Universitat Politècnica de Catalunya

ESEIAAT - Escuela Superior de Ingenierías Industrial, Aeroespacial y Audiovisual de Terrassa

Master thesis

Submitted in partial fulfilment of the requirements for the degree of

Master of Technology and Engineering Management (MEM)

Title:

Study applying simulation to improve a real production process in the context of Industry 4.0

Academic year: 2019/2020

Director: Toni Guasch

Collaborating company: Ratti S.pA.

Submission date: 15/01/2020

Author

Lorenzo Tosini

1. Summary

1. Introduction

Industrial automation and the latest technological innovations have led to ever higher quality standards and shorter production times.

The goal that each company sets is to provide the customer with a customized product, with a high level of quality at minimum cost and with fast delivery times.

To have a competitive advantage over competitors, every company must be flexible and know how to adapt promptly to market changes, respecting time-to-market.

With the need for new paradigms for Industry 4.0, the need arose to create a flexible production system, which was able to create a wide variety of products and in limited volumes. The most frequent problems in this type of system concern the planning of activities and the sizing of the company and resources (Klement N. et al., 2017).

The planning, scheduling, and sequencing phases of production activities can, in some cases, be automated.

At the same time, however, they tend towards continuous improvement: they are continually looking for high levels of quality and efficiency to reduce waste time, and, more generally, the costs related to the company's functions.

If before the strategy involved the creation of stocks of products and raw materials in meeting ever-increasing demand, today, we are more likely to have what is strictly necessary due to the uncertainty of the demand and the possibility of customization of the products by the customers. It can be said that from production for the Make To Stock (MTS) warehouse, we have moved to an Assembly To Order (ATO) production or even Make To Order (MTO). Therefore, if the management system works efficiently, it is possible to produce and purchase quickly only when necessary, allowing for the reduction or elimination of waste. In a sense, we have gone from a push logic to a pull logic.

This ambition involves the constant redesign of the organization, the re-engineering of the processes, and the redefinition of competences and resources, increasing more and more the complexity of the system.

Also, due to the numerous factors of variability and the continuous evolution of the market, it is becoming increasingly difficult to make a decision, evaluate the different scenarios and predict what the behavior of the system will be if there is a change in the variables involved.

Production systems become more and more complex, making it difficult to gauge, balance, and identify its limits.

The digital transformation process involves all business realities, be they large, medium, or small. This transformation deeply reshapes organizations, which, called upon to take up the challenge linked to new technologies, must innovate processes, the management of information flows, and, often, business models. The fourth industrial revolution and its technologies have undoubtedly contributed to this evolution. These have been defined as enabling, as an essential element for new businesses or in general for smart factories.

To cope with the growing complexity of production systems, it is necessary to develop new control procedures, optimization schemes, analysis techniques, and design tools. It is precisely in this respect that companies could benefit from the use of simulation techniques.

1.1 Origin and Contents

During the double degree experience, I was lucky enough to carry out simulation-related subjects for two consecutive years. Its potential immediately struck me, and as soon as the opportunity arose for this thesis, I decided to propose myself. A further motivation was represented by the possibility of dealing with real problems, an experience that will surely give me great support for my future.

The thesis will concern the important Smart4CPPS project in the industry 4.0 sector, with funding from the Lombardy region in collaboration with the Ratti S.p.A. company, a partner of the University of Bergamo. I had the honor of being chosen for this project, helped by the great passion for the subject that I hope will carry on to represent my field of work in the future.

The aim of the thesis is the use of a discrete event simulation for the re-engineering of production processes. The outcome will display general improvement prospects for the Ratti S.p.A. company. My task is the completion of the project in collaboration with the associates of the company using the years of experience of those who have offered to assist me in developing my thesis.

During the thesis development, simulation theories and techniques have been applied to a part of the production process of the Italian company. A simulation model of the finishing department has been developed to outline the automated and manual procedures that are performed in the AS-IS state. What-if scenarios will be then envisioned and simulated to analyze how the production activities could be re-engineered in the light of the new technological advancements, such as the introduction of full traceability.

The thesis was of an experimental nature, giving me the freedom, obviously directed by my coordinators, to propose a personal logic for the development of a real simulation project using more software and touching more subjects. The company in question relied on my skills by providing me with great motivation in the desire to create a concrete improvement. In fact, the company had never carried out such a project.

Specifically, the thesis can be divided into two parts:

- The first theoretical part where the main concepts of industry 4.0 are clarified, which still cause many doubts today. In particular, the enabling technologies, the smart factories, and above all, the influence that the digital twin is having in industrial development with the related implementations have been discussed. The spacial relationship between the digital twin and the simulation will also be highlighted.

- In the second part, instead, the theoretical themes of the simulation matter were treated to provide a solid basis for the study of the project. Great importance was also given to the data analysis phase with which I dealt with stimulating problems — finally, the simulation model project following the steps provided by Law&Kelton.

Part of the thesis is also the R file with the related datasets and the arena model with the related inputs.

2. Industry 4.0

2.1 Overview

We are at the beginning of a revolution that is fundamentally changing the way we live, work, and relate to one another. In its scale, speed, and complexity, what we consider to be the fourth industrial revolution is unlike anything humankind has experienced before.

Consider the unlimited possibilities brought about by having billions of people connected by mobile devices, giving rise to unprecedented processing power, storage capabilities, and knowledge access. Alternatively, think about the staggering confluence of emerging technology breakthroughs, covering wide-ranging fields such as artificial intelligence (AI), robotics, the internet of things (IoT), autonomous vehicles, 3D printing, nanotechnology, biotechnology, materials science, energy storage, and quantum computing, to name a few.

We are witnessing profound shifts across all industries, marked by the emergence of new business models, the disruption of incumbents and the reshaping of production, consumption, transportation and delivery systems, creating new markets and growth opportunities, new products, services, and strategies.

Therefore, companies, especially those that fail to adapt quickly enough to these changes, risk falling behind and not being competitive in a rapidly changing market.

This disruptive process identifies a new paradigm shift concerning the three previous industrial revolutions. In fact, as a result of mechanization (1784), thanks to the use of electricity (1814), we moved on to mass production in the assembly lines (1870), then the automation favored by information technology (1969) and finally today to the merger of the physical world with the virtual one thanks to the cyber-physical production systems (2011).

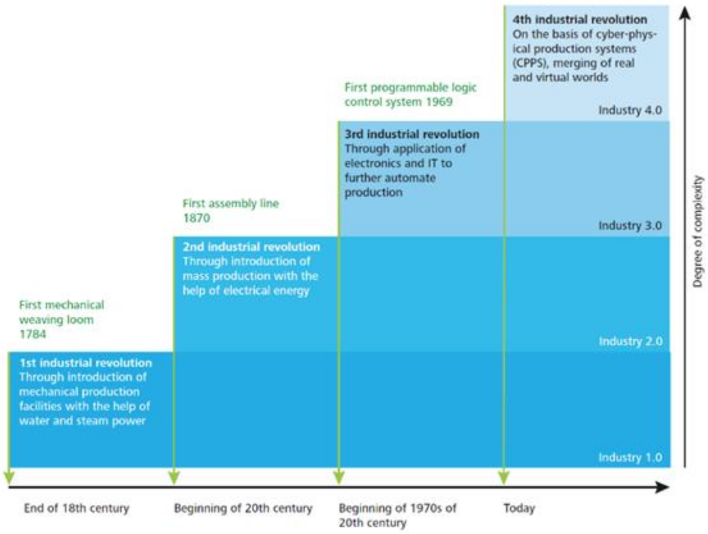


Figure 1

The industrial sector is essential to every country's economy and remains the driver of growth and employment. Industry, which in this context focuses on manufacturing, provides added value through the transformation of materials into products. The term "Industry 4.0" became publicly known in 2011 at the Hannover Fair when an initiative called "Industry 4.0" where an association of representatives from business, politics, and academia began to promote the idea as an approach to strengthening the competitiveness of German manufacturing industry (Mohd Aiman et al., 2016)

The Fourth Industrial Revolution is struggling to spread because, as with the other revolutions, it involves a radical change in society and the relationship with work. Many companies are wary of innovation: for these companies, innovation threatens the stability of a well-established business organization that has enabled growth, development and created vast amounts of profit. Besides, the fear is that robots and machines, as they become increasingly sophisticated and precise, will replace men.

Nevertheless, if specific tasks are no longer necessary, new ones surely will be. The digitalization of enterprises, adding new professional figures necessarily, increases productivity, leading to the expansion of the enterprise itself and the economy. Thus more professionals will be needed in all sectors.

Companies that put the search for innovation at the heart of their business, both in terms of processes and the powerful functions of the business itself, by investing in technology and collaboration between humans and robots will have the most significant competitive advantage in a constantly changing market.
(Min Xu et al., 2018)

2.2 What is Industry 4.0?

Industry 4.0 indicates the emerging industrial paradigm whose focus is on information, codified explicitly as data, and its exploitation through the pervasive use of digital technologies to connect, innovate and govern the entire value chain in manufacturing sectors.[1]

Although there is still no definitive description of the phenomenon, it is often cast as a revolution that will lead to totally automated and interconnected production. [2]

The real added value is linked to how companies create and distribute the right value. The product as a physical object finds a new dimension in the technological field. It is the bearer of information throughout its life cycle. The manufacturing company, for the first time, supports the physical product and offers personalized services, which offer a source of further profitability. Manufacturing goes from being product-oriented to service-oriented, a considerable technological shift with which all companies will have to face in the coming years. (Dr. Andreas H. Glas June et al., 2016)

The innovations introduced will have impacts on:

- management and storage of increasing amounts of data to be accessed (Big Data, Open Data, and Cloud Computing);
- interconnection and communication between objects: this will be achieved through the Internet of Things and appropriate sensors;
- techniques and algorithms that analyze data and information (Analytics);
- development of artificial intelligence techniques, such as machine learning. To date only 1% of the data collected by companies is used by the companies themselves who ignore the advantages that would derive from their analysis;
- human-machine interactions, which were becoming more and more frequent through the use of touch devices and augmented reality. Cobot3 able to work and interact directly with employees;
- the transition from digital to real, allowed by additive manufacturing, robotics, and machine-to-machine interactions (Michael Rüßmann et al., 2015)

Industry 4.0 aims to work with a higher level of automatization to achieve a higher level of operational productivity and efficiency, connecting the physical to the virtual world. It brings proper development for the industrial scenario focusing on creating smart products, smart processes, and smart procedures. Companies are expected to increase the level of digitalization, working together in digital ecosystems with customers and suppliers (V. Alcácer et al., 2018).

Industry 4.0 is a new area where the Internet of things alongside cyber-physical systems interconnect in a way where the combination of software, sensor, processor and communication technology plays a huge role for making "things" to have the potential to feed information into it and eventually adds value to manufacturing processes. Industry 4.0 ultimately aims to construct an open, smart manufacturing platform for industrial-networked information applications. The hope is that it will eventually enable manufacturing firms of all sizes to gain easy and affordable access to modeling and analytical technologies that can be customized to meet their needs (Willliam M. D. 2014).

The industrial manufacturing life cycle becomes orientated towards the increasing individualism of customer requirements and encompasses the idea and the order for development and production, the distribution of products plus recycling, and including all related Services. The interconnection of human beings, objects, and systems lead to dynamic, real-time optimized and self-organized inter-company value creation systems that are evaluated and optimized using criteria such as costs, availability, and resource efficiency. Industry 4.0 emphasizes the idea of consistent digitization and the linking of all productive units in an economy (Mohd Aiman Kamarul Bahrain 2016)

It is possible to summarise then advantages for applying I4.0

- Flexibility: production of small lots at large-scale costs with essential repercussions in terms of customization
- Speed: from the prototyping phase to mass production through innovative technologists that reduce set-up times and accelerate go-to-market times
- Productivity: increased process dynamics and greater operational flexibility and system reconfiguration, with consequent reduction of costs and waste, increased the reliability of production systems and yield quality (reduction of errors, defects, and downtime)
- Integration: supply chains and sub-supply chains through improvements in supply and logistics systems, more efficient warehouse and order management, optimization of relations with suppliers, with the consequent lower conflict of open ecosystems and collaborative
- Safety: improvement of the man-machine interface which leads to a reduction of errors and accidents, and improvement of safety and ergonomics in the workplace
- Sustainability: reduction of energy consumption and use of raw materials, emissions, with a consequent reduction in the environmental impact on the entire product life cycle
- Product innovation: the smart reinterpretation of many products and the development of new service models and market approaches [3]

2.3 Enabling Technologies

A study by Boston Consulting shows that the fourth industrial revolution focuses on the adoption of 9 technologies defined as enabling;

The technologies used to satisfy customers' needs are called enabling technologies because, despite having similar costs to mass production, they allow us to create knowledge, manage it, set the company and the customer in communication, be fast in performance, and produce products. However, these technologies alone are not enough. There is a need for new socio-technical systems, global organizational networks, flexible organizational units and a new conception of culture and ethics (Butera F., 2017).

2.3.1 Big Data And Analytics

Big Data is a "term that describes large volumes of high-speed, complex and variable data, which require advanced techniques for the acquisition, storage, distribution, management and analysis of information" (Babiceanu RF et al., 2016).

The goal is to extract additional information relative to those obtainable from small data sets.

The amount of heterogeneous data, structured and unstructured, generated by the web, mobile devices and apps, social media, machinery, and connected objects grows exponentially: today, this data is counted in terms of zettabytes: 10 ^ 21.

The techniques of big data analytics can provide companies original insights, for example, on the market situation, on the competition, and at the same time on the behavior of the customers and thus how to refine the marketing strategies.

Amazon has taken advantage of this technology to develop "anticipatory shipping" solutions by crossing order histories, wish lists, but also research, reviews, social feedback, blogposts for each customer. In this way, it was able to increase the accuracy in forecasting demand and customer loyalty, while optimizing stocks and deliveries.

Therefore, with Big Data, we refer to a continuous collection of data that would have no value without an accurate analysis. Although data collection was already performed through traditional databases, the concept of BD goes further in terms of volume, speed, and variety of data processed. (*Gandomi A., et at, 2015*).

Various stages in the data lifecycle, where manufacturing data is exploited, are depicted in Fig. 2, consisting of the complete manufacturing data journey.

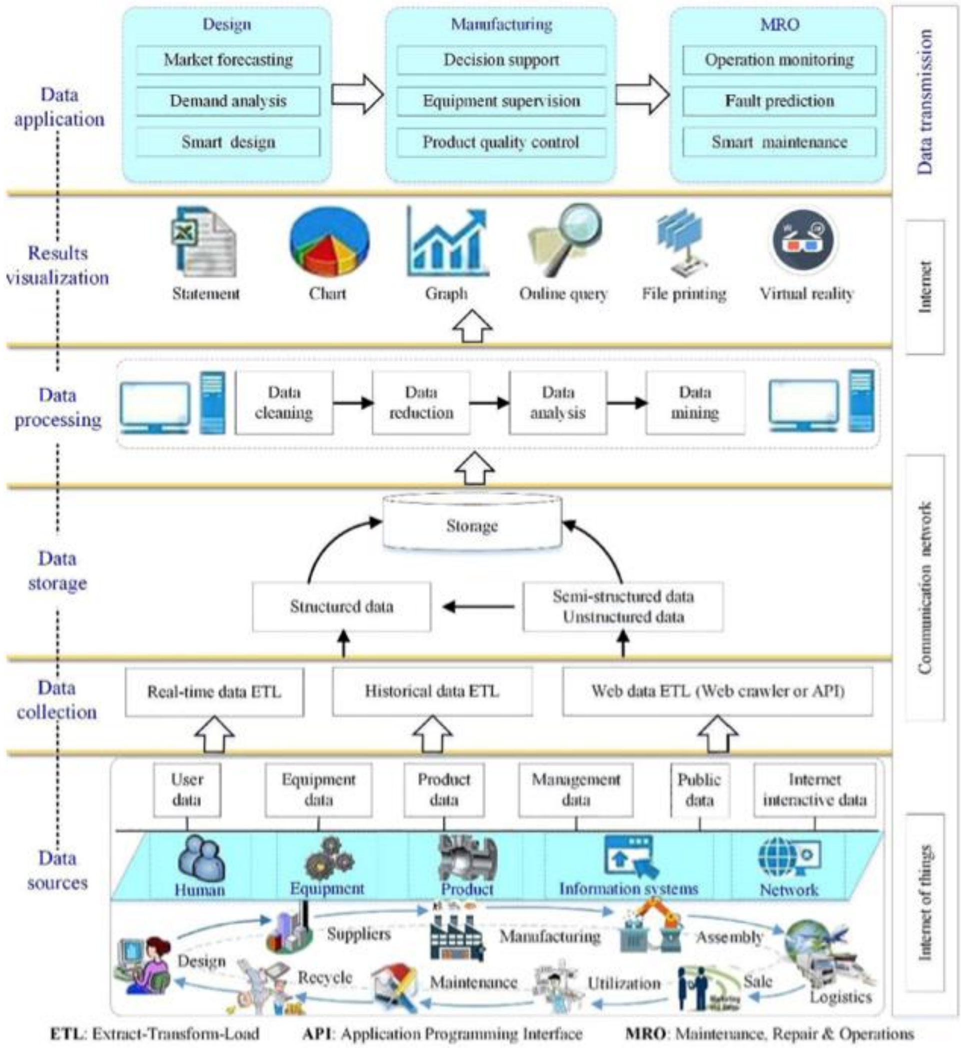


Figure 2

According to Mourtzis et al., in a framework structured according to the processes of a manufacturing enterprise, the lower level generates data directly from machine tools and operators. For an enterprise, this data is crucial, providing valuable information when used and analyzed, enabling adaptivity and flexibility on the higher levels of the enterprise.

