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GUIDE TO IMPLEMENTING DIGITAL TWINS IN ADDITIVE MANUFACTURING WITH RAMI 4.0

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ABSTRACT

This study was designed to guide the creation of digital twins for Industry 4.0 in additive manufacturing, especially for the RAMI 4.0 standard. As additive manufacturing tends to grow and evolve in the coming years, a guide is of fundamental importance to facilitate its implementation in the most varied types of the production process. The method used for the preparation of this guide was the scientific-technological one, mainly it's the technological part, which consists of the elaboration of a prototype, proceeds with the accomplishment of the tests and necessary adjustments to adapt to the previously established performance parameters, and ends with the presentation of the final product. The results showed the need for knowledge of the execution of eight technologies that facilitate the implementation of digital twins: G-Code, Wi-fi, FDM Additive Manufacturing, Printer Configuration, Controller Board, OPC UA, MongoDB, and System Architecture.

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INTRODUCTION

This study combines some technologies in industry 4.0, articulating them with digital twins. Digital twins are becoming a growing trend in the industry, as is additive manufacturing. When a new technology appears, it is expected to be integrated with older technologies. It will likely only be a matter of time before both technologies cross paths. In both cases, monitoring the manufacturing process will be crucial. Imagine that a factory has equipment whose part has broken, and the domain is not available in the local market. The information gathered from previous productions makes it possible to decide whether the best decision is to buy imported or locally produced parts. Another situation will be tracking errors; if a printout occurs, a failure occurs,and a remote decision is made. If the mistake were reasonable and did not affect the function of the part, printing would continue, if the error is something more serious, the stop must be requested remotely, and material and energy will be saved. In this sense, this study was designed to guide the creation of digital twins for industry 4.0 in additive manufacturing, especially for the RAMI 4.0 standard. The method used was the scientific-technological one developed by Nascimento-e-Silva (2020; 2021a; 2021b; 2021c), especially since it's a technological part, which shows the paths for the production of scientifically based technologies. The application of the method resulted from the observation that additive manufacturing tends to grow in the coming years. Due to its high degree of flexibility, many parts and designs can be developed with the same structure. Many of these projects are from different branches. Industries can choose to have a dedicated additive manufacturing area or outsource production.

Digital Twins: Um gêmeo digital é um tipo de representação, como mostram os estudos de Moya et al. (2022) and Toso et al. (2021). A representation is understood as a symbol of something abstract or tangible. This symbol is portrayed so that the main aspects of what it is intended to represent are accentuated. Different spectators often mean the same object in different ways. It is due to minimal and intrinsic discrepancies between individuals. Such differences are linked to genetics, emotional experience, professional experience, and countless other characteristics that are more or less relevant depending on what one wants to represent. If we were to place a stone in the center of a table and ask several people to do an oil painting of it, each person would paint a different representation of the same object. See several images that try to represent a particular moment.

Table 1. What are digital twins

References	What are digital twins
Moya et al. (2022)	Digital twins can be defined as digital representations of physical entities that employ real-time data to understand these entities' operating conditions.
Bondoc,Tayefeh&Barari (2022)	Digital Twins are a real-time, two-way data exchange from a physical entity and its cybernetic manifestation.
Gao et al. (2022)	Digital twins can be defined as the evolving digital data of physical objects' history and current behavior or processes that help optimize business performance.
Toso et al. (2021)	Digital Twins are a virtual representation of physical assets enabled through data and simulators for real-time prediction, optimization, control, and decision-making improvements.
Andrade,Lepikson& Machado (2021)	Digital Twins can be virtual copies of physical assets that interact in real-time with their physical counterparts.
Zhang; Zhou; Horn (2021)	The digital twin can be defined as a digital model of a physical object, and the model can evolve in real-time by receiving data from the physical object to keep it consistent with the physical object throughout its lifecycle
Chen et al. (2021)	Digital twins can be defined as machines or computer-based models mirroring, emulating, simulating, or "twining" the life of a physical entity.

Source: data collected by the authors.

Table 1. Examples of functions in G code

Code	Parameters	Function
M105	None	Request the temperature of the currently used extruder or table
G1	XnnnYnnnZnnn	Linear movement of the axes
G4	Pnn ou Snn	Pause the machine for some time

Source: REPRAP (2022).

