to select between identified delivery (where the system informs the color to the MES and that part is produced) or requested delivery (where the system will only output the selected part discarding any that do not fulfill the requirements)
b) Arm/Processing: Where parts are moved and can be tested and drilled. Production possibilities are what is done in the processing station (testing only, testing / drilling, drilling only)
c) Vision: Where a photo of the part is taken for quality purpose. Production possibilities are to take or not take a photograph.

d) Robot: Where several operations can be made with the robot. Production Possibilities are installation of a lead/ a lead with a coil inside or manipulation of the part.
e) Storage: Where unfinished parts can be stored for future use. Production possibilities are the type of storage and system (FIFO, FILO and etc.) and how the shelves are filled. Future research will include the possibility of using external process to change characteristics between parts.
f) Arm/Sorting: Where parts are transported and sorted and exit the line. Production possibilities select the color of the parts that exit for each of the three possible outputs that could lead to other production lines of final delivery.

The main issues with the Legacy system are the lack of integration with the most current protocols and communications, that are presented by the S7-300 SIEMENS PLC´s that do not have an embedded OPC UA Server on them or even the capability to handle publish/subscribe servers. The information of sensors and actuators are local only with control signals from outside the PROFIBUS network not being a reality.

There was need for programming to adapt the PROFIBUS and the AS-i Networks so that the data provided by each station could be visible in Node-RED and inserted into OPC UA. This research led to the development of the "Integration Layer", a fundamental part of the study that makes the adaptation to AAS and other Industry 4.0 implementations a possibility, since now it was possible to control and see all the information of the modules in an internet-based platform that allows multiple clients to be connected at once and can have independent applications using the information generated by this system for diverse purposes.

The current structure of what is installed in the laboratory can be summarized in the diagram of Figure 4 below. We have 3 modules: the FMS itself comprised of its sensors, actuators and industrial networks (PROFIBUS and AS-i), an Integration Layer that is developed in Node-RED with OPC UA to allow access to Industry 4.0 protocols - the continuation of previous published research by the group such as (Sousa et al., 2024; Sousa & Caldana, 2023) -and the RFID infrastructure.

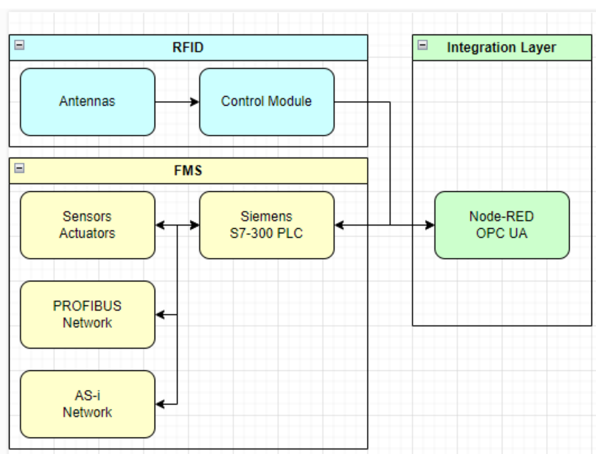

Figure 4. FMS Current Structure (The Authors).

3.2. State-of-the-art FMS

The FMS installed at Politecnico di Milano, as seen in Figure 5, was installed in 2017 for both education and research purposes. The system has 7 stations connected by a conveyor system. It is design to carry parts on a cart that has an RFID tag built into it, that once it reaches the station will be read to determine what needs to be done inside.

Figure 5. The FMS installed at Politecnico di Milano

The system produces mobile phones by performing the following steps: 1. A front-cover is dropped on the pallet; 2) Four holes are drilled on the cover; 3) The product undergoes the robot operations; 4) A camera inspection controls the product quality; 5) A back-cover is dropped on the product; 6) The two covers are pressed together and 7) The finished product is downloaded by an operator. The stations are listed below:

a) Front-Cover: drops the front cover on the RFID Cart for transportation
b) Drilling: A station can perform different type of drilling patterns dependent on the product type identified by the RFID tag. This information comes from the MES.
c) Robotic Cell: Has three different processes inside: Camera inspection, PCB Mounting and Fuses Mounting. There are several combinations possible that are determined by the MES via the RFID.
d) Camera Inspection: Lights up the product to determine if the PCB and Fuses mounted correspond to the part features.
e) Back-Cover: drops the back cover on the RFID Cart for transportation
f) Press: A pneumatic press that allows the fixation of both covers together.
g) Manual Station: The finishing point of the FMS, where an operator removes the finished product from the pallet and inform the system via an HMI that the pallet is once more available to restart production.

The current structure of what is installed in the laboratory can be summarized in the diagram of Figure 6 below:

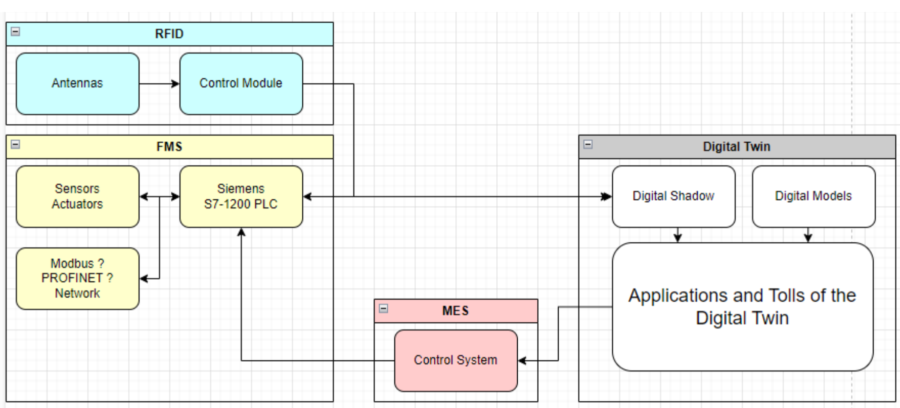

Figure 6. Current Structure at Politecnico di Milano FMS

4. Proposed Model and Discussion

Taking into consideration the bibliographic review, the research that has been done already by the group and both FMS described in Section 3 the proposed final model is showed Figure 7, representing in this particularly model the adaptation in UNESP Sorocaba´s Legacy FMS. The interpretation and understating gained by the FMS structure in Politecnico di Milano is essential to adapt the current structure of the Legacy system.