BD analytics is key to digital manufacturing, playing a role as an enabler for technologies. Moreover, the possibility of mass customization, which focuses on the needs of individualized markets depends on BD analytics.

Analytics based on large data sets has emerged only recently in the manufacturing world, where it optimizes production quality, saves energy, and improves equipment service. The challenge has shifted from collecting a sufficient amount of data to analyzing and making decisions based on the massive amount of data available. Data analytics (DA) can help understand and gain insights from the big data and, in turn, help advance towards the vision of smart manufacturing.
(Guodong Shao Seung et al., 2014)

In an Industry 4.0 context, the collection and comprehensive evaluation of data from many different sources—production equipment and systems as well as enterprise and customer management systems—will become standard to support real-time decision making.
(Philipp Gerbert et al., 2015)

Unlike many technological fashions, Big Data is not a trend but a management necessity for any organization. Those growing data sets that fill business databases will be the keys to competitiveness, business growth, and innovation gaining in prediction, thanks to a history of information so extensive and punctual to allow simulations much more than likely.

2.3.2 Autonomous Robots

Manufacturers in many industries have long used robots to tackle complex assignments, but robots are evolving for even greater utility. They are becoming more autonomous, flexible, and cooperative. The new robots will be more autonomous, collaborative, and adaptive: they will interact with each other, work in safety side by side with humans and learn from them, they will be able to perform more activities. The robots will be connected or directly to the cloud to gather information and be an active part of the production process.

The robotic agent in a context of industry 4.0, while remaining an automatic machine will be characterized by almost human interactional capabilities: in contact interactions, the sensory and perceptive experience will be very similar to the natural one, while the movements and behaviors of robots will follow "cognitively acceptable" patterns (low speeds, soft trajectories, non-hostile forms, predictable operations, contacts with compliance)

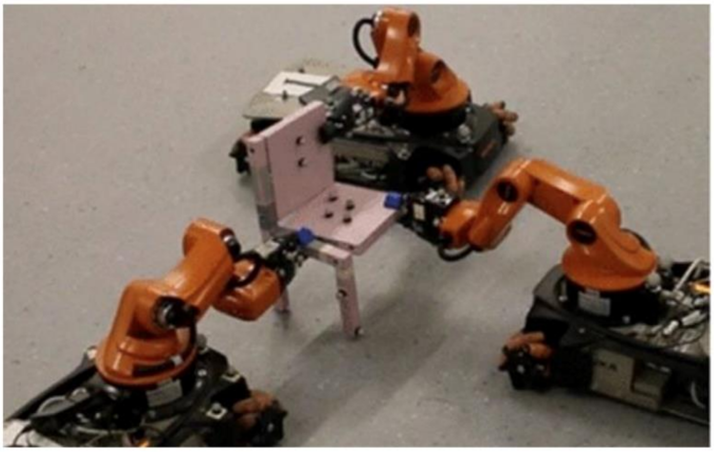


Figure 3

Autonomous vehicles are complex forms of automation and can be used, for example, for handling goods in the factory. They are intrinsically collaborative in that they can interact with other machines, but also with human beings, autonomously reconfiguring their trajectory based on process needs or adapting to the normal flow of workers within the production areas.

In recent years we have heard more and more discussion of the concept of Artificial Intelligence (AI), which is a technology capable of reproducing the typical human behavior and decision-making capacity of human beings in robots through hardware, software, and artificial neural networks. It was through the use of AI that it was possible to create completely autonomous robots able to make decisions in complete autonomy and to carry out activities even in continuously changing environments (Wu Q et al., 2018).

A branch of AI is machine learning, which is closely linked to pattern recognition and computational learning theory. Machine learning focuses on the study and construction of algorithms that can learn from a set of data and make predictions about these, constructing inductively a model based on samples.

Machine learning includes a range of different mechanisms that allow an intelligent machine to improve its capabilities and performance over time. Therefore, the machine will be able to learn to perform specific tasks by improving, through experience, its skills, responses, and functions.

Simulation provides vital insights into system behavior and performance, especially with design optimization and validation. However, there are many instances where simulation or design exploration is not applicable because of limited computational resources. Artificial Intelligence is a promising approach to help reduce the less essential simulation scenarios by studying the existing simulation data.

In many instances, an AI-model is not required to have the same fidelity as an actual simulation model, since most engineers expect the trained AI-model to be better and more consistent than the engineering judgment or simplified models. When there is not a sufficient amount of physical data available, the simulation generates the simulation data to train a reliable AI-model.

This natural extension of simulation can produce behavioural models that answer questions beyond 'what-if?'. The result is sometimes referred to as a knowledge-based simulation.

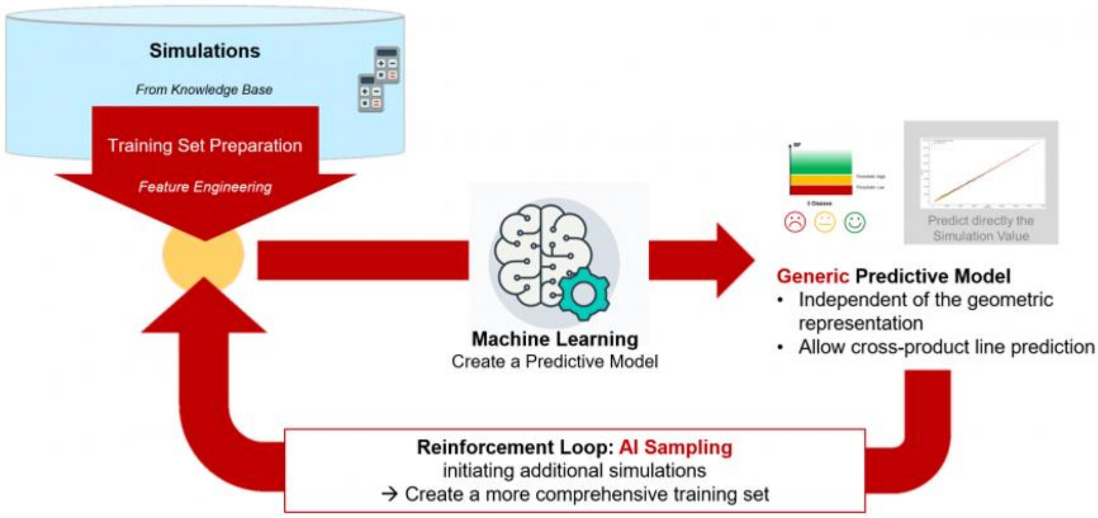


Figure 4

2.3.3 Horizontal And Vertical System Integration

Most of today's IT systems are not fully integrated. Companies, suppliers, and customers are rarely closely linked. Nor are departments such as engineering, production, and service. Functions from the enterprise to the shop floor level are not fully integrated. Even engineering itself—from products to plants to automation—lacks complete integration. However, with Industry 4.0, companies, departments, functions, and capabilities will become much more cohesive, as cross-company, universal data-integration networks evolve and enable truly automated value chains. [4]

The integration of production systems is fundamental to keep the entire production process under control and for the rapid dissemination of information. In this regard, the integration of I4.0 systems can be of two types: vertical and horizontal integration.

By vertical integration, we mean the communication and dissemination of data between the hierarchical levels of the company, which is allowed to collaborate and interact, making the production system faster, more efficient, and reconfigurable. Vertical integration is what underlies a Smart factory (Alcàcer V. et al., 2018).

A factory owns several physical and informational subsystems, such as actuator and sensor, control, production management, manufacturing, and corporate planning. It is essential to vertically integrate actuator and sensor signals across different levels right up to the enterprise resource planning (ERP) level to enable a flexible and reconfigurable manufacturing system. Enacting this integration allows the smart machines to form a self-organized system that can be dynamically reconfigured to adapt to different product types.
(Shiyong Wang et al., 2016)

The Smart Factory stands out because it offers the possibility of an individual and highly customized production based on customer requests. Thus, to guarantee the fulfillment of a variable number of orders and a high number of customizations, vertical integration becomes a distinctive element which allows the independent management and organization of production, but also allows the factory to react quickly to changes in demand, levels of stocks, defects.

Figure 5 a

By horizontal integration, on the other hand, we mean the inter-company integration, which, thanks to the use of information systems, keeps more companies in contact to enrich the knowledge about the product life cycle.

One corporation should both compete and cooperate with many other related corporations. By the inter-corporation horizontal integration, related corporations can form an efficient ecosystem. Information, finance, and material can flow fluently among these corporations. Therefore, new value networks, as well as business models, may emerge.

The horizontal integration, therefore, allows optimizing the entire flow of information and goods that cross the chain, from the supplier to the company, to the final customer.

Transparency within the chain is fundamental in this case; all the actors have free access to information, thus ensuring the absence of the bullwhip effect. Many legal issues arise related to the protection and ownership of the data, so a high level of security and a risk management framework are essential.

(E. Blunck et al., 2017)

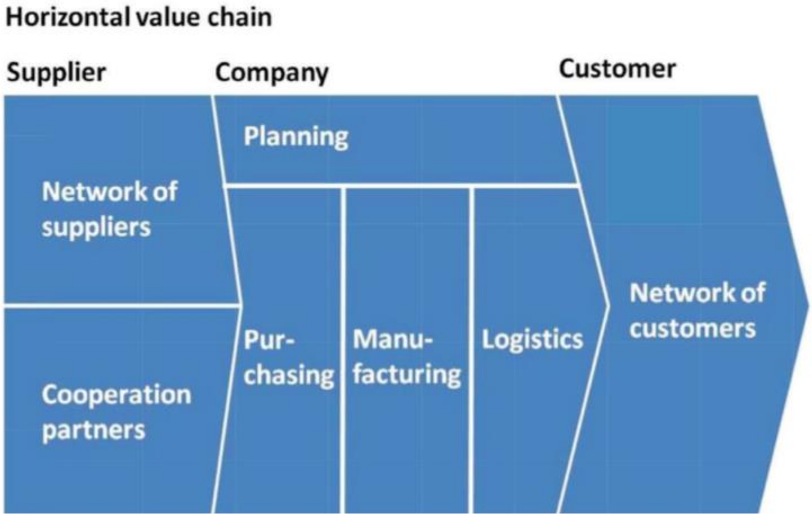


Figure 5 b

End-To-End Engineering Integration

According to several authors, the paradigm of I4.0 in manufacturing systems has another dimension between horizontal and vertical integration, considering the entire product lifecycle.

(T. Stock, 2016)

Product-centric value creation processes involve a chain of activities, including customer requirement expression, product design and development, production planning, production engineering, production, services, maintenance, and recycling. By integration, a continuous and consistent product model can be reused at every stage.

For holistic digital engineering, as the natural flow of a persistent and interactive digital model, the scope of the end-to-end digital integration is on closing gaps between product design and manufacturing and the customer, e.g., from the acquisition of raw material for the manufacturing system, product use, and its end-of-life. The phase of end-of-life product contains reusing, remanufacturing, recovery and disposal, recycling, and the transport between all phases.

(J. Posada et al., 2015)

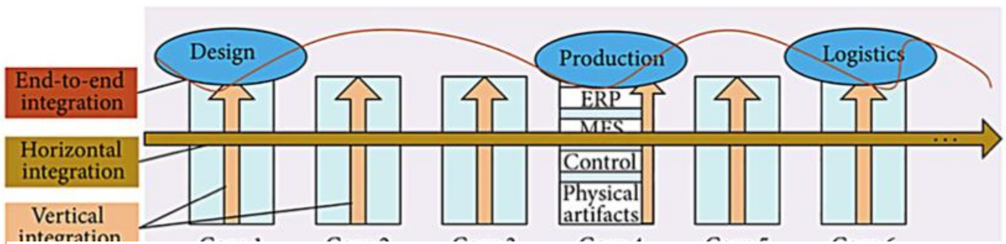


Figure 6

2.3.4 The Industrial Internet Of Things

The miniaturization of measurement and communication technologies (wired or wireless) allows devices (embedded systems) specialized in gathering information, communicating with the outside world, and in some cases, even able to make decisions to be integrated into every physical object autonomously (smart objects). Even objects that are born without such devices can have similar features added.

The Internet of Things (IoT) is the set of physical objects that have the technology to detect and transmit information about their state or external environment through the Internet.

When the Internet of things becomes industrial (Industrial Internet of things ": IIoT), we speak of a set of devices that must interact with each other through existing standards, protocols and technologies together with new technologies and ways of operating.

(S. Madoka er al, 2015)

Figure 7

Even if there is no globally recognized definition of IoT, what the definitions have in common is the idea based on the fact that the first version of the Internet concerned the data created by users while now referring to data created by things. In particular, the Internet of Things can be defined as "an open and complete network of intelligent objects that can self-organize, share information, data, and resources, react and act in the face of situations and changes in the environment" (Madakam et al., 2015). Alarms ring earlier in case of traffic, for example.

"Thing" or "object" can be more precisely understood as categories such as devices, equipment, plants and systems, robust materials and products, machines, and equipment. These connected objects that are the basis of the Internet of things are defined as smart objects and are distinguished by specific properties or functionality. The most important are identification, connection, localization, data processing, and the ability to interact with the external environment.

IoT applications can embrace all human-object activities such as smart home & cities, online-business, smart environment, security & emergencies, smart transportation, smart energy consumption, smart industrial process, and education.

(Alberto Segura et al., 2017)

In a sense, IoT refers to the coding and networking of everyday elements so that everyone can read them and track them on the Internet. For companies, this rapid interconnection and dissemination of information facilitate the management and resolution of problems. (Biddlecombe E., 2009).

The goal is to map the real world through the electronic world by giving a virtual identity to the things and places of the physical environment. Objects and locations with radio frequency identification (Rfid) or QR Codes shall communicate information over the network or to mobile devices.

(M.N.O. Sadiku, 2017)

2.3.5 Cybersecurity

With the increasingly widespread use of the Internet and the need for interconnection between devices, there is an increase in the propagation of new vulnerabilities to which people and companies are constantly subjected. In this regard, the concept of cyber-security was born, a technology capable of preventing and identifying any cyber attacks to protect Internet users' data (Piedrahita et al., 2018).

The secrecy and integrity of data are essential for industrial success, and it is good that only authorized persons have access to it. Cyber attacks can come from external malware or internal sources (Kannus K. and Ilvonen I., 2018).

Given that in the Smart Factory there is a tendency to have an interconnection network between all the activities and the machines, some cyber attacks can even change the product design or tamper with the robot software; this is entire to the disadvantage of the company since it can cause a delay in the launch of a product on the market, the loss of confidence on the part of customers and suppliers and considerable losses in terms of money (Alcácer V. et al., 2019).

If on the one hand, the paradigm of Industry 4.0 requires an openness to the world, to enable the integration between different systems, on the other, it is essential to have strict control of the communication ports to the world to protect themselves from attacks and improper uses of data generated and shared.

Cybersecurity technologies allow IT systems to be protected and, therefore, to avoid or limit damage to these systems and, more generally, to systems that depend on them (such as industrial control systems (ICS)).

Today, thanks to the continuous development of Artificial Intelligence, it is easier to identify possible attacks and offer better protection to users. However, these risks never cease as malware is continuously evolving, as is the technology to combat it.

The cyber-security approach focuses on what and how to prevent a security incident and how to behave in the event of such an incident involving a series of steps (NIST cyber-security framework)

[5]

Figure 8

During the past year, several industrial-equipment vendors have joined forces with cybersecurity companies through partnerships or acquisitions.

[6]

2.3.6 The Cloud

Marston et al. (2011) define Cloud Computing as "an Information Technology service model in which IT services (both hardware and software) are provided on-demand to customers on a self-service network, regardless of device and location."

This technology allows companies many opportunities to improve their business. These include agility, low costs, and the relative safety inherent in remote data storage (Assante D., Castro M., Hamburg I., and Martin S., 2016). Cloud Computing offers different accesses: private, public, hybrid, and community.

Private access means, for example, the cloud of a company, public refers to a data center managed by suppliers and available to public users while the hybrid is a combination of public and private cloud; finally, the cloud community is shared by several organizations that have common interests
(Alcàcer V. et al., 2018).

Cloud computing relies on sharing of resources to achieve coherence and economies of scale.

Thanks to the CC, small and medium enterprises can more easily enter the market, avoiding investing in expensive hardware and software but simply exploiting the services offered by Cloud Computing (Assante D. et al., 2016).

In the area of production, to improve existing production systems, the concept of Cloud Manufacturing was introduced, which allows users to request services throughout the life-cycle of the product: from design to the withdrawal of the exhausted product (Zhang Y., at al Xi D., Yang H., Tao F., Wang Z., 2017). Thanks to this approach, the tendency is to shift the orientation of production towards service with the Cloud Manufacturing stakeholders, suppliers, operators, and consumers in continuous contact and to work together to enable efficient management of the production system.