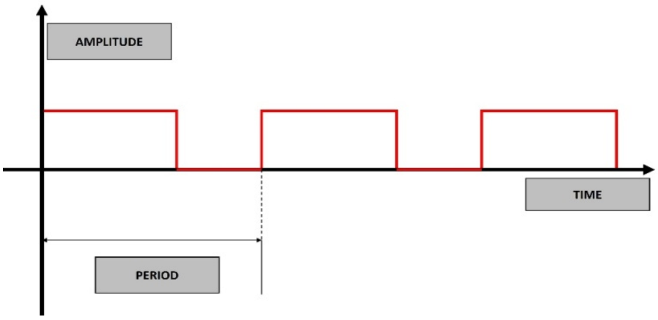
Digital twins can be a type of exchange (Bondoc et al., 2022). Exchange is understood when two or more entities cooperate by substituting particular objects or characteristics for one another and vice versa. When only one of the entities cooperates, there is no exchange. Cooperation is, therefore, a two-way flow of benefits to and from both participants. The relationships between bees and flowering plants show an example of an exchange. When attracted by the pollen of flowers to produce honey, part of the pollen is fixed in their body, and when visiting other flowers, they inseminate other plants. To Gao et al. (2022), digital twins are digital data. Digital data is binary data from electronic equipment. A binary data is a sequence of zeros and ones associated with some electrical signal, normally 0 and 5 Volts. But there are other patterns, such as 0 and 24 Volts, 0 and 3 Volts, among countless others possible. Thus, electronic equipment that produces or processes binary data is called digital electronic equipment. Andrade, Lepikson, and Machado's (2021) study relate digital twins to virtual copies. Digital twins would be digital copies. The definition of copy refers to an original model and later to its replica in the most exact way possible. Forthis creation, the main features of the original model must be mirrored. One way of reproducing is using the digital world. The digital world is not a specific physical place; a compilation of information accessed correctly will give us what we want. An example is digital photos, stored in files that are nothing more than matrices storing information about colors and light intensities. Digital twins can also be seen as role models (Zhang et al., 2021; Chen et al., 2021). Models are objects that can be taken as a reference. The reference is consulted when one wants to know something about a certain situation or object and cannot be directly observed. Ships use lighthouses as a reference to reach landfall, for example. Digital twins are a type of model because they mirror, emulate, simulate and interlace what exists in reality. In other words, what reality is or appears to be is modeled through digital twins. The standards governing the RAMI 4.0 standard regarding digital twins are IEC 61987, ISO 13584, IEC 61300-4, IEC 62541, and IEC 61987 (Heidelet al., 2015). The IEC 61987 standard concerns the standardization of industrial measuring equipment. The ISO 13584 standard talks about the physical modeling of parts in the digital world. The IEC 61300-4 standard deals with the physical connection and components connected through an optical fiber. The IEC 62541 standard deals with the OPC UA protocol. And the IEC 61987 standard deals with the AutomationML markup language.

G-Code: The G-Code or G-code is a code developed by the NIST RS274/NGC standard (Reprap, 2022). A code is a series of symbols that, when correctly interpreted, generate a message. G-Code is code because the machine that performs the action described in the code and the person (or software) that wrote it must follow the same standards. A pattern is anything that follows a certain logic. For a message to exist, there must be both a receiver and a transmitter that follow the same standards. When the sender sends a message through a code to a receiver capable of following the same pattern and decoding the message, then the message is successfully delivered. The Portuguese language is an example of code, both the transmitter and the receiver must use the same standard for the correct understanding of the message. RS274/NGC is a software system defined by the NIST (National Institute of Standards and Technology) made for machines to interpret a dialect called "Next Generation Controller" and can be numerically controlled (Kramer, Proctor& Messina, 2000). A system is a set of functions that, when receiving an input, responds with action on its output. Numerically controlled machines have their movements described in the form of coordinates. The coordinates are entered in the G code to know where and how much the device is. In this case, the system is the machine; the input is the G codes entered into it, and the movements are the output responses. Such machines are also called CNC (Computer Numerical Control). An example is the CNC lathe, a device that machines material automatically when a G code is entered. There are several ways to prepare the G code for 3D printers (Reprap, 2022). The first way is using a specific program for this. The program uses a CAD file to generate G code. Another way is using a library in a particular programming language, such as Python. The library helps create the code, but the format's creativity is entirely up to the programmer. The last way is to write the code directly without any tools. The syntax of the G code is formed by a function represented by a letter followed by a number, then the function's parameters are written afterward if necessary. Some examples of functions in G code are shown below in Table 2.