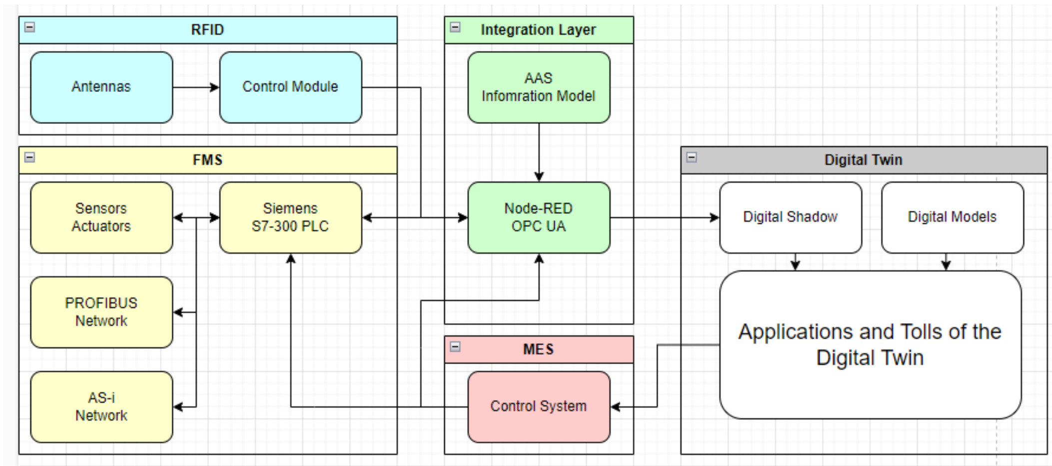

Figure 7. FMS Proposed Structure (The Authors).

The FMS block contains all the physical assets that will be part of the Manufacturing system. In the case study of the Legacy system described in section 3.1 this will comprise the S7-300 PLC´s from SIEMENS, their I/O that are represented by the sensors and actuators. Both communication protocols (PROFIBUS and AS-i) are also displayed, as they need to be integrated into OPC UA using the AAS information model.

The PROFIBUS network is responsible for the I/O signals of the stations and the Control signals that the MES will eventually via the Digital Twin, allowing full control of the stations. The AS-i network is where all the signals for the conveyor are located. It is important to notice that the PROFIBUS Master PLC also have an Ethernet connection, which is the reason why all signals from all stations could be mapped even though the individual PLC´s do not have them. This is a known limitation of this model, where ate least on component of the physical production line must have at least an Ethernet connection to allow an integration layer to be set up.

The Integration Layer is one of the main contributions of this work. It is the key component that acts as a bridge between the existing Legacy System and the digital transformation and technologies of Industry 4.0 that allows the information to flow from the physical to the digital world. It is centered on open protocols as described by RAMI and uses mainly OPC UA and Node-Red. The development that has been proven before is now upgraded with AAS as the information structure.

The addition of AAS created its own challenges and obstacles, however they were overcome and the new structure presents a possibility for inputting new information into AAS making the level of integration even bigger and more complete, especially when considering all the aspects of RAMI and product life cycle and value stream. The integration layer with AAS permits new modules and features to be added to the DT via new submodels without interfering into the operation and functionality of the previous submodels.

The RFID block is responsible for the flexibility of the line and allows for production changes and tracking during the production cycle. By having, in each produced part, a unique Electronic Production Code (EPC) stored in the Integration Layer on a specific AAS submodel, the MES system knows the real-time position and production can be checked at each stop to make sure the part is doing what is necessary. RFID Tags will allow for orders to be placed on hold if a top priority order is entered, verify is a production change request is feasible and enforce it along many other features that the DT can now take into consideration on their simulations.

The Digital Twin block will be composed of several applications running to implement the new technologies and elevate the Legacy System to Industry 4.0. Digital Models and Digital Shadows will be inserted to allow for the applications mentioned in sections 2.2.1 and 2.2.2. Since this module is still only theoretical, the continuation of the research in the field will shed more light into the opportunities that it will have, enhancing the knowledge of what can be adapted into legacy systems as well as state-of-the-art ones.

The Digital Shadow block will work with real-time information and can create a 3D visualization of the current line status. It can also indicate errors in production when combined with a Digital Model. Since in AAS the information for "Operational Data" and "Simulated Data" are kept in the same structure the comparison between both can instantly yield valuable information for the DT as well as the MES.

The MES block, as well as contain the habitual rules for production control, is the "feedback" that the DT will use to infer change and exercise control over the production line. The integration between the MES, the DT and the Integration Layer is critical to this project and will operate as the second bridge between the FMS and the DT, allowing the information from the digital world to be interpreted by the physical counterpart.

5. Conclusion

The proposed model represents the fusion of the current layout of a Legacy system with the structure of a state-of-the-art system. AAS has the ability to connect to the Digital Twin, to the MES and to be the information model for the "Integration Layer" that Legacy Systems need to have a similar language to the Industry 4.0 solutions. Since AAS is still under development, this proposal and the future research on the area will contribute to diminish the gap in AAS research as well as provide a foundation to understand the applicability of the solution proposed in this paper in real-life cases.

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