Using this technology, users connected to a cloud provider can process, store, retrieve programs, and data with a simple internet browser. They can, for example, use remote software not directly installed on their computer and save data to mass storage on-line.

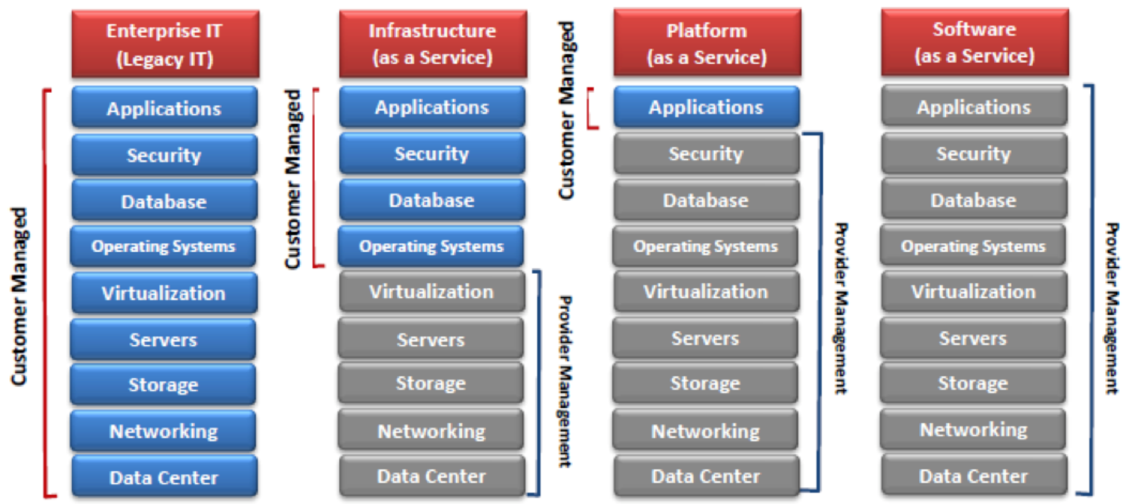


Figure 9

Different forms of Cloud Computing define different service models:

SaaS stands for Software as a Service and corresponds to an application executed on the infrastructure of a supplier and is recognized as a service. The consumer does not necessarily have an awareness of the infrastructure and its complexity but pays to use a service based on its use.

PaaS stands for Platform as a Service acts as a facilitator for the development of applications without the need to purchase and manage internal servers and software. The platform provides programming languages, libraries, and dedicated services developed by the provider; in this way, the customer can reduce fixed costs, while the provider does scale.

IaaS stands for Infrastructure as a Service, real outsourcing of resources in terms of space, network, and computational power.

CaaS stands for Container as a Service, an online container virtualization service. The cloud service provider allows the user to develop software in application containers, then subsequently execute them, test them, and distribute them using ad hoc IT infrastructures.

(Ch Chakradhara Rao et al., 2013)

2.3.7 Additive Manufacturing

Additive Manufacturing means all those technologies through which three-dimensional objects can be created by generating and adding together successive layers of materials. This represents an alternative to traditional processes, in which the objects are made purely by welding different components or by removing material through the use of computerized Numerical Control (NC) machine tools such as milling machines, lathes, presses, machining centers, etc. (Soppelsa M., 2015).

Companies have just begun to adopt additive manufacturing, such as 3-D printing, which they use mostly to prototype and produce individual components.

The main advantages deriving from the use of this technology are the possibility of product customization, the production of parts directly from CAD files, the production of complex geometries that would not be achievable with traditional techniques, the creation of hollow parts, the maximization of use of materials with consequent minimization of waste, lower operating costs for production and the possibility of making changes even during the production phase (Tofail et al., 2018).

High-performance, decentralized additive manufacturing systems will reduce transport distances and stock on hand.

For instance, aerospace companies are already using additive manufacturing to apply new designs that reduce aircraft weight, lowering their expenses for raw materials such as titanium.

2.3.8 Augmented Reality

The term Augmented Reality indicates a series of elements and tools that allow a man to increase his knowledge and to have specific information for carrying out a specific task. AR technology increases the perception of the operator's reality, thanks to the use of false information related to the surrounding environment (Palmarini R., Ahmet Erkoyuncu J., Roy R., 2017).

New challenges are coming with Augmented Reality (AR) usage every day. Applied to industry, AR aim to improve human performance, supplying the needed information to complete given tasks.

Augmented-reality-based systems support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices. These systems are currently in their infancy, but in the future, companies will make much broader use of augmented reality to provide workers with real-time information to improve decision making and work procedures.

(Riccardo Palmarini, et al., 2017)

For example, workers may receive repair instructions on how to replace a particular part as they are looking at the actual system needing repair. This information may be displayed directly in workers' field of sight using devices such as augmented-reality glasses.

(L. Rentzos, et al., 2013)

Another application is virtual training. Siemens has developed a virtual plant-operator training module for its Comos software that uses a realistic, data-based 3-D environment with augmented-reality glasses to training plant personnel to handle emergencies. In this virtual world, operators can learn to interact with machines by clicking on a cyber representation. They also can change parameters and retrieve operational data and maintenance instructions.

[7]

2.3.9 The Simulation

Simulation is a technique that is implemented to conduct experiments on a computer to monitor the behavior of a production system over time. In recent years it is becoming the most used technology to better understand the dynamics of business systems (Rodi B., 2017).

A system can be defined as a set of objects or entities that interact to reach a specified objective. The state of a system can be defined as the minimum set of necessary variables to characterize or describe all those aspects of interest of the system in a specific instant of time.

(D. Rossetti, 2015)

In general, we are talking about simulation both when a concrete model is used and when an abstract model is used, which reproduces reality through the use of the computer. An example of a concrete model is the scale model of a ship, which is then placed in a particular container to perform simulated tests to estimate appropriate performance measures. It is clear that there are theoretical laws of physics from which to obtain information on the performance of the ship, but analysis of these laws is often too complicated to be carried out; of course, it can also be impracticable (or at least not convenient) given the need for the actual construction of the ship and direct testing at sea.

Within Operative Research, the simulation uses abstract models that are built to "replicate," the features of a system. It plays a significant role, especially in designing a stochastic system and in defining its operating procedures: the functioning of a system is "simulated" using probability distributions to generate system events randomly, and from the simulated system, you get statistical observations on system performance. Of course, for this to be achieved, it is necessary to construct a simulation model, which allows describing the operations of a system and how they must be simulated. The crucial aspects that make the simulation a widely used instrument are

linked to the fact that it allows representing real and complex systems taking into account also the sources of uncertainty;
(M. Roma, 2015)

Thanks to this technology, it is possible to reproduce the real production system and see how it reacts to changing processing parameters. It, therefore, allows finding solutions to complex problems that could not be solved with traditional mathematical models. (Alcàcer V. et al., 2019).

These simulations will leverage real-time data to mirror the physical world in a virtual model, which can include machines, products, and humans. This allows operators to test and optimize the machine settings for the next product in line in the virtual world before the physical changeover, thereby driving down machine setup times and increasing quality.
(Philipp Gerbert et al., 2015)

Simulations are of great importance as they prevent catastrophic failures in the system due to the impact of a change. New changes, procedures, information flows, etc. can be examined without interrupting the smooth working of real systems. A simulation model is developed to study the working of a system as it evolves. A fully developed and validated model can answer a variety of questions about real systems.

(P Sharma, 2016)

On the other hand, it should always be borne in mind that while simulation guides the behavior of the system, it does not determine the exact “responses”; analysis of the output of a simulation may be complicated, and it may be challenging to determine the best configuration; The implementation of a simulation model may be laborious and also, high computation times may be necessary to perform a meaningful simulation.

Simulation is a very flexible tool: it can be applied to study most existing systems, and it is impossible to enumerate all the specific areas in which it is used. As examples, here are just a few essential typical categories of applications where simulation is used:

• Design and definition of the operating procedures of a service system.

• Management of stock systems.

• Design and definition of operating procedures for production systems.

• Design and operation of distribution systems.

• Analysis of financial risks.

• Management of projects.

(Franco Landriscina, 2014)

2.4 The Smart Factory

The framework of the I4.0 is the development of the Smart Factory (SF). In conceptual terms, SF is the heart of I4.0. CPS, IoT, and IoS have also been discussed as the main components of I4.0.

These components are very closely linked to each other, enabling the SF. They are built on the concept of a decentralized production system with a social network connecting persons, machines, and resources.
(E. Hofmann et al., 2017)

Using cloud-based manufacturing in SF, both IoT and CPS technologies converge to the IoS to create, publish, and share the manufacturing processes, represented as services that could be supplied by virtual enterprises.
(F. Pérez et al., 2015)

2.4.1 Cyber-Physical Systems

CPS is the merger of ‘‘cyber” as electric and electronic systems with ‘‘physical” things. The ‘‘cyber component” allows the ‘‘physical component” (such as mechanical systems) to interact with the physical world by creating a virtual copy of it. This virtual copy will include the ‘‘physical component” of the CPS (i.e., a cyber- representation) through the digitalization of data and information. By this, CPS can be assumed as a range of transformative technologies to manage interconnected computational and physical capabilities.
(A.J.C. Trappey et al., 2016)

In other words, the CPS core is the embedded system that processes information about the physical environment. This embedded system will perform tasks that are processed by dedicated computers. The CPS model can be described as a control unit with one or more microcontrollers, controlling sensors and actuators that interacts with the real world and processes the collected data.
(P. Bocciarelli et al., 2017)

To sum up, CPSs are systems featuring a tight combination of and coordination between network systems and physical systems. By organic integration and in-depth collaboration of computation, communications, and control (known as the ‘‘3C”) technology, they can realize the real-time sensing, dynamic control, and information services of large engineering systems. (Yang Liu, et al, 2017)

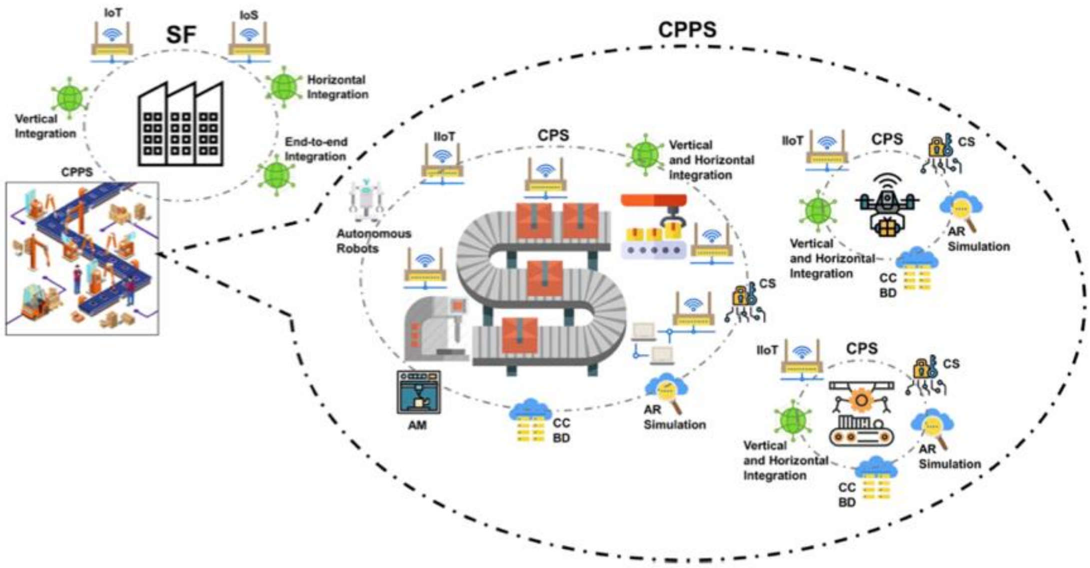


Figure 10

Referring to a manufacturing system and according to Keil, Fig. 10 shows a schematic representation of a CPS, an embedded system integrated into physical systems such as production lots or machines. The sensors collect physical data, and the electronic hardware and software will save and analyse it. The interaction between data processing and other physical or digital systems is the CPS bases.

Several CPSs linked within digital networks form a Cyber-Physical Production System (CPPS), based on sub-systems and autonomous and cooperative elements linked across all levels of production. According to Rojas et al., CPSs are the building blocks for the SF, structured as CPPS.

(A. Humayed et al., 2017)

2.4.2 Automation pyramid evolution

The implementation of CPPS in SF leads to a fundamental design principle as real-time management in industrial production scenarios. CPPS will make the automation pyramid approach differently.

(E. Hozdić. et al., 2015)

The classical automation pyramid paradigm is a striking example of the different levels of automation in a factory or industry. It also serves as a visual example of how technology communicates and how it is being integrated into the industry.

[8]

The traditional pyramid, as shown in Fig. x is partly broken at the PLC's level. The field level and control remain, including the closest PLCs of the technical processes, to improve critical control loops, and the highest levels of the hierarchy will be decentralized.

The idea of decentralized automation faces the challenges encountered by production industries, such as rapid production changing conditions, increased product variants, reduced batch sizes, decreased product life cycles, etc. Thus, the use of decentralized automation systems helps in achieving increased flexibility, higher efficiency, and overall adaptability in automation systems.
(Rainer Müller et al., 2016)

The traditional concept is collapsing into Cyber-Physical System (CPS) based automation.

The automation pyramid was theorized in the 1980s when comprehensive control software was practically unheard of. Today, however, this software is becoming ubiquitous to the operation of manufacturing facilities.

Starting from process and field levels, working up to the corporate level of manufacturing processes, the traditional pyramid illustrates how devices, actuators, and sensors on the factory floor are distinct and separate from other areas, such as process control, supervisory networks and enterprise systems.

Manufacturers are widely practicing IT/OT convergence to integrate enterprise systems, such as Enterprise Resource Planning (ERP) and Customer Relationship Management (CRM) applications, with operational technology like MES and SCADA systems.

Traditionally, these areas have remained separate layers of the pyramid, but their ability to influence a company's performance means it makes business sense to allow these layers to communicate and inform one another.

The traditional automation pyramid does not allow for fluid communication between its different levels; importantly, the control level as it might be possible today.

[9]

In the CPS-based Automation of the Fig. 11a, the squares represent input/output devices, the lines represent service interactions, and the colored points represent the corresponding functionalities of the five-layer architecture of the traditional automation pyramid.

(R. Harrison et al., 2016)

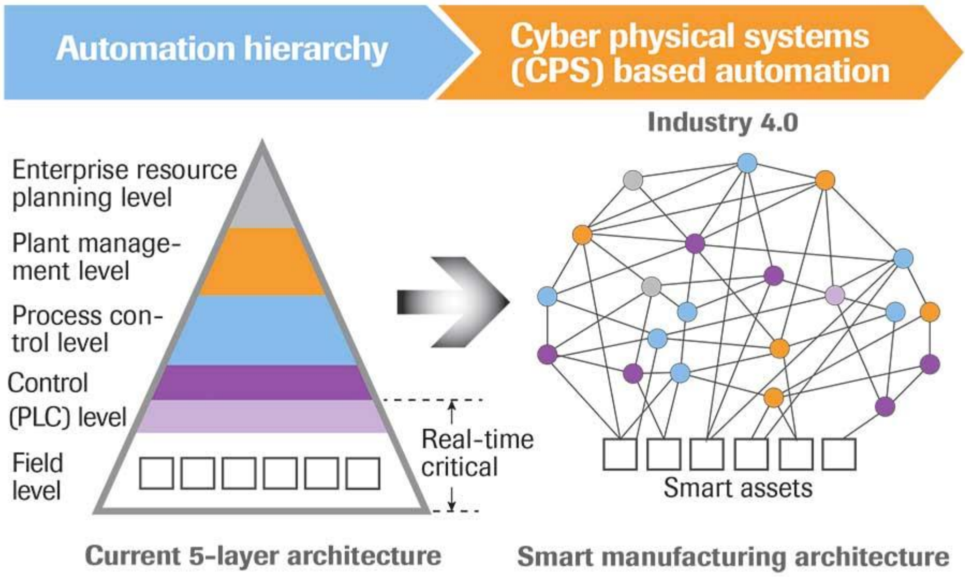


Figure 11 a

The five technological levels that take part in this evolution are:

Field level

These are the devices, actuators, and sensors that you see in the field or on the production floor that do the physical work and monitoring. Thee include electric motors, hydraulic and pneumatic actuators to move machinery, proximity switches used to detect that movement or specific materials, photoelectric switches that detect similar things will all play a part in the field level.

Control level

This includes logical devices such as PCs, PLCs, PIDs, etc. The control level uses these devices to control and “run” the devices at the field level that do the physical work. They take in information from all of the sensors, switches, and other input devices to make decisions on what outputs to turn on to complete the scheduled task.

A PID is usually integrated into the PLC and stands for proportional–integral–derivative. That is what can keep a variable within a set of parameters.

A conventional industrial PID controlled item is a heater. Many systems in manufacturing plants have to be heated. We control this with a PID block within the PLC. When a set point is entered, the PID will determine when the PLC needs to turn the heater on and off to maintain a constant temperature.