Wifi: The physical medium by which information is transmitted is through radio (electromagnetic) waves. Wi-fi is a wireless transmission technology defined by the IEEE 802.11 standard. Within this standard, there are several subtypes of applications. These applications vary according to certain parameters, some of which are: signal frequency and bandwidth.

Equation 1. Definition of frequency. $f = 1/T$

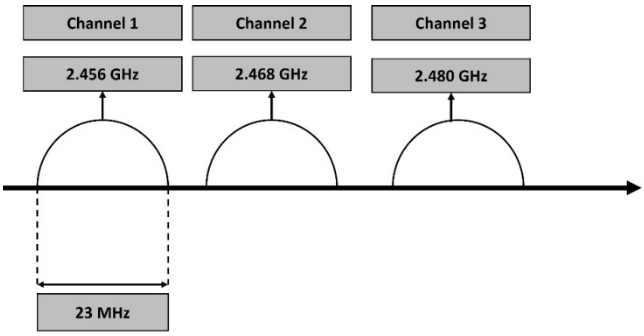
The signal frequency refers to the speed of information exchange. The higher the frequency, the higher the information exchange rate. Usually, the standards used are 2.4GHz and 5GHz. The frequency of a wave is defined as the inverse of the period (Equation 1). The period of a wave is the minimum length of time measured for the signal to repeat its shape. Figure 1 exemplifies this case. Note that the signal propagates through time, so the period of a wave is given in a time unit (second, minutes, hours). When the period of time that the wave has is given in seconds, its frequency assumes the unit Hertz (acronym Hz). It is equivalent to saying that mathematically Hertz is the inverse of seconds and vice versa. The 5GHz frequency, for example, has a period of 0.2 µs (0.0000002 seconds).



Source: data collected by the authors.

Figure 1. Example of a wave with period

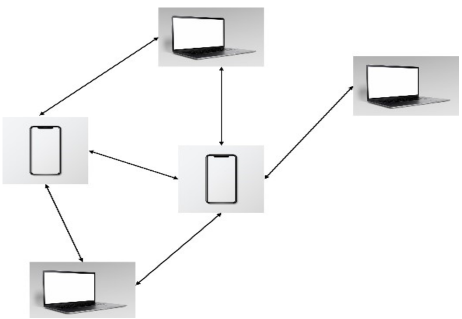
Bandwidth is where channels are divided according to the chosen signal-sending frequency. This division is necessary so that there is no interference between different information sent simultaneously. Wi-Fi is not the only protocol that uses this type of device. Bluetooth also uses channel splitting for communication. Figure 2 shows an example of this division.



Source: data collected by the authors.

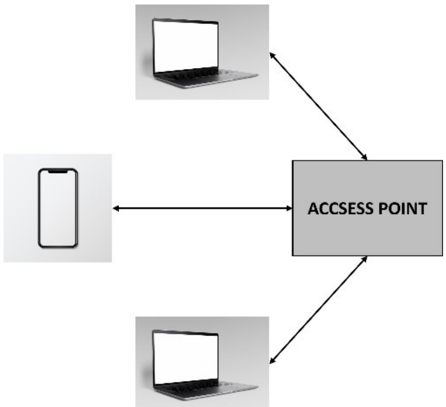
Figure 2. Example of Wi-Fi channels

The architecture of a Wi-Fi network is formed by client devices and an Access Point (AP). There are, however, ways to communicate without using the AP. Wi-Fi networks that do not use an AP are called IBSS (Independent Basic Service Set). When the AP is used, a BSS (Basic Service Set) network is set up, and when connecting one BSS to another through a wired network, for example, an ESS (Extended Service Set) architecture is set up. Figure 3 shows an example of an IBSS network, and Figure 4 shows a BSS network. There are several types found commercially. The Access Point is a device such as a router. Even when developing devices at lower hardware levels, there is no need to worry about implementing the Wi-Fi protocol from scratch. Many manufacturers already provide libraries with the main Wi-Fi functions for the developer to implement.



Source: data collected by the authors.

Figure 3. IBSS Network

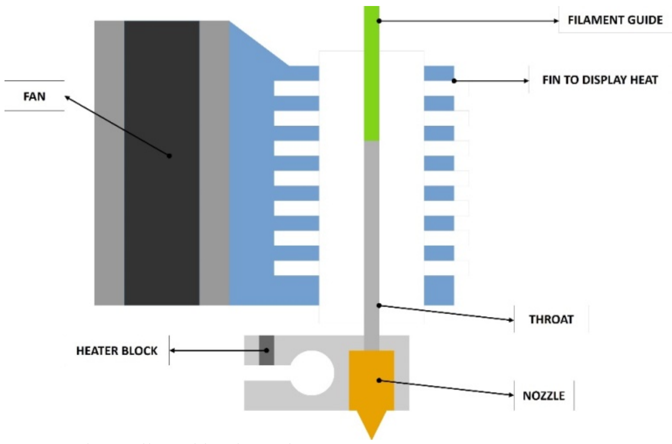


Source: data collected by the authors.

Figure 4. BSS Network

The importance of these types of networks in constructing a digital twin is related to the sending of the message. An object with its characteristics monitored by several sensors must send the current state information to a specific location. The way it is done is through a network. The network, therefore, constitutes the path that the data will take to an endpoint. At this point, the data can be passed on or processed for decision-making. Graphs, tables, or programs can be generated in diverse programming languages. For example, by observing an overheating in part of a specific process through a diagram, a person can decide to stop it. The reverse flow can also occur because a command can come from anywhere on the network if configured.

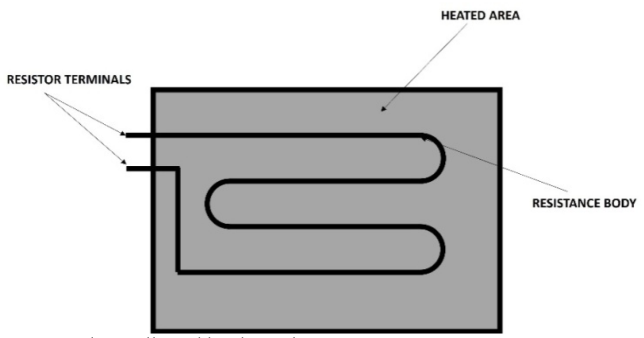
FDM Additive Manufacturing Technology: In contrast to subtractive manufacturing, such as machining materials, there is additive manufacturing. Its basis is the addition of material through various technologies. The most common of these technologies is Fused Deposition Modeling (FDM). It works by extruding a molten material (usually plastic) through a nozzle and depositing the extruded material on the table. The extrusion mechanism is shown in figure 5. Also called "Hotend," this mechanism melts a filament introduced through the guide and passes through the throat until it reaches the heating block. The heater block has a resistance and a temperature sensor that control the temperature. The fin and fan are responsible for ensuring that the filament is heated only in the heater block. If the heat spreads beyond the heater block and nozzle, reaching the throat, the mechanism will likely become clogged, and its functioning will be impaired.



Source: data collected by the authors.

Figure 5. Filamentextrusionmechanism

FDM technology allows the extrusion of a series of materials, some of them: PLA, PETG-G HIPS, ABS, etc. A series of parameters different from each other are required to print (extrude) each of these materials. These parameters range from the temperature the heater block must maintain to the speed at which the material must pass through the mechanism. Sometimes these parameters are discovered empirically. Often, the part to be manufactured must be designed considering aspects of the material.

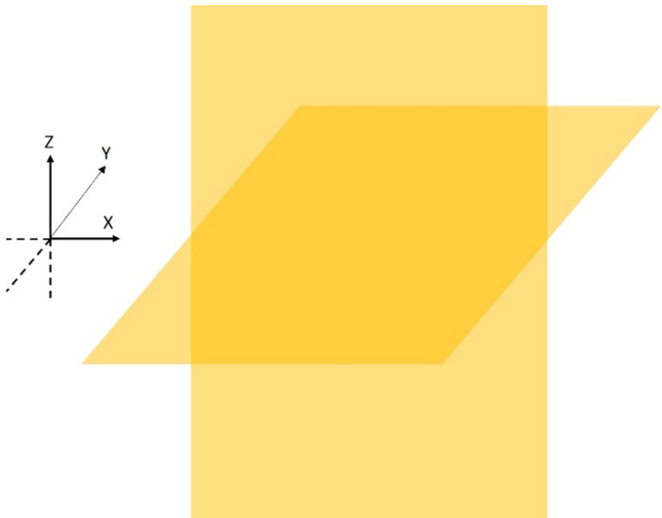


Source: data collected by the authors.