Supervisory level

This corresponds to supervisory control and data acquisition (SCADA) that is essentially the combination of the previous levels used to access data and control multiple systems from a single location, and it is not limited to a single machine. It also usually adds a graphical user interface, or an HMI, to control functions remotely.

Planning level

This level utilizes a computer management system known as MES or manufacturing execution system. MES monitors the entire manufacturing process in a plant or factory from the raw materials to the finished product. This allows management to see exactly what is happening and allows them to make decisions based on that information. They can adjust raw material orders or shipment plans based on real data received from the systems we talked about earlier.

Management level

This level uses the companies integrated management system, which is known as the ERP or enterprise resource planning. This is where a company's top management can see and control their operations. ERP is usually a suite of different computer applications that can see everything going on inside a company. It utilizes all of the technology of the previous level plus some more software to accomplish this level of integration.

[10]

While MES tends above all to collect and summarize information in the various management areas (administration, production, etc.), an ERP is an integral part of the organizational flows of the company: it controls them, manages them and also proposes what to do and when it is advisable to perform certain activities. An ERP is able, for example, to propose what and when to buy, from which suppliers, and what and when to launch into production. To do this, ERP uses much more information.

The integration of the ERP promotes efficiency and transparency within a company by keeping everyone on the same page.

A further feature that distinguishes ERPs from MES lies in the ability to offer at the same time greater flexibility of configuration to adapt to company flows and, at the same time, a structure that already contains "best practices" and organizational models.

[11]

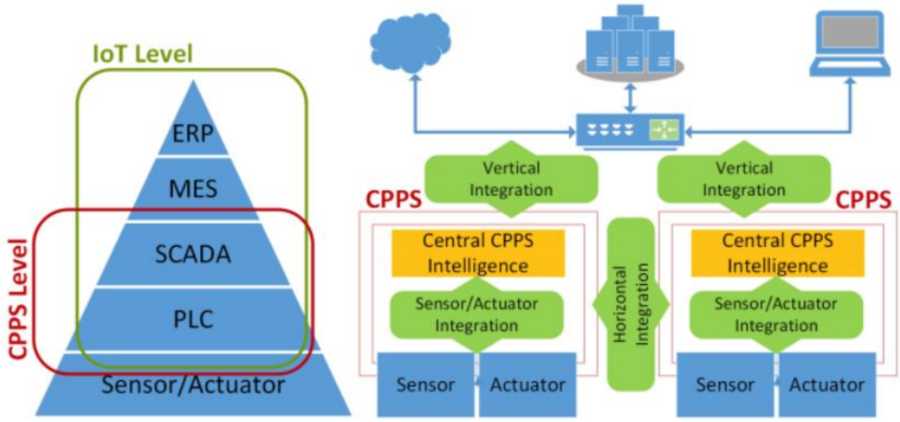


Figure 11 b

2.4.3 Internet of Services

Replacing physical things by services, the Internet of Services (IoS) is based on the concept that services are available through the internet so that private users and/or companies can create, combine and offer new kinds of value-added services.

(E. Hofmann et al., 2017)

IoS can enable service vendors to offer their services on the internet. Thus, the manufacturing industry trend of thinking in terms of product is rapidly shifting in favor of a service-oriented approach to enable gaining revenue through all lifecycle of a product-service system. By this, the high quality of products can be enabled by SoA, and side-by-side gives a strong competitive position for companies through the value-added service.

(M. Andulkar et al., 2018)

Service-oriented architecture (SOA) generally indicates a software architecture suitable for supporting the use of Web services to guarantee interoperability between different systems to allow the use of individual applications as components of the business process and to satisfy users' requests in an integrated and transparent way.

(Liang-Jie et al., 2007)

IoS enables collecting product information, e.g., during its operation, for updates, and the development of new services, increasing the perceived product quality. IoS is considered as the technology to monitor the product lifecycle.

(M. Andulkar et al., 2018)

3. The Digital Twin

With the advent of Industry 4.0 and the consequent introduction of new technologies within the factory, a profound change in the structure of the production facilities is taking place thanks to the simulation technologies.

At the base of the simulation, there is, therefore, a model that describes all the characteristics and behaviors of the system and reacts precisely in the same way as the real system, allowing it to be studied and analyzed.

In this context, a new paradigm is introduced, the Digital Twin, which aims to realize what the Fourth Industrial Revolution seeks to achieve.

The creation of digital twins or virtual duplicates of machinery, processes, activities, and people simplifies interfacing with the digital counterpart. Above all, it centralizes information in a unique tool, capable of analyzing all information flows and facilitating management decision-making activities. The process becomes top-down: the product is firstborn digitally and then concretely materialized.

Its content is essential during all life cycle stages and within different types of platforms and tools, from engineering to after-sales services.

The DT, as a connected set of simulation models and systems, can exploit data to provide adequate responses to business requests and lead to improvements not only from an economic point of view but also from an organizational one.

3.1 Background

The term digital twin is entirely new and was first brought to the public by Shafto et al. (2010, 2012; Schroeder et al., 2016, p. 13) However, ideas very similar to the digital twin had already been developed in the early 2000s

Wong et al. (2002) introduce the concept of an original product and examine the effects on its lifecycle. They define an original product as having at least some of the following characteristics:

1. Unique identity
2. Ability to communicate with its environment
3. Can retain or store data about itself
4. It can express its features, production requirements, etc.
5. A capability of participating in or making decisions relevant to its destiny

Wong et al. define software agents as “a distinct software process, which can reason independently, and can react to change induced upon it by other agents and its environment, and can cooperate with other agents.” The figure shows an example of the tagged jar sauce. The tag is used to link products through a local or remote network to information about itself as well as its software agent. (Wong et al., 2002)

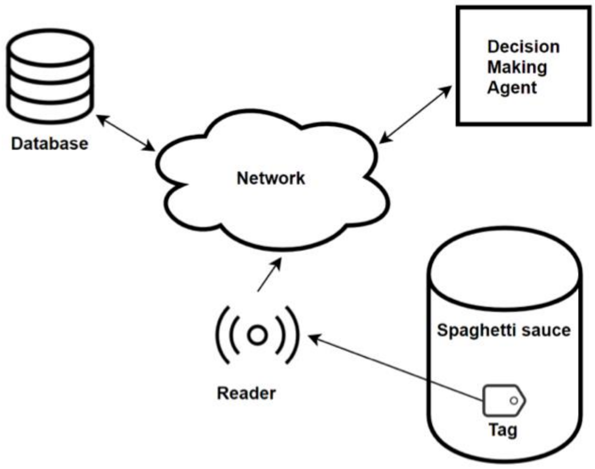


Figure 12

Figure 12. The original product is identified with an RFID tag, after which it can be linked to the information about itself and its software agent. In a digital twin concept, there is bi-directional communication between the physical and digital twin. (Wong et al., 2002, p. 2).

The concept of the Digital Twin dates back to a University of Michigan presentation to the industry in 2002 for the formation of a Product Lifecycle Management (PLM) center. The presentation slide, as shown in Fig. 13 was simply called "Conceptual Ideal for PLM." However, it did have all the elements of the DigitalTwin: real space, virtual space, the link for data flow from real space to virtual space, the link for information flow from virtual space to real space, and virtual sub-spaces.

(Michael Grieves et al., 2018)

At the time this concept was introduced, digital representations of actual physical products were relatively new and immature. In addition, the information being collected about the physical product as it was being produced was limited, manually collected, and mostly paper-based.

(Michael Grieves, 2015)

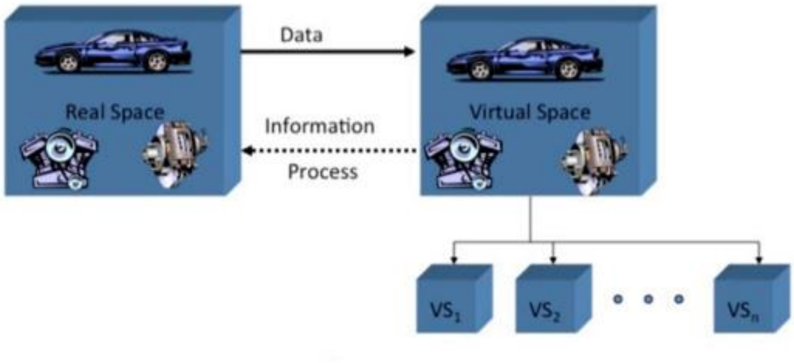


Figure 13

Conceptual ideal for PLM. Dr. Michael Grieves, University of Michigan, Lurie Engineering Center, Dec 3, 2002

Hribernik et al. (2005) use the above definition by Wong et al. (2002) to describe the properties of the Product Avatar concept. Each product has a digital counterpart called Avatar in virtual reality. Avatar is capable of autonomous decision-making and is an individual object itself. A Product-Centric Approach (Hribernik et al., 2005, 2006) (Figure 14a) is proposed to manage product-related information in which the product itself manages and acts as a link between the information relevant to itself. In the traditional approach (Figure 14b), information is stored by private parties and therefore is not easily accessible. Access to data collected during the product lifecycle allows the optimization of, for example, operation, maintenance, and repair.

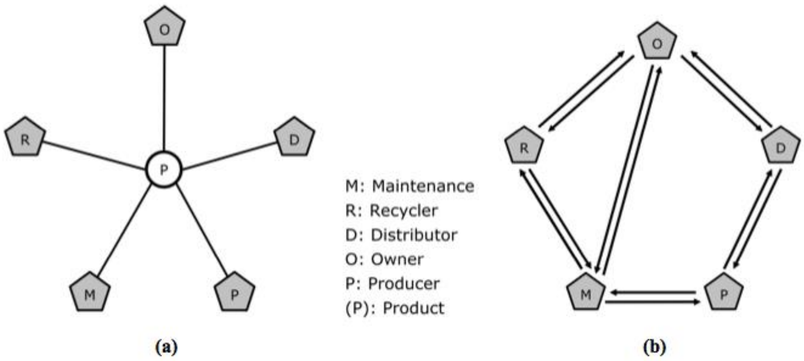


Figure 14

Figure 14. Relationships between actors in the Product Life-cycle with Product-Centric Approach (a) vs. traditional approach (b) (Hribernik et al., 2005, pp. 2–3)

Grieves (2005) introduces the Mirrored Spaces Model (MSM). Objects in the virtual space are linked to their physical counterparts in the real space and mirror their state. MSM enables the product lifecycle management by making the product data available throughout its lifecycle. MSM was first renamed as IMM (Information Mirroring

Model) and later as Digital Twin (Grieves & Vickers, 2017, pp. 93–94).

In the decade that has followed, the information technology supporting both the development and maintenance of the virtual product and the design and manufacture of the physical product has exploded.

Virtual products are rich representations of products that are virtually indistinguishable from their physical counterparts. The rise of Manufacturing Execution Systems on the factory floor has resulted in a wealth of data collected and maintained on the production and form of physical products. Besides, this collection has progressed from being manually collected and paper-based to being digital and being collected by a wide variety of physical non-destructive sensing technologies, including sensors and gauges, Coordinate Measuring Machines, lasers, vision systems, and white light scanning.

Grieves is generally considered as the creator of the concept of a digital twin, even though Shafto et al. (2010) first presented the term digital twin.

Here some definitions of digital twins used in the existing literature:

Table 1

Definition	**Authors**
An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin	Shafto et al. (2010)
"Ultrahigh fidelity model of an individual aircraft", which is "ultrarealistic in geometric detail, including manufacturing anomalies, and in material details, including the statistical microstructure level"	Tuegel et al. (2011)
A tail number specific cradle-to-grave ultra-realistic as-built and maintained a computational model of an individual aircraft. "An integrated collection of submodels."	Tuegel (2012)
A cradle-to-grave model of an aircraft structure's ability to meet mission requirements, including submodels of the electronics, the flight controls, the propulsion system, and other subsystems	Gockel et al. 2012
"An integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc. to mirror the life of its corresponding flying twin."	Glaessgen & Stargel (2012)
A coupled model of the real machine that operates in the cloud platform and simulates the health condition, which can continuously record and track machine condition during the utilization stage	Lee et al. 2013
"Digital equivalent to a physical product"	Grieves (2014)

A high-fidelity structural model that incorporates fatigue damage and presents a fairly complete digital counterpart of the actual structural system of interest."	Bazilevs et al. (2015)
"'As-built' digital structure of a physical product."	Rios et al. (2015)
Very realistic models of the current state of the process and their behavior in interaction with their environment in the real world	Rosen et al. 2015
Ultra-realistic multi-physical computational models associated with each unique aircraft and combined with known flight histories	Bielefeldt et al. 2015
"The Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physically manufactured product can be obtained from its Digital Twin."	Grieves & Vickers (2016)
An ultra-high fidelity simulation integrating previously separated structural models	Gabor et al. (2016)
Virtual substitutes of real-world objects consisting of virtual representations and communication capabilities making up smart objects acting as intelligent nodes inside the internet of things and services	Schluse et al. 2016
A virtual representation of a real product in the context of Cyber-Physical Systems, which can monitor and control the physical entity, while the physical entity can send data to update its virtual model	Schroeder et al 2016
An integrated multi-physics, multi-scale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin	Kraft 2016
A unified system model that can coordinate architecture, mechanical, electrical, software, verification, and other discipline-specific models across the system lifecycle, federating models in multiple vendor tools and configuration-controlled repositories	Bajaj et al. 2016
A comprehensive physical and functional description of a component, product or system, which includes more or less all information which could be useful in all the current and subsequent lifecycle phases.	Boschert & Rosen (2016)
"A digital replica of additive manufacturing hardware", which integrates models for temperature, microstructure and properties, and residual stresses and distortion	DebRoy et al. (2017)
"Sophisticated virtual product model" with "a bi-directional relation between a physical artifact and the set of its virtual models"	Schleich et al. (2017)
"An exact cyber copy of a physical system that truly represents all of its functionalities."	Alam & El Saddik (2017)
"Virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time	Negri et al. (2017)

synchronization of the sensed data coming from the field”	
“Using a digital copy of the physical system to perform real-time optimization”	Söderberg, R., Wärmefjord, K., Carlson, J. S., & Lindkvist, L. (2017)
"A digital twin is a real-time digital replica of a physical device"	Bacchiega (2017)
“An integrated multi-physics, multi-scale, and probabilistic simulation of a complex product that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin.”	Tao et al. (2018)
“digital twin is a real mapping of all components in the product life cycle using physical data, virtual data and interaction data between them”	Tao, Sui, Liu, Qi, Zhang, Song, Guo, Lu & Nee, (2018)
“a dynamic virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding, learning, and reasoning”	Bolton, McColl-Kennedy, Cheung, Gallen, Orsingher, Witell & Zaki, (2018)
"A digital twin is a digital replica of a living or non-living physical entity. By bridging the physical and the virtual world, data is transmitted seamlessly allowing the virtual entity to exist simultaneously with the physical entity."	El Saddik, A. (2018)
In the context of Digital Built Britain, a digital twin is “a realistic digital representation of assets, processes or systems in the built or natural environment”	The Gemini Principles (2018)

While the terminology may have changed over the years, the concept of creating a digital and physical twin as one entity has remained the same since its emergence. While it is commonly thought to have been developed in 2002, digital twin technology itself has been practiced as a concept since the 1960s. NASA used basic twinning ideas during this period for space programming. They did this by creating physically duplicated systems at ground level to match the systems in space. An example is when NASA developed a digital twin to assess and simulate conditions on board Apollo 13.

After the launch of Apollo 13 in April 1970, no one could have predicted it would become a fight for survival as the oxygen tanks exploded early into the mission. It became an important rescue mission with technical issues needing to be resolved from up to 200,000 miles away. A key to the rescue mission, however, was that NASA had a digital twin model of Apollo 13 on earth, which allowed engineers to test possible solutions from ground level. Of course, systems have now become predominantly virtual rather than physical simulations.

[12]

The digital twin paradigm has been applied in the NASA U.S. Air Force Vehicles project where it was defined as, " A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."