Figure 6. Heated table

Another instrument is also widely used to facilitate the additive manufacturing process. However, some printers do not use it; printing certain materials is considered mandatory. Here we talk about the heated table, a device with an electrical resistance controlled by the printer board. This device allows a better adherence of the material to the table. Figure 6 shows a schematic of the heated table.

Printer Mechanical Configuration: The extrusion mechanism does not allow a machine to make shapes by itself. The mechanism must be coupled to a device to enable movement to the extrusion. This device has axes, belts, and motors for its motion and is controlled by an electronic board. It forms the structure of the 3D printer. The two main structures are Cartesian and Core XY.



Source: data collected by the authors.

Figure 7. Printer Axes

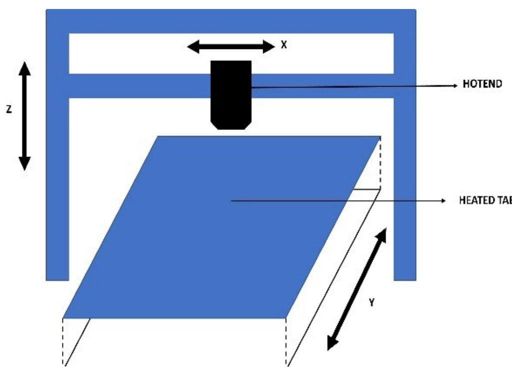
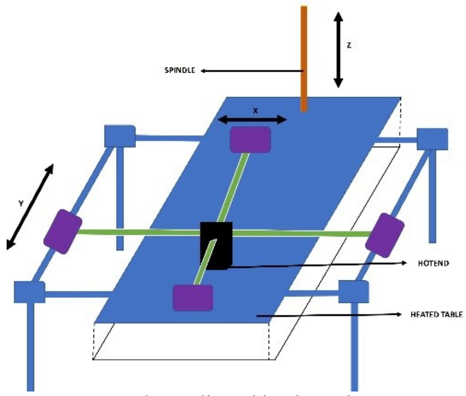


Figure 8. Printer Axes

Printers have benchmarks and are adopted by many manufacturers and enthusiast communities. One of these patterns is the name of printer axes. The three axes are the X, Y, and Z. When viewing the printer from the front, the X and Y axes form the horizontal reference plane of the machine. The X axis is responsible for the left and right movements of the Hotend, and the Y axis for the depth movements. The Z axis is responsible for moving the vertical axis of the printer structure. Figure 7 shows the conventional axes. Note that the heated table is in the XY plane.

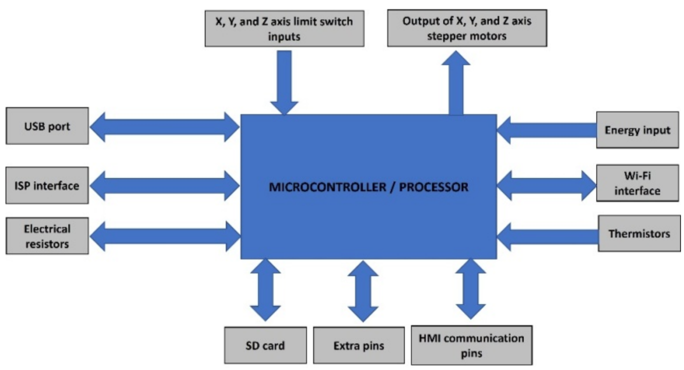


Source: data collected by the authors.

Figure 9. PrinterAxes

The big difference between the Cartesian printer and the Core XY is how the axes movement occurs. The Cartesian printer moves the extruder along the X and Z axes; the table drags along the Y axis. While in the Core XY printer, the extruder is moved along the X and Y axes; the table moves along the Z axis.

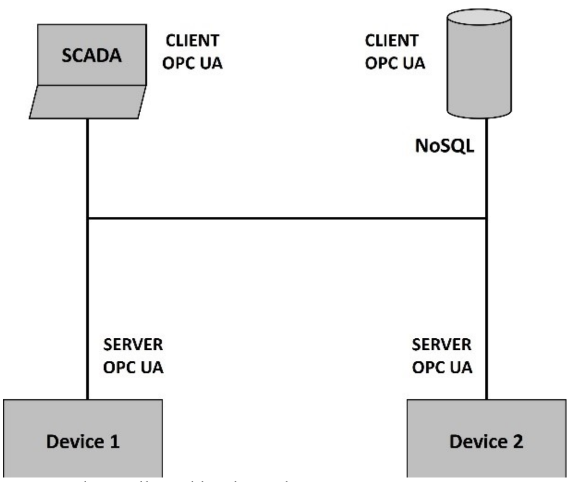
Controller Board: Although the extruder, heated table, and frame are fundamental parts of the 3D printer, they do not perform any function alone. The controller board is responsible for all the information processing in G-code form and turning this into motion. It does this using motors along the structure that are interconnected through drivers. Drivers are electronic circuits that allow lower power boards to control higher power motors. The controller board is also responsible for managing the performance of the heated table and the extruder. Another essential function that the board performs is communication with the outside world. Either through an LCD screen or another output, such as an extension to a Wi-Fi card. LCD is used with HMI (Human Machine Interface). An HMI is a device used for a human being to use a machine more intuitively. Through the HMI, you can interact with the machine by sending or reading the information shown on the screen. Sensor information, current process percentage, and the extruder's positionabout the table or the program line being executed are examples of what may appear on the HMI screen. Figure 10 shows a diagram of the main components of a 3D printer controller board. The arrows indicate the direction of information or, in the case of energy input, the focus of energy. The direction can be unidirectional or bidirectional. When it leaves the microcontroller and enters the device or leaves it and enters, the microcontroller is called unidirectional.



Source: data collected by the authors.

Figure 10. Diagram with the main components of a 3D printer board

There are several on the market, the most common are written with Arduino technology. Arduino is an architecture for prototyping electronic boards that range from the type of microcontroller used to the program written inside the device. The microcontroller or processor is where all the information will be processed, and the machine's algorithm will be executed. The program inside the device is called Firmware and varies according to the device's characteristics or the type of printer structure. Firmware is written based on algorithms written in open source; these algorithms are modified as manufacturers see fit and inserted into their machines. The ISP (In-System-Programmer) interface is used to make firmware updates. Updates are necessary when you want to improve part of the algorithm, for example. Another time you wish to update the software is when you change components for a similar one but with different models. It occurs when you want to change the HMI for another brand. The communication pins of the HMI are responsible for maintaining the communication between the board and the device that serves as HMI. Before installing a new device that serves as an HMI, it must be verified that communication is physically possible. Suppose the board is in a different standard than the one necessary to communicate with the device. In that case, there will be no firmware modifications that allow the integration of the HMI in the printer through the board. The printer's USB port can also be used for external printer communication or board control. The USB port is connected to a computer that sends and receives information from the printer. This information is entered into a programming terminal via G code. It is even possible for a part to be made entirely by automatically sending a G code via the USB port. The most common way to print an object is to insert a G code via an SD card file. This code is generated through a 3D model of the thing to be printed. The model is put into software that uses finite element method math tools and transforms the 3D model into a sequence of G codes that the printer must follow. The printer can also, if so programmed, input data to the SD card, hence the bidirectional flow in figure 10. Another way to interface the 3D printer with the outside world is wireless communication. The board model must have a pinout compatible with another board with Wi-Fi communication. This card with Wi-Fi communication will receive information from the printer's controller card; the Wi-Fi card in turn will send the information to another, such as a computer. The card with Wi-Fi communication must also be programmed with the desired settings. It is also possible for the Wi-Fi card to receive information from an external device and input it to the printer, which enables remote control of 3D printing. The board's power input typically connects to a standard DC source at 12V or 24V. The devices that consume the most power are the heating table resistors, the extruder resistor, and the stepper motors. Both resistors and stepper motors have outputs that control them. For the resistors, there are inputs connected to thermistors; these thermistors allow the reading and control of the temperature. For the motors, there are inputs connected to limit switches; these sensors will enable the motor axes to locate their origin, calibrating the position of the axes when necessary.