From the publication of NASA, three main functions of the Digital Twin can be summed up:

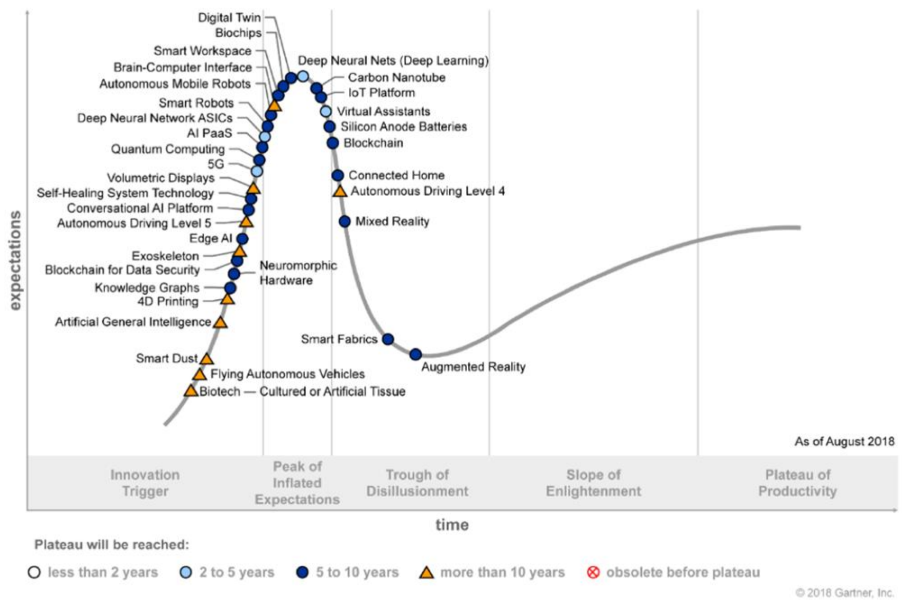
1. Prediction – execution of studies ahead of the system run
2. Safety – monitoring and control of the system state in terms of a continuous prediction during the system run
3. Diagnosis – analysis of unpredicted disturbances during the system run

(Shafto M. et al., 2010)

But the term took off after Gartner named digital twins as one of its top 10 strategic technology trends for 2017 saying that within three to five years, "billions of things will be represented by digital twins, a dynamic software model of a physical thing or system."

Gartner's 2018 hype cycle for emerging technologies places digital twins at the "Peak of Inflated Expectations," while successful use cases are still low in number and estimates that digital twins are 5 to 10 years away from the "Plateau of Productivity," otherwise known as operational technology.
(Jonathan Eyre et al., 2018)

Figure 15



Thirteen percent of organizations implementing Internet of Things (IoT) projects already use digital twins, while 62 percent are either in the process of establishing digital twin use or plan to do so, according to a recent IoT implementation survey by Gartner, Inc.

Gartner defines a digital twin as a software design pattern that represents a physical object of understanding the asset's state, respond to changes, improving business operations, and adding value.

"The results, especially when compared with past surveys, show that digital twins are slowly entering mainstream use," said Benoit Lheureux, research vice president at Gartner. "We predicted that by 2022, over two-thirds of companies that have implemented IoT would have deployed at least one digital twin in production. We might reach that number within a year."
[13]

For Boschert and Rosen (2016), the Digital Twin is the next level of simulation. Mainly used for single or multiple analysis, the simulation will become the primary tool for decision support, once the Digital Twin is fully integrated, as shown in Fig. 16. Instead of comparing the Digital Twin with a single simulation model, they define it as an abstract concept. The Digital Twin will have its architecture that connects engineering data, operational data, and behavior descriptions through different simulation models. These models will be manually generated and later updated by a model management system. Moreover, the model management system will choose the right simulation model for specific problems.
(Boschert S et al., 2016)

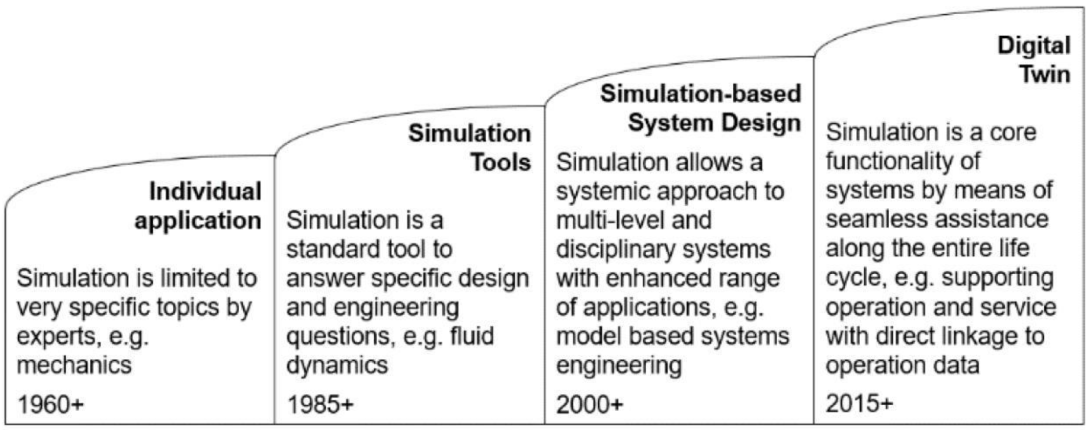


Figure 16

3.2 Pillars of DT

Digital Twin is not meant to function, relying on a single technology but requires many solutions to work hand-in-hand. Recent technological advances have resulted in an increasing trend of Digital Twin development and adoption among enterprises. Indeed, Digital Twin is based on three main pillars, enabled by technology: Connectivity, Digitalization, Intelligence.

The DT uses Industry 4.0, enabling technologies to create a digital duplicate of a physical object.

Connectivity

Sensors: sensors distributed throughout the processes and operations create signals that enable Digital Twin to capture operational and environmental data about the physical process in the real world. One of the breakthroughs in this field has been the emergence of Micro-Electro-Mechanical- Systems (MEMS) technology, which has substantially reduced the price of many standard sensors.

Big data: real-world operational and environmental data from the sensors are aggregated and combined with data from the enterprise, such as the bill of materials (BOM), enterprise systems, and design specifications. Data may also contain other items such as engineering drawings, connections to external data feeds, and customer complaint logs. The costs related to the storage and computation capacity required to manage vast databases have decreased over the past years, making it affordable for small and medium-sized enterprises (SMEs).

IoT: sensors communicate the data to the digital world through integration technology (which includes edge, communication interfaces, and security) between the physical world and the digital world, and vice versa. Significant improvements have been achieved regarding relevant technologies such as IoT, which facilitates Digital Twin projects.

Digitalization

Simulation modeling: the “digital” side of Digital Twin itself is an application that combines the components above into a near-real-time digital model of the physical world and processes. The technologies needed to realize the simulation depends on the physical asset; while a mechanical component can be simulated using physics-based and mathematics-based techniques such as CFD and FEM, a more complex system like an assembly line or complicated process can be modeled using other simulation modeling techniques such as agent-based-modeling or discrete event simulation.

Data-driven modeling: similar to simulation models, data-driven models (DDMs) provide the "digital" side of the Digital Twin. In contrast to Simulation models that consider explicit knowledge about the physical twin, DDMs borrow advanced mathematical and statistical techniques to analyze the data that characterize a system to find relationships among inputs and outputs. In recent years, DDMs are also catching attention beside the simulation models due to the massive amounts of data that are, in turn, become available thanks to the fast development of advanced sensors and data collection technologies.

Intelligence

Artificial Intelligence (AI): AI makes it possible for machines to learn from experience, adjust to new inputs, and perform human-like tasks. Due to the recent technological advances such as availability of massive datasets, the capability to processing large amounts of data and reinforcement learning, AI can effectively perceive the environment, analyze the situation and identify the best decision to reach the predefined goal. AI can be successfully employed in different levels of a Digital Twin to guarantee the best business performance under uncertainty.

Analytics: Analytics techniques are used to analyze the data through algorithmic and visualization routines applied to the collected information by sensors in time. These techniques help to discover, interpret, and communicate meaningful patterns in the data so that effective decisions can be made. Due to the recent advances in machine learning techniques, numerous successful applications of analytics have emerged, which in turn allow to conveniently gain quantitative and qualitative insight into the factors affecting the business.

Actuators: should action be warranted in the real world, the AI behind the Digital Twin produces the action by using actuators, subject to human intervention, which triggers the physical process. The necessary action usually regards the operative decision such as those needed in a dynamic control system; nevertheless, the necessary actions can be more strategic like business decisions that change the course of a process or how some part of the business is carried out.
(Luigi Manca et al., 2019)

To allow interaction, communication, and collaboration between physical space and cyberspace, the use of CPS is fundamental. Data collection takes place through sensors and actuators (IoT) that send information to the DT in the cloud. Applying Big Data Analytics techniques processes the information, and where possible, the results are compared by an AI using ML algorithms. At the same time, the DT simulates its operation based on the information gathered and uses these simulations either as a benchmark for comparison with the actual trend or to modify the operation/setting of the duplicated physical object.

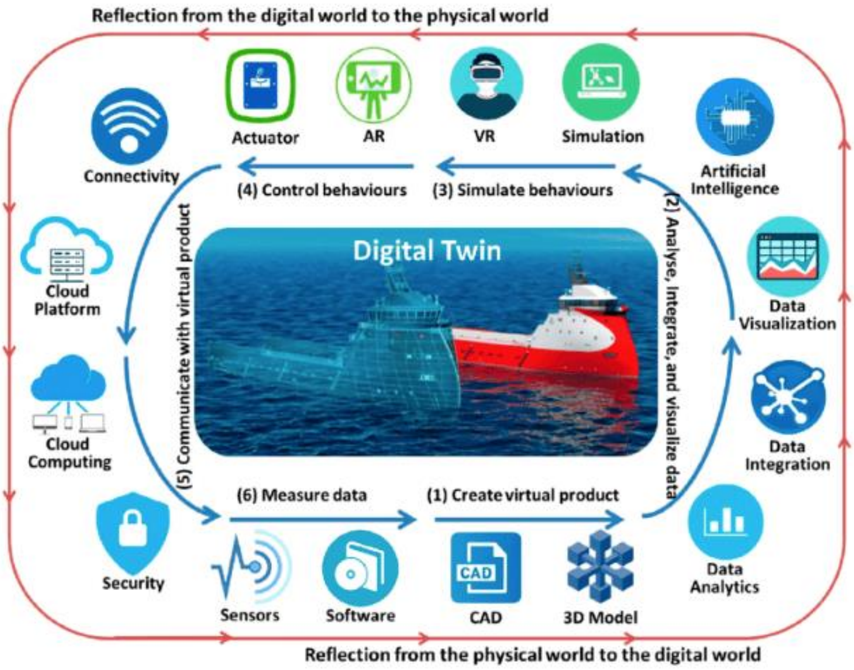


Figure 17

3.3 The concept

There is not any unique, globally accepted, and standard closed definition of the DT concept; however, there are certain aspects on which most existing definitions agree. (l. Negri et al., Sept 2017)

The digital twin concept model contains three primary components (Grieves, 2014):

1) A physical object in real space;
2) A virtual object in virtual space;
3) Data and information connections that converge the physical and virtual systems.

DT is virtual (that is, digital), it includes both static (that is, design documents, process specifications, and so forth) and dynamic (that is, data acquisition and simulation) parts, and it addresses every instance of its twin product or process for its total life cycle.
(Koulamas, at al, 2018*)*

The vision for DTs is to provide a comprehensive physical and functional description of a component, product, or system. The first and most crucial step is to create high-fidelity virtual models to realistically reproduce the geometries, physical properties, behaviors, and rules of the physical world. These virtual models are not only highly consistent with the physical parts in terms of geometry and structure, but also able to

simulate their spatiotemporal status, behaviors, functions, and more. In other words, the virtual models and physical entities have a similar appearance, like twins, and the same behaviors, like a mirror image. Also, the models in the digital environment can directly optimize the operations and adjust the physical process through feedback. Using bi-directional dynamic mapping, the physical entities and virtual models co-evolve. A virtual model, which integrates geometry, structure, behavior, rules, and functional properties, represents a specific physical object.
(Fei Tao et al., 2019)

We define the Digital Twin of a physical object as the sum of all logically related data, i.e., engineering data and operational data, represented by a semantic data model. While engineering data is generated once and updated when necessary, e.g., 3D models, specific simulation models, or material specifications, operational data is gathered and processed in real-time. Following this definition, the Digital Twin can represent historical and real-time states of the physical object. Using specific applications, real-time visualization of the physical object can be generated, combining a 3D model with real-time data. Furthermore, different simulations can be performed using existing simulation models or by generating new models that will become part of the Digital Twin.
(Martin Kunath et al., 2018)
Being the cyber twin of a material thing and having access to real-time information regarding the real thing as well as to related historical data, the DT can help optimize physical asset performance through efficient predictive and preventive maintenance operations, thus reducing overall maintenance costs and downtime.

Furthermore, the DT can simulate the behavior of the real thing that it is twinned with—or of an associated process—and can thus contribute significantly to performance optimization. It can act as a tool for predictive analysis, predicting the performance of the real thing or its associated process.

Potential benefits include, among others, optimizing production scheduling, identifying potential bottlenecks, assessing asset utilization, and minimizing production lead times.

The DT offers a total life cycle approach concerning its physical twin, either a thing or a process. Product design, new product launch, manufacturing process setup, and integrated supply chain management are facilitated.
(Koulamas et al., 2018)

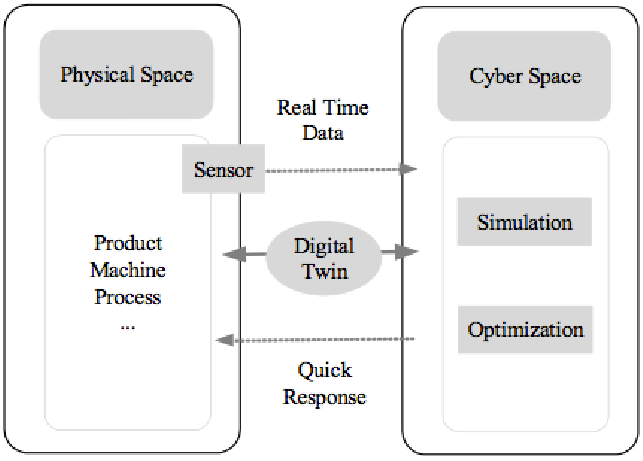


Figure 18

The characteristics of a digital twin can be summarized as real-time situation reflection, physical/ cyber convergence and interaction, and self-evolution. In the manufacturing field, sensor-equipped machines could collect data in real-time from the production system. By connecting physical and cyberspace, the digital twin would reflect the system's real state. By updating data in real-time, the model can undergo continuous improvement by comparing cyberspace with physical space in parallel (Boschert & Rosen, 2016; Tao et al. 2017)

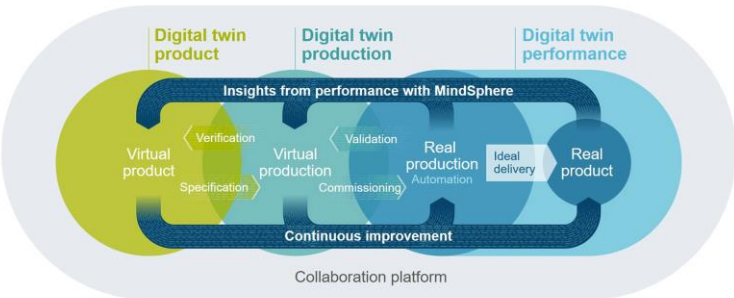


Figure 19

3.4 Differences between the Simulation and the Digital Twin

An aspect that has been noted since the very first interpretations of the DT concept is the intimate connection to simulation, which can be seen in two different ways:

- For most of the authors, the DT is a model that represents the system that different types of simulations can be based upon.
- Others consider the DT as the simulation of the system itself.

In the aerospace industry, the most mentioned simulations replicate the continuous-time history of flights (with historical data, maintenance history information), generating enormous databases of simulations to understand what the aircraft has experienced and to forecast future maintenance needs and interventions, with the use of Finite Element Methods (FEM), Computational Fluid Dynamics (CFD), Montecarlo and Computer-Aided Engineering (CAE) applications-based simulations. In the robotics field, the simulations are mainly performed for the Virtual Commissioning to optimize the control algorithms for robots during the development phase. In manufacturing, the main objective of simulations is to represent the complex behavior of the system, also considering the possible consequences of external factors, human interactions, and design constraints.

(Elisa Negri et al., 2017)

It is essential, though, to point out the principal difference of the virtual representation of a DT compared with well-known and widely used relevant modeling engineering in design, simulation, and testing: the permanent connection between the real and the virtual part for the total life cycle of a specific system instance. This connection means that information exchange between the system instance and its DT counterpart (that is, sensing and often also actuating infrastructure) can be part of a cyber-physical system on its own, depending on the type of information exchange—whether a real-time data flow or some systematic data collection that is integrated offline in the behavior of the DT.
(Koulamas et al, 2019)

Organizations usually start their digital twin journey with simulations of critical assets. Such simulations are suitable for playing out the what-if scenario for the asset. Nevertheless, in the real world, when assets intersect with other products, people, and processes, there arise many undesired and unexpected behaviors. Digital Twins with their view on the real-world will help operators to understand the interactions and incorporate them into their simulations.

[14]

The main differences are shown below:

- To-Be vs. As-Is: Simulation modeling enables the decision-makers to evaluate if the outcome of their decisions and actions is as they intend. In addition to that, the objective of a Digital Twin is to identify intolerable deviations from optimal conditions along any of the various dimensions. Such a deviation is a signal for business optimization and opportunity for saving costs, improving quality, or achieving greater efficiencies. The resulting opportunity may result in action back in the physical world.