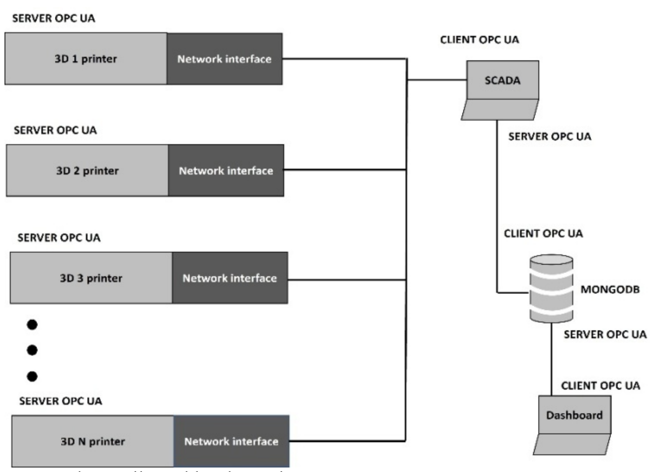
Source: data collected by the authors.

Figure 11. The architecture of an OPC UA network

OPC UA: OPC UA is an open communication protocol based on client/server logic for machine-to-machine communication. The protocol emphasizes communication between machines; its main objective is to communicate between clients and servers. A client device is connected to one or more server devices to exchange communication. It is possible for a device to be both a client on part of one system and a server on another. OPC UA can communicate through XML, a description language designed to transfer shop floor information. Figure 11 shows how an OPC UA network can be set up. Servers request information from the client, and clients respond with information or by acting. A client is not directly linked to another,nor a server to another, even if that link was made physically. For the NoSQL database in Figure 11 to communicate directly with the SCADA system, one of the two should become the other's server. Becoming the other's server would not change the client state of devices 1 and 2.

Mongodb: MongoDB is a NoSQL database, interpreted as "Not Only SQL" (not just SQL); it was first used in 1998 by CalorStrozzi as an open-source relational database with no SQL interface (Kanojia&Tanwani, 2022; Li et al., 2022). NoSQL emerged from the need to optimize the performance of applications when dealing with large volumes of data because the relational model presents difficulties in terms of scalability. In NoSQL databases, information is grouped into a single record without the need to relate multiple tables to obtain information. In addition, within NoSQL, there are some subdivisions according to the way it will be used for data storage. The ease of working with large amounts of data makes MongoDB the ideal tool to support RAMI 4.0 real-time industrial environment data collection frameworks. MongoDB can store one or more distinct databases. Each database comprises one or more collections, andeach can have one or more documents. From the point of view of the industrial area, each line can have several 3D printers. These printers have sensors that generate information in real-time,which can be stored so that they can then be read and analyzed by supervisory systems and MES. These documents are structured JSON and stored in BSON (Binary JSON) format.JSON (JavaScript Object Notation) is a data structure created in javascript, consisting of the attribute/value pattern, similar to arrays. JSON can be an alternative to XML, where it sometimes excels in terms of the speed of reading the stored data.

Architecture: To build a digital twin architecture, you must first know what information to obtain. This information will come from sensors that the IEC 61987 standard will standardize. The printer's sensors can get information such as extruder temperature, heated table temperature, current print nozzle position, and printing percentage. Other information, such as ambient temperature and checking whether the printer is on or off, must be done through a parallel system. At first, however, the information from the printer's G code is enough to create the device's digital twin. Figure 12 shows an example of this architecture.



Source: data collected by the authors.

Figure 12. The architecture of a digital twin network

3D printers send information at predetermined time intervals to network cards (Wi-Fi) that communicate with a SCADA system present locally. The SCADA system connects to the MongoDB database, which stores the information remotely and sends it to a Dashboard. In the Dashboard, the data will be processed following ISO 13584, and the digital twins will appear clearly for decision-making. The entire system is connected through the OPC UA protocol defined by IEC 62451, with the data organized by a description language called AutomationML standardized by the IEC 61987 standard. Finally, to guarantee the issue of real-time visualization of the system, the remote connections must be connected via optical fiber and follow the IEC 61300-4 standard.

CONCLUSION

This study presented a guide for implementing digital twins by the recommendations of the Rami 4.0 architecture. The digital twins allowed the articulation and interconnection of different technologies in a didactic way, with the deliberate intention of letting their implementation in various production processes. This concern is because additive manufacturing tends to continue expanding and being part of the daily life of different types of organizations and their manufacturing systems. Although the company decides to outsource the execution of projects for this purpose, the knowledge that this guide provides will be of great use.

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