- One-time built vs. continuous evolution: Simulation modeling is generally carried out once for a system or process improvement and would be extended if new functionality is required or the system is changed. Digital Twin, on the other hand, has a more holistic approach, and its implementation and deployment is a continuous project which evolves in time.
- Single vs. multiple foci: Simulation modeling is designed to answer a set of specific questions relevant to the owner of the system or process. Digital Twins have different users at different roles and therefore cover broader points of view, such as those relevant to maintenance, operation, strategy, or sales.
- Offline vs. Online: Simulation modeling is generally carried out in an offline fashion such that the necessary logistics and data are once collected, and the model is constructed. On the contrary, Digital Twin is realized to collect the item or process data in a continuous and online mode to enable the user to gain access to the current state and update the predictions and analyses.
- Analysis vs. action: Simulation modeling addresses the analytical and decision support requirements by proving detailed and accurate replication of the system or process state in the imaginary scenario being either in the past or future. Digital Twin not only provides this functionality but also can suggest possible courses of action and execute them depending on the nature of the necessary steps.
- Logic-based vs. data intensiveness: Simulation Modeling is generally realized on top of the logic behind how a system or a process is behaving. Digital Twin accounts not only for those logics governing the behavior of systems or processes but also for the vast amount of data they generate while operating.
- Stand-alone vs. connectivity: Simulation models are usually on each user's system, and its computation platform does not require other systems and applications. On the contrary, technologies like cloud, edge, and IoT are indispensable for realizing Digital Twins.

3.5 DT Implementation in the manufacturing field

State-of-the-art technologies such as the Internet of Things (IoT), cloud computing (CC), big data analytics (BDA), and artificial intelligence (AI) have greatly stimulated the development of smart manufacturing.

The term smart manufacturing refers to a future state of manufacturing, in which real-time transmission and analysis of data from across the product life-cycle, along with

model-based simulation and optimization, create intelligence to yield positive impacts on all aspects of manufacturing.
(Fei Tao et al., 2018)

Cyber-physical integration is an essential prerequisite for smart manufacturing, as well as being its core. As the preferred means of such integration, CPS and DTs have gained close attention from academia, industry, and government. Smart manufacturing can be considered a specialization of the prominent technologies of CPS and DT.
(Fei Tao et al., 2019)

To realize the Digital Twin as a real-time representation, the physical object needs to be digitalized, combining engineering data and operational data. In the context of a manufacturing environment, sensors, communication systems, and embedded systems must be integrated into machines and further elements of the manufacturing system. The gathered data needs to be transferred via a network from the physical object to its digital representation in the information world. Adding actuators to the physical object, computed instructions can be retransferred from the Digital Twin to the physical world. This concept of combining physical processes with computation is already known under the term cyber-physical system (CPS).
(Lee E.A. et al., 2017)

Hence the term Smart Factory, ie, factories where CPS communicates through IoT assisting people and machines in the execution of activities. The increase in process interoperability is tangible, allowing processes to be dynamically changed and adapted.
(J. W. Strandhagen et al., 2017)

In traditional production, the activities are sequenced in such a way that each depends on the completion of the previous ones on specific workstations; so that the breakdown of a machine interrupts the production flow. In a Smart Factory, this does not happen, as each machine knows its operating status and can indicate in advance the need for changes to the production plan. Also, in this case, it is the CPS that collects and analyzes all the information of the various machines and sends them to other actors, or decides independently based on the set decision rules.

Some researchers are developing a five C's structure for better analyzing I4.0. This five C's architecture can guide the development of I4.0, and it is dependent on CPS attributes. These five levels are Connection Level (the main attribute is self-configurable), Conversion Level (the main attribute is early-aware), Cyber Level (the main attribute is controllable), Cognition Level (the main attribute is informational) and Configuration Level (the main attribute is communicable).

Following the 5C architecture for implementing CPS, the Digital Twin can be seen as the cyber-part of CPS.

(Lee J., Bagheri, et al., 2015)

The proposed 5-level CPS structure provides a step-by-step guide for developing and deploying a CPS for manufacturing applications. In general, a CPS consists of two main functional components: (1) the advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyberspace; and (2) intelligent data management, analytics and computational capability that constructs the cyberspace. However, such a requirement is very abstract and not specific enough for implementation purposes in general. In contrast, the 5C architecture presented here clearly defines, through a sequential workflow manner, how to construct a CPS from the initial data acquisition to analytics, to the final value creation.

The 5C architecture proposed by Lee et al. to build the CPS consists of 5 levels, namely the connection, conversion, cyber, cognition, and configuration levels. Fig.20 depicts the 5C architecture. Below is described the details for each level.

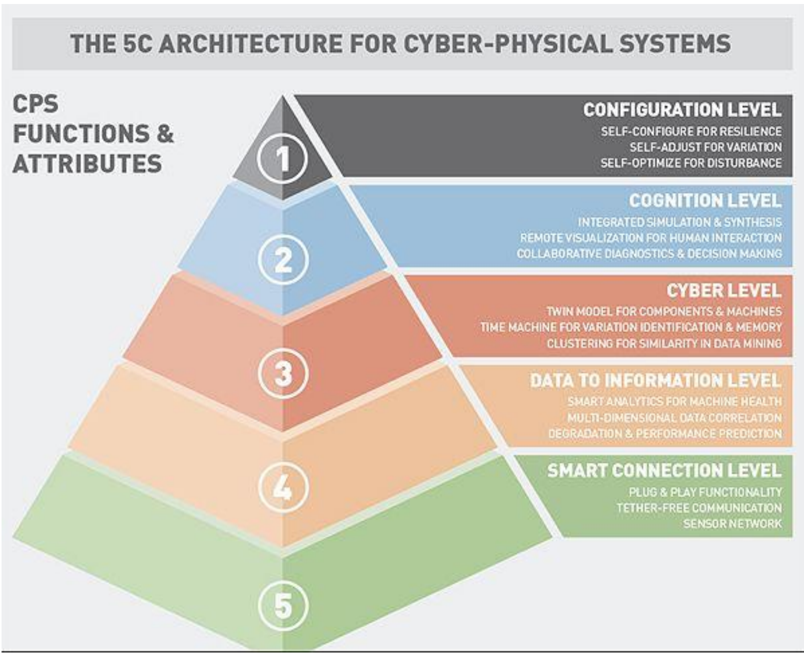


Figure 20

A. Connection level: connecting machines and their components for acquiring accurate and reliable data is the first step in developing a CPS for smart factories. Data may also come from the PLC or manufacturing systems, such as ERP, MES, SCM, and Coordinate Measuring Machinery (CMM). Specific protocols, such as those used in the Internet of Things (IoT) technology, are used to realize data transfer.

B. Conversion level: data are converted into information at this level. Several mechanisms can be used to realize the data to information conversion. Some mechanisms are developed for prognostics and machine health management. This level brings the self-awareness property to the machines.

C. Cyber level: The cyber level acts as a central information hub in this architecture. Information is being pushed to it from every connected machine to form the machine's network. Having massive information gathered, specific analytics have to be used to extract additional information that provides better insight into the status of individual machines among the fleet. These analytics provide machines with self-comparison ability, where the performance of a single machine can be compared with and rated among the fleet. On the other hand, similarities between machine performance and previous assets (historical information) can be measured to predict the future behavior of the machinery.

D. Cognition level: A proper presentation of analytic information is provided to users for making decisions. The priority of tasks for the maintenance process can be easily determined due to the availability of comparative information and special machine status.

E. Configuration level: The configuration level gives feedback from the cyber part back to the physical part. This level performs the supervisory control for making machines self-configured and self-adaptive. It acts as the Resilience Control System (RCS) to apply the controls corresponding to the decisions made in the cognition level to machines.

(Ahmadzai AHMADI et al., 2017)

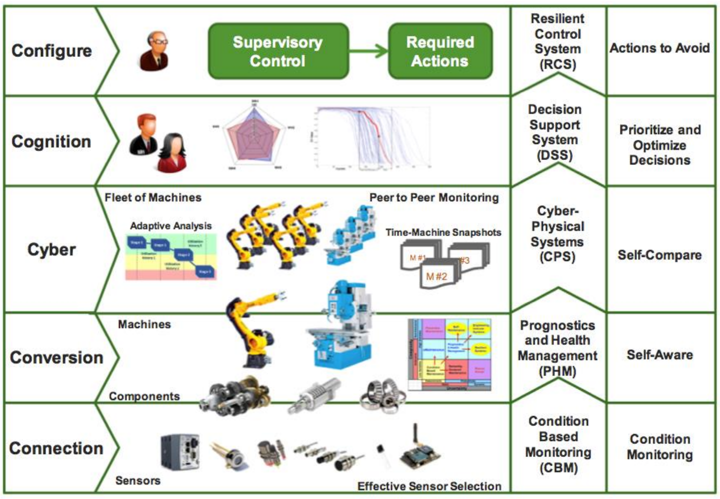


Figure 21

Some authors moreover propose an 8C architecture by adding 3C facets into the 5C architecture to emphasize more on horizontal integration. The 3C facets are coalition, customer, and content. The coalition facet focuses on the value chain integration and production chain integration between different parties in terms of the production process. The customer facet focuses on the role that the customers play in the production process. The content facet focuses on extracting, storing, and inquiring all contents related to products, such as the design, the manufacturing parameter, the product traceability record, and the after-sales service record.

(John-Ruey Jiang 2018

The concept of CPS has emerged a few years earlier than a digital twin, and the amount of publications related to CPSs is twentyfold compared to digital twins. The Cyber-Physical Systems can be seen as another path leading to the development of a digital twin because CPS can use a digital twin to process the sensor data and control the physical system (Alam & El Saddik, 2017).

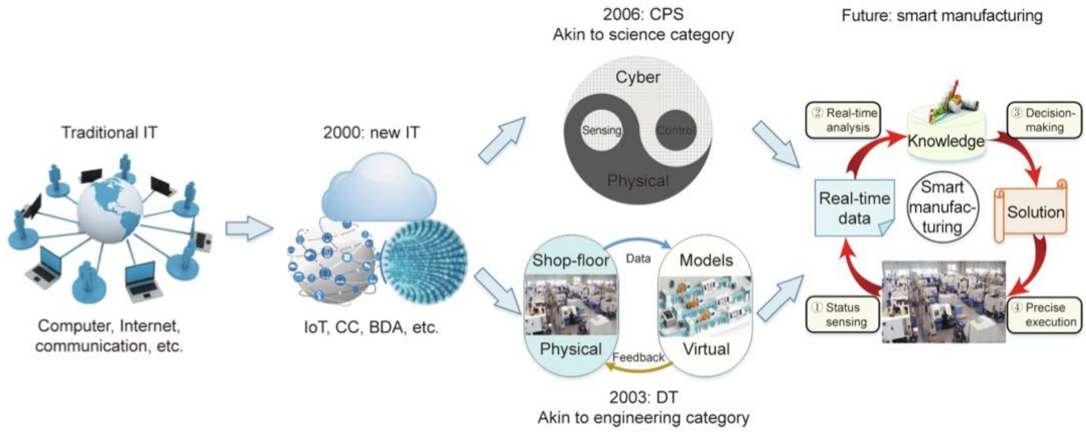


Figure 22

In comparison, CPS is more akin to a scientific category, whereas DTs are akin to an engineering category. Thus, sensors and actuators can be considered as the core elements in CPS, while models and data are the core elements in a DT.

(F. Tao et al., 2019)

In conclusion, we define the Digital Twin of the manufacturing system as a data-oriented representation of all elements of the manufacturing equipment system, the material flow system, the value stream system, the operating materials system and the human resource system in the information world, which are linked to their physical elements by the information system. These elements are connected and to the information system by sensors, actuators, and communication systems, to support the concept of a CPPS. Simultaneously, data and information of these systems are exchanged with production planning and control (PPC) systems, e.g., MES or ERP systems. The main purpose of the Digital Twin of the manufacturing system is to facilitate the decision-making process and to enable decision automation through simulation.

(Martin Kunath et al., 2018)

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.

(Chiara Cimini et al., 2019)

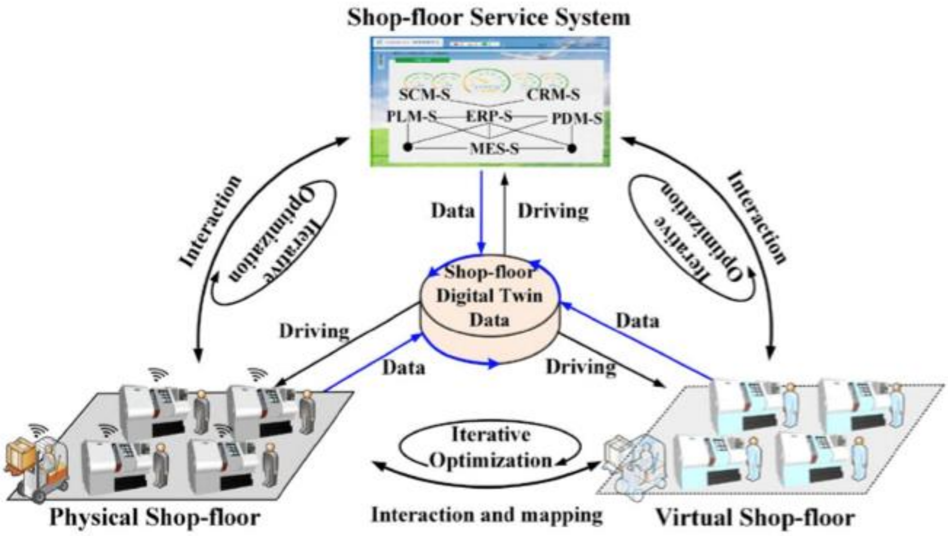


Figure 23

Above the concept of interlinking CPS to create a CPPS, the Digital Twin of the manufacturing system can be seen as an intelligent linkage of the Digital Twins of elements of the manufacturing system. Therefore, the Digital Twin of the manufacturing system will have its semantic data model that describes the relations of all these elements.

Furthermore, simulation models can use real-time data to perform simulation experiments considering the actual state of the system. If a decision is needed that cannot be supported by the existing models; new models have to be created.

(Martin Kunath et al., 2018)

3.6 DT supporting decisions framework

The concept of integrating the Digital Twin of the manufacturing system into the decision support system is shown in Fig. 24. Logically, the information world contains the Digital Twin of the physical manufacturing system.

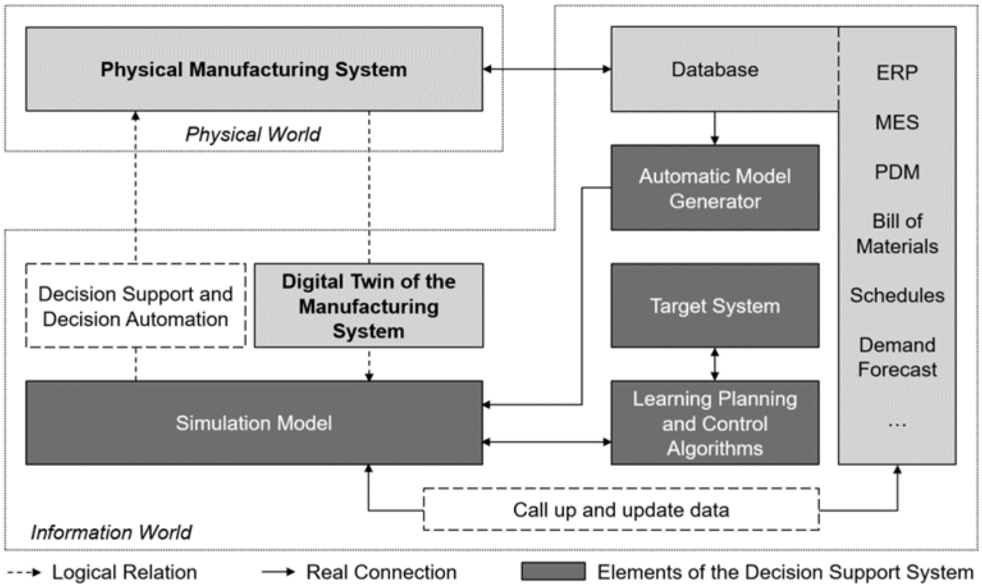


Figure 24

The Twin is used as a simulation model for decision support and automation. In practice, the elements of the physical manufacturing system are connected to information systems and databases. The automatic model generator will choose and update a proper simulation model or generate a new one, using data and information from all these databases and information systems. During the simulation, the learning planning and control algorithms will search for the best solution for the decision problem considering the company´s target system. When a solution is found, the solution and maybe some alternative solutions are presented to a decision-maker. Furthermore, the best solution could automatically be returned to a specific information system or database and if necessary, forwarded to the manufacturing system.

3.7 Digital twin integration

ISO 16100 defines interoperability as "the ability to share and exchange information using a common syntax and semantics to meet an application-specific functional relationship across a common interface."
(KosankeaFet al, 2015)

In smart manufacturing, interoperability takes two general forms. The first form corresponds with vertical integration, e.g., interoperability between the manufacturing software, the shop–floor departments, the processes performed by different equipment, the various shop–floor systems, and so forth.
(Chen, D, et al., 2003)
.

The second form corresponds with horizontal integration; the interoperability between smart automation devices, cloud services, cloud platforms, and enterprises. Successful implementation of enterprise-wide interoperability would result in effective and smooth operations of the manufacturing industry, thus cutting costs, increasing production, and product quality.

The factors that affect interoperability are bound to be multivariate, considering the complexity of the processes. The Manufacturing Interoperability Program at NIST (the National Institute of Standards and Technology) list several factors that impact the effectiveness of interoperability:
(Kemmerer et al., 2009)

- Transfer of data between systems that may be similar or dissimilar (commercially).
- Transfer of data between software made by the same vendor (or creator) but having different versions on the systems.
- Compatibility between different versions of software (newer and older versions).
- Misinterpretation of the terminology used or in the understanding of the terminology used for the exchange of data or information.
- The use of non-standardized documentation on which the exchange of data is processed or formatted.
- Not testing the applications that are deemed conformant, due to the lack of means to do so between systems.

Other barriers to interoperability include inconsistent data formats or standards, connectivity in the IoT realm, and a wide variety of commercially available products.

3.7.1 Reference Model of I4.0

The need for a bidirectional life cycle- extended integration between the physical world and its DT mandates a relevant supporting reference architecture. Different initiatives deal with the IIoT providing relevant reference architectures, the most important of which are Industry 4.0 (RAMI 4.0)(Germany), the Industrial Internet Consortium (IIC)(USA), and Society 5.0 (Japan).
(Christos Koulamas et al., Nov 2018)

Probably the most famous one is RAMI 4.0. It was published in 2015 by the German Commission for Electrical, Electronic and Information Technologies of DIN and VDE (DKE).
(TC 65 "*IEC 62890, 2013)*

The Reference Architecture Model for Industry 4.0 (RAMI 4.0) is a three-dimensional model along three axes (hierarchy, architecture, and product life cycle), with IT security and data privacy as enablers.

(Christos Koulamas et al., Nov 2018)

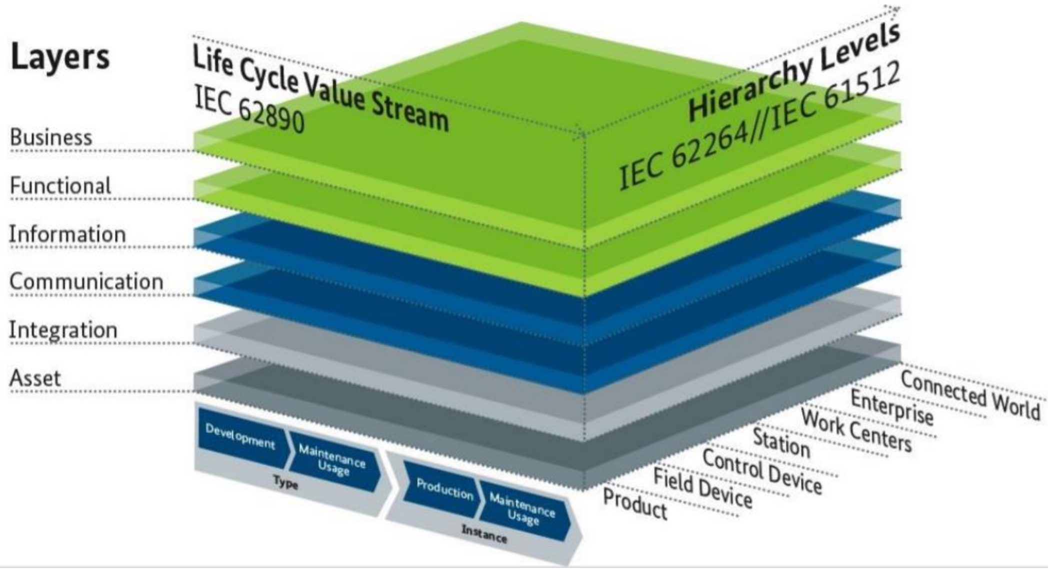


Figure 25

This 3D model in Fig. 25 is the development of a shared language and a structured framework that describes the fundamental bases of I4.0. It is intended to assist with the I4.0 technologies implementation.

The Reference Architecture Model Industrie 4.0 (RAMI4.0) should enable the identification of the existing standards and, among it, identify and close the gaps, loopholes, and identify the overlaps.

The life cycle of an asset is represented by the Life Cycle & Value Stream dimension, both as a product type and as a product instance. As a product type, a design is produced and refined; as a product instance (of a design), a product is manufactured, used, maintained, and disposed of. This dimension is based on IEC 62890, "Life-cycle management for systems and products used in industrial-process measurement, control, and automation."
(M Wollschlaeger et al., 2013)

A type is always created with the initial idea, i.e., as a product comes into being in the development phase. This covers the placing of design orders, development, and testing up to the first sample and prototype production. The type of the product, machine, etc. is thus created in this phase. On the conclusion of all tests and validation, the type is released for series production. Products are manufactured industrially based on the general type. Each manufactured product then represents an instance of that type, and,

for example, has a unique serial number. The instances are sold and delivered to customers. For the customer, the products are initially once again only types. They become instances when they are installed in a particular system. The change from type to instance may be repeated several times. Improvements reported back to the manufacturer of a product from the sales phase can lead to an amendment of the type documents. The newly created type can then be used to manufacture new instances. Similarly to each instance, then, the type is also subject to use and updating.
(Sino-German, 2018)

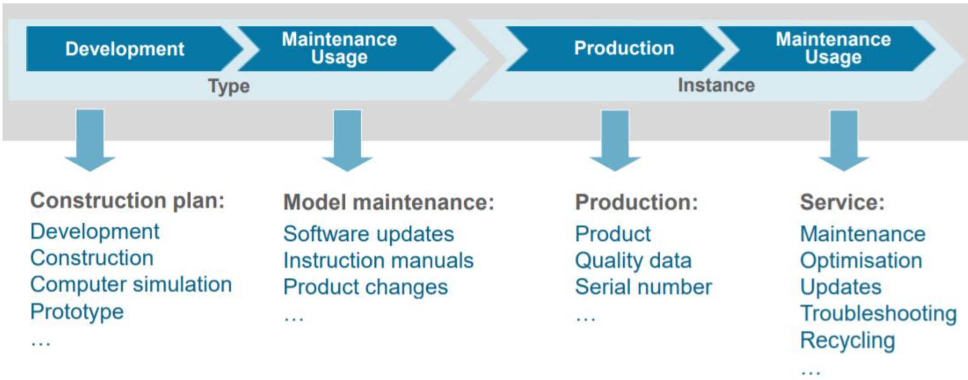


Figure 26

The right-hand horizontal axis is the location of functionalities and responsibilities within the factories/plants. This represents a functional hierarchy, and not the equipment classes or hierarchical levels of the classical automation pyramid.
(Sino-German et al. 2018)

The Hierarchy Layer is based on the international standards for enterprise control system integration (IEC 62264 and IEC 61512). In addition to the four layers named 'Enterprise', 'Work Centers', 'Station', and 'Control Device', the last two layers at the bottom are added (but are not included in standards) and are called 'Field Device' and 'Product'. The layer 'Field Devices' makes it possible to control the machines or systems intelligently and smartly, e.g., smart sensors. The layer 'Product' takes into account the product homogeneity and the production capacity with their interdependencies.
(Resman, M.a et al., 2019)

The two IEC standards mentioned only represent the levels within a factory. Industrie 4.0, however, goes a step further and also describes the group of factories, and the collaboration with external engineering firms, component suppliers and customers, etc. For observations above and beyond the Enterprise level, the "Connected World" has therefore been added.
(Sino-German et al. 2018)

The layers on the vertical axis represent a reminder to integrate all aspects of the enterprise digitalization. The functional layer of the organized vertical axis describes:

- ‘‘Asset Layer” represents reality, for instance, physical components including linear axes, robots, conveyor belts, PLCs, metal parts, documents, archives also persons that form a part of the connection to the virtual world via the ‘‘Integration Layer.” Also, non-physical objects such as software or ideas;
- ‘‘Integration Layer” provides processed information for the digitization of the assets. Elements connect to Information Technologies (IT) such as sensors, Radio Frequency Identification (RFID) readers, integration of Human-Machine Interface (HMI), and computer-aided controls the technical processes. Persons via HMI also participate in this layer. In the virtual domain, each significant event is mirrored through the enabler;
- ‘‘Communication Layer” with the function of communication standardization. It makes use of uniform data format and predefined protocols, providing services for the ‘‘Integration Layer”;
- ‘‘Information Layer” to process and integrate the different available data consistently into useful information. Also receives and transforms events to match the data which are available for the next layer;
- ‘‘Functional Layer” to enable formal descriptions of functions. It creates a horizontal integration platform of several functions that can be with remote access, resulting in the necessity of data integrity. It supports business procedures. It generates the logic of the rules and decision (in some cases can be achieved on lower layers);
- ‘‘Business Layer” enables mapping of the business model and links between different business models. It ensures, within the value stream, the integrity of the functions.

It’s possible to map all crucial aspects of I4.0, allowing the classification according to the model, of objects such as machines. This model allows the step-by-step migration from the actual to the future manufacturing environments.
(V. Alcácer, et al, 2019)

3.7.2 Reference architecture of a smart manufacturing

There is a long way to go before being able to apply RAMI4.0 in the manufacturing practice. Therefore, Haijun Zhang, Guohui Zhang, and Qiong Yan propose a new reference architecture for smart shop-floor, which is a reusable integration of components engineered to facilitate development and deployment for enterprises. Since the proposed architecture is a weak-coupling structure, the dependency between layers is downward, and the bottom is "ignorant" to the upper layer, the change of the upper layer does not affect the bottom. This is also an advantage of the proposed architecture, which consists of five layers as follows:

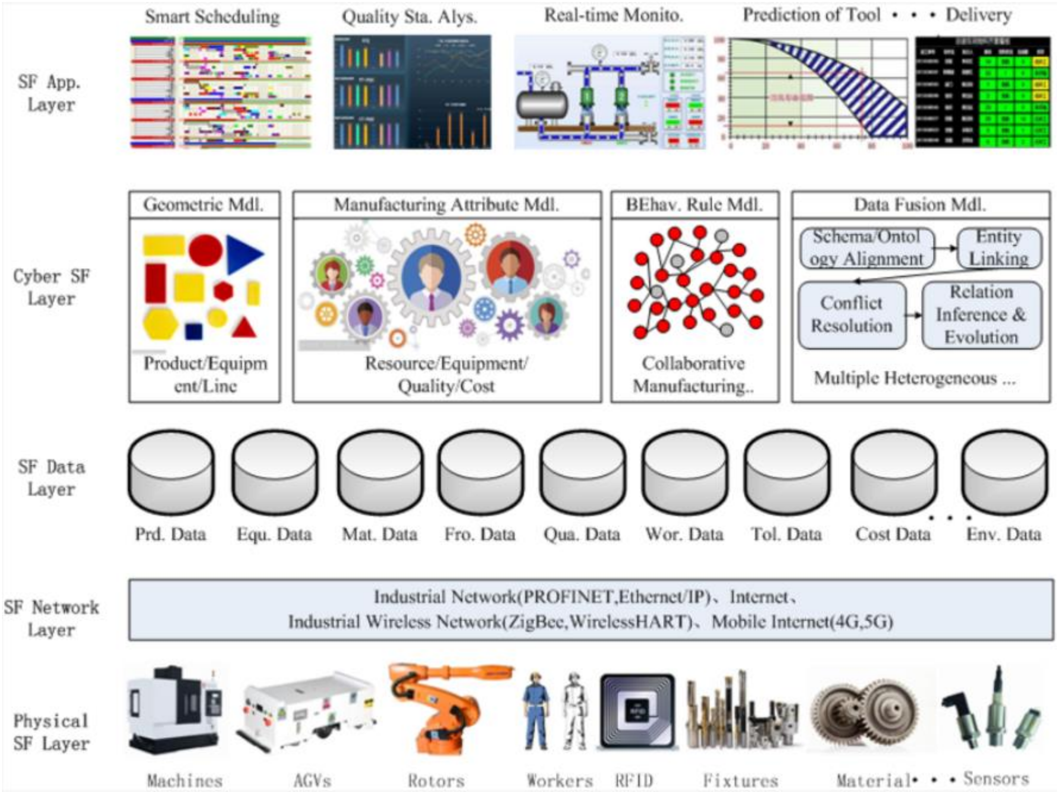


Figure 27

Physical Layer: Refers to physical entities in the shop- floor, e.g., machine tools, Automated Guided Vehicles (AVG), robots, workers, parts, sensors, Radio Frequency Identification (RFID), materials, etc. The physical entities can accept manufacturing instructions and perform manufacturing tasks. For example, Distributed Numerical Control (DNC) can realize: (a) transfer NC code; (b) collect and upload the machine status; (c) transfer the tool data; (d) manage and trace NC code. In addition to the common functions of the shop-floor, this layer can perceive and treat the heterogeneous, multi-source, real-time data based on the Internet of Things (IoT). For example, various sensors should be installed in smart shop-floor, such as temperature sensors, voltage sensors, pressure sensors, speed sensors, displacement sensors, and laser sensors. As a result, the data sources and data formats might not be exact. If AVG (electromagnetic, laser, magnetic belt) encountered obstacles, it needs to stop and/or reroute in time.

Network Layer Refers to the network infrastructure, which is the bridge between the physical space and the virtual space. These technologies include the Industrial Internet, Industrial Ethernet, Industrial Wireless Network, Mobile Internet (5G), etc. The network employed in this layer focuses on reliability, real-time, and convenience. In the physical layer, there are many heterogeneous and multi-source of shop-floor data. The isomorphism should be carried out towards the network topology and protocol among various heterogeneous systems. The unified inter-faces should be provided to access heterogeneous systems identically in this layer. For example, the wireless Internet of Things technology of shop-floor includes Bluetooth, WIFI, Zigbee, RFID, 4G/5G, Profinet, etc. The technology of the shop-floor field bus includes Profibus (Germany), P-Net (Denmark), WorldFIP (France), etc.

Database Layer Includes production data, tooling data, equipment data, material data, quality data, cost data, personal data, environmental data, etc., which are the base of digital twin-driven CPPS. Owing to the network technology and the sensor technology, the shop-floor tends to Big Data "3V" characteristics, namely Volume, Variety, Velocity (Qi and Tao 2018). This layer focuses on not only the efficiency, visualization of data processing, but also the seamless connection of multi-source and heterogeneous data. For example, the semistructured data (e.g., equipment maintenance orders) and unstructured data (e.g., part drawings) can be stored in the Hadoop Distributed File System. In shop-floor, the data in various production systems (e.g., MES, ERP, WMS, etc.) is structured. The structured data can be exported by Sqoop from the relational databases (e.g., Mysql, SQL Server, Oracle, Sybase, DB2) to Hbase. Mahout allows for the distributed processing, analysis, and mining of the data in Hbase through the principal component and cluster analysis.

Model Layer It is a very important layer to digital twin driven CPPS, which consists of various models, e.g., Production Definition Model (PDM), Geometric and Shape Model (GSM), Manufacturing Attribute Model (MAM), Behavior and Rule Model (BRM), Data Fusion Model (DFM). PDM can employ Model-based Define (MBD) technology (Virgilio et al. 2010), which has been applied in Boeing 787. There has been a lot of mature 3D modeling technology for GSM, such as Unigraphics NX, Inventor, Solidworks, PTC Creo. The technology for MAM includes XML, Ontology, and so on. The technology for BRM includes STEP, UML, IDEF, Petri Net, and so on. The key technology for DFM includes schema/ Ontology alignment technology, entity linking technology, conflict resolution technology, relation inference, and evolution.

Application Layer Including various services of the production system, which are responsible for decision support, e.g., job scheduling optimization, real-time monitoring of manufacturing resources, quality management, tool life prediction, material delivery optimization, etc.

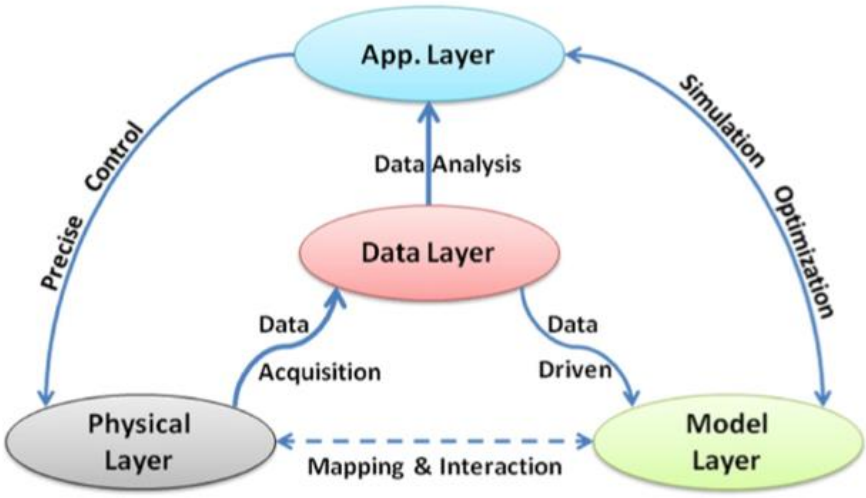


Figure 28

3.8 Example of a real physical system modeled base on Digital Twin concept

(YANG, W et al., 2017)

YANG, W.; TAN, Y.; YOSHIDA, K. & TAKAKUWA, S. focused on attaining digital twin-driven simulation and implement simulation experiments with real-time data. Using a distributed model equipped with a sensor as the physical system, a simulation model is constructed to reflect the physical system, and simulation experiments are carried out. The proposed modeling method can be further applied in the simulation-based support tools for decision-making with real-time data.

Physical System

An image of the distributed system is shown in Fig. 29. The mini-vehicle is driven by a dry battery and controlled by an on/off switch; as long as the switch is turned “on,” the vehicle continues to run until the battery runs down. In this manner, the mini-vehicle model can be seen to represent a flow production line, with the defined position assumed to represent a processing point.

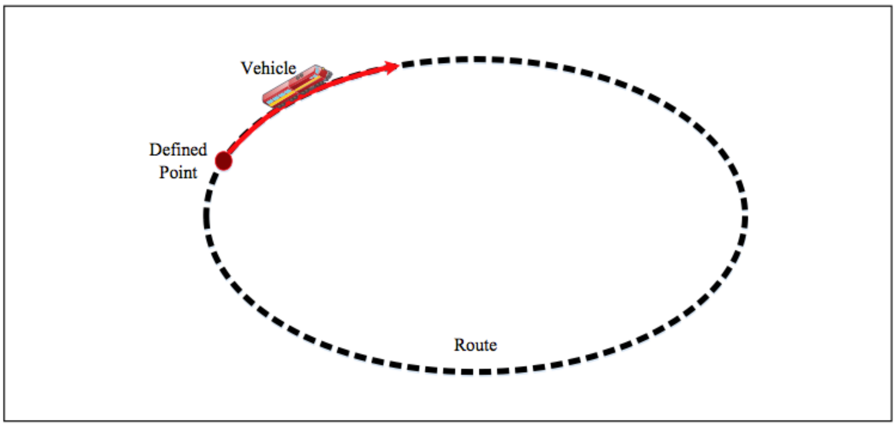


Figure 29

In the study, a light sensor (peak wavelength 540 nm ***) was set at the position of the defined point. The sensor generates an output signal (0/1), indicating the intensity of light. To acquire real-time data from the system, a simple shading item was tied to the left side of the vehicle. The signal was set to turn to one when the received light wavelength was less than 100 nm and to remain at zero otherwise. In this manner, a changed signal could be sent by the sensor when the vehicle passed the defined point.

Furthermore, an Excel VBA program was developed to record the times at which the sensor single turned to one, i.e., the times at which the vehicle passed the defined point. The time difference between each successive signal could, therefore, be defined as the system cycle time, allowing real-time data from a physical system to be recorded in the cyber system (in this case, i.e., in a Microsoft Excel Workbook).

To constructing the simulation model, two main objectives were as follows:

1) To reflect the physical system's real situation to use sensing data;

2) To experimentally assess the ability of the twin model to use real-time and historical data.

Digital Twin-driven Simulation

1) Simulation Model

To achieve the first objective above, a simulation model to reflect a real distributed model was constructed. The model was developed using the simulation software Arena. The main parameter used in the model is the system cycle time, which is defined as a route time required for the entity to travel through the defined point.

Additionally, the ReadWrite module was used to import the real-time cycle time from Microsoft Excel into the Arena model.

2) Improved Model To achieve the second objective, the simulation model was

improved with the following procedures: Firstly, a VBA input interface was developed to define a lap number that implements the experiment. Subsequently, run the simulation model. The model reads the cycle time data acquired from the sensor, which precisely like the processes discussed until the defined number of laps is reached. From the (defined number+1)th lap, the cycle time of the model was generated randomly based on the average and standard deviation of the historical data. An Excel VBA program was designed to control the model.

By combining the simulation capabilities of Arena and VBA via the sensor data, a customized integrated simulation model could be constructed that is both dynamic and flexible.

<u>Experiments</u>

Simulation Experiments were designed to demonstrate that the model can reflect the system's real state and implement run time experiments using historical data.

In this case, the lap number to generate cycle time based on the historical data was set to 30. A screenshot of the simulation model in the run mode is shown in Fig. 30. A partial output data example of the model is shown in Tab. 2. There are five columns: Column A shows the times at which the vehicle passes the defined point, as recorded automatically by a light sensor. Column B shows the difference (millisecond) between the time in column A and 0:00:00 of that day. Column C shows the cycle time calculated from the differences between the adjacent rows in column B. Column D shows the model input data using as the vehicle route time. Moreover, Column E shows the output of the cycle time written by the simulation while the model is running.

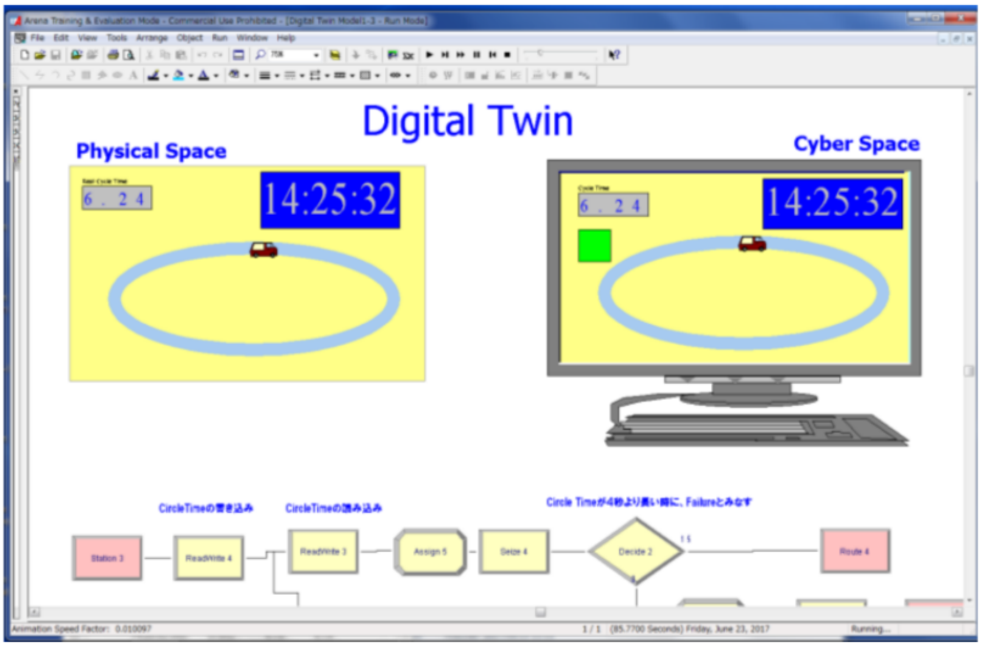


Figure 30

As shown in Tab. 2, the output cycle time from 1st to defined (30th) laps are the same with the sensor tracking data in the real-world system, which proved that the simulation model reflects the physical system real situation correctly. Whereas, the cycle time from the 31st lap is not equal to the corresponding real data from physical space. The model uses an estimated cycle time based on historical data, which shows that the simulation experiments can be carried out successfully in the run-time.

	A	B	C	D	E
1	14:24:38.570	51878.57	6.13	6.13	6.13
2	14:24:44.700	51884.7	6.09	6.09	6.09
3	14:24:50.790	51890.79	6.02	6.02	6.02
4	14:24:56.810	51896.81	6.05	6.05	6.05
24	[illegible]	[illegible]	6.05	6.05	6.05
25	14:27:05.900	52025.9	6.22	6.22	6.22
26	14:27:12.120	52032.12	6.18	6.18	6.18
27	14:27:18.300	52038.3	6.16	6.16	6.16
28	14:27:24.460	52044.46	6.18	6.18	6.18
29	14:27:30.640	52050.64	6.18	6.18	6.18
30	14:27:36.820	52056.82	6.21	6.21	6.21
31	14:27:43.020	52063.02	6.12	6.15	6.15
32	14:27:49.140	52069.14	6.16	6.23	6.23
33	14:27:55.300	52075.3	6.15	6.22	6.22
34	14:28:01.450	52081.45	6.11	6.07	6.07
35	14:28:07.560	52087.56	6.10	6.20	6.20
36	14:28:13.660	52093.66			

Table 2

3.9 Real applications

Despite a digital twin concept being developed continuously, there is a lack of real-world implementations of it. This is because a digital twin is a complex system involving multiple sub-systems with numerous functionalities.

Attempts to fully implement digital twinning technology runs into several problems:

- insufficient synchronization capabilities (real-time synchronization) between physical and digital environment, without the possibility of creating stable closed relationships
- the problem of missing sufficiently precise and beautiful models necessary to simulate processes at different levels
- insufficient accuracy evaluation of models of the real environment
- generally problematic prediction of the state of complex systems

- globally unhandled issues of collecting and processing large data blocks (Big Data processing)

(Igor Halenar et al., 2019)

To understand the potential of the Digital Twin, it may be useful to take a look at some application cases of large companies, which have managed to implement it to enhance their industry leadership.

3.9.1 General Electric

GE is one of the first players in the world to have used the Digital Twin for the product development of aircraft turbines and power plants. They then extended the use of digital twins to the entire PLC to obtain a reliable forecasting and decision tool.

According to GE, the Digital Twin is:

"A living model that drives business outcomes."

GE's business model is based on developing the capabilities offered by the Industrial Internet of Things (IIoT) in various industrial sectors. The Intelligent Platforms division focused on creating value-added solutions based on Big Data. It has done so by building digital twins for all its manufacturing processes and industrial assets. This has allowed us to increase production efficiency and provide better service to customers. At the end of 2016, the company launched the Predix platform on the market, capable of making each machine an intelligent asset. Predix is a suite of software and services able to give visibility and control to the industrial assets, thanks to a series of updated continuous summary indicators. Moreover, it allows us to optimize maintenance costs, operational risks, and to reduce the total costs of ownership.

The end customer can easily query the twin remotely, even using voice commands or wearing an AR viewer. The system returns consistent search results and, in the case of identification problems or deviations from the simulated trend, suggests more solution scenarios.

[15]

3.9.2 Siemens

Within the Digital Twin, the most active multinational is certainly Siemens. His investments in this sector are huge but have allowed him to develop a series of products capable of really supporting the development of the paradigm.

Siemens is probably the only company capable of covering the entire product chain, from the mechanical to the electronic side up to the software. For these reasons, it provides DT solutions for design and prototyping, but also production and logistics management.

[16]

The proposal of the multinational is that of a suite of products aimed at different areas and business needs. This suite, dedicated to PLM, allows us to digitize entire production lines and redefine the prototyping and product testing phases. Thanks to the MindShere operating system dedicated to the IoT and based on the cloud, it is possible to connect products, systems, systems, and machines with their digital duplicates, archiving the collected data and using them for analyzes capable of closing the information loop.

[17]

The use of artificial intelligence (AI) and ML algorithms guarantees a simpler and more robust testing process support, an improved ability to identify relevant information and, therefore, anomalies and finally, the self-learning ability of the models used by the twin. In this regard, Industry Knowledge Graph is the solution that Siemens proposes to overcome the lack of data for its predictive algorithms. This type of knowledge is semantic. Therefore it does not need instructions and is met in situations where a robot or a machine is faced with an unexpected event. For this to work, it is necessary to process a large amount of data previously collected by the DT.

[18]

3.9.3 SAP

SAP has also launched its business solution on the market, capable of managing the assets connected through the IoT. The name, SAP Leonardo, alludes to a product that aims to revolutionize the future; in reality, the expectation is to manage the innovation brought by the Digital Twin.

SAP Leonardo provides a DT modeling and device management system, as well as connectivity, messaging, archiving, and API services for implementing the DT.

The leading SAP Leonardo solutions are:

- SAP Predictive Maintenance and Services: this uses complex models to identify anomalies, assess the status of assets and their residual life, predict errors, and provide support for scheduled maintenance decisions.
- SAP Asset Intelligent Network (AIN): it acts as a repository of shared assets and a collaboration system for all business partners related to the asset view cycle. AIN also allows the implementation of collaborative scenarios related to the Digital Twin.

- SAP Digital Twin for structural dynamics: a structural analysis system that allows the evaluation of the status of digital assets and therefore of physical considerations. AR and Voice Assistant technologies are integrated. Then there are a whole series of applications that, by managing DT notifications, facilitate the work of technicians and managers thanks to smartphone apps and guarantee interconnections with external systems.

[19]

3.10 Benefits And Values

The Digital Twin, like Industry 4.0, has an essential impact on business models.

The DT Value Proposition is characterized by a Product as a Service offer, meaning that only the physical product is no longer sold, but this is accompanied by added value-added services for the customer.

As for Value Creation, it is the possession of data that creates actual value. The collection, use, data efficiency, and scalability of the models based on them, guarantee the functioning of the DT and make it possible to multiply business opportunities. Focusing attention on the actors of a supply chain, it is the interoperability of the DT to create value, guaranteeing general efficiency, and reducing time-to-market.

Finally, Value Capture is obtained thanks to the use of IoT technology, which makes it possible to collect information on the product even after the sale. This allows, on the one hand, to increase recurring revenue and, on the other, to increase profits for sales of new products developed, thanks to the analysis of Big Data. Furthermore, the application of the As-a-Service approach also guarantees a new flow of revenues with a business model entirely based on data.

J. Meierhofer et al., 2019

The main benefits and values of Digital Twin lie within its name: a digital copy of reality, where “seeing,” “thinking,” and “acting” is a risk- free. The concept of the Digital Twin is a compelling one; the application of this concept typically brings a set of benefits. Here are the main differences:

Continuous improvement: implementation of the Digital Twin concept encompasses many other digital technologies and innovations, which in turn can lay the necessary foundation, whether know-how or infrastructure, for future business improvements.

Predictive: using various modeling techniques (simulation-based, mathematics- or data-based modeling), the Digital Twin model can be used to predict the future state of the assets and the impact of disruptions.

What-if Analysis: through properly designed interfaces, it is easy to interact with the Digital Twin and simulate different scenarios to identify the best actions to be then applied to the physical twin.

Visibility: the Digital Twin enables visibility and transparency in the operations of the machines and assets as well as in the larger interconnected systems such as a manufacturing plant or an airport.

Insight: Digital Twin model can be used as a communication and documentation mechanism to understand as well as explain the behaviors of an individual machine or a collection thereof.

System Integration: if designed correctly, the Digital Twin model can be used to be connected with the backend business applications to achieve business outcomes in the context of supply chain operations, including manufacturing, procurement, warehousing, transportation and logistics, field service, etc.

Disruptive business models: Digital Twin not only boosts the traditional business models and value chains but also expands them by developing new value creation mechanisms via data-driven or product-as-a-service business models. These are delivered into an ecosystem that attempts to reach new customers and other partners to exploit new revenue streams and opportunities.

(Luigi Manca et al., 2018)

3.11 Future challenges

Digital Twin concept offers many great opportunities; however, several challenges must be adequately addressed to attain the benefits that such technology brings.

- Connectivity: many Digital Twin candidate assets are not stationary applications. Providing real-time connectivity to assets that might always be moving or in remote areas is challenging. Also, constant connectivity demands a significant bandwidth and computation power to gain value that is not a trivial issue.
- Hardware: a Digital Twin project would require a significant number of sensors. Additionally, managing the deployment of so many sensors is complicated and time-consuming. The maintenance of the sensor network is also a troubling issue.
- Extended access life: many Digital Twin candidate assets have long life cycles. These cycles generally extend well beyond the life spans of the formats for proprietary design, simulation or analytics software. This means that a careful selection of the technologies to be used becomes a crucial real success factor in the long run.

- Personnel: successful implementation of Digital Twin requires a set of skills for which a set of personnel must be trained appropriately. Besides, the effective utilization of this technology alters the work paradigm in some business areas. This triggers the opportunity to empower the personnel, promoting them to be actors of the digital transformation.
- Security: Digital Twins accumulate data and intellectual capital, which becomes more valuable over time; it is vital to ensure the security of the data management systems to avoid data loss or other possible damage.

(Luigi Manca et al., 2018)

In practice, research on CPS and DT is still ongoing, and in most cases, manufacturing systems at companies are equipped with traditional machinery which is hierarchically based on the automation pyramid: the production is planned in the long run by the company information systems (such as ERP), and the sequence of operations is controlled by the MES of the systems. In these cases, it is more difficult to introduce an implementation of DT in the systems and to integrate it with existent MES-based equipment.

(Chiara Cimino et al., 2019)

The collaborative design has long been a challenge for manufacturers (Wang et al. 2002), while digital twin paves the way for new modes of design collaboration. Firstly, DT will greatly facilitate customer involvement (i.e., the endeavor of engaging customers in product design) by presenting customers with both physical and virtual products. Secondly, DT will support global product development by the virtual design teams, through the collection, convergence, and integration of physical data obtained from the same product sold to different markets. Finally, product-oriented DT and production-oriented DT can collaborate to enhance the effectiveness of ‘design for manufacturing.’

(Fei Tao et al., 2019)

3.11.1 BIM

In the industrial sector, the individual components belonging to a production line can have a very high degree of complexity. An example is given by the need to understand the activity of each machine and what this means in terms of monitoring, with the need to establish kinematic models with a degree of detail that also includes micro-operations. All this requires extreme complexity, but the connection of the individual machines is simple. Instead, in a world such as a building, it does not involve such complex operations: some people move in environments, the quantities to be manipulated are not so problematic.

The essential simulator, adopted in the industrial and real estate sector, is different because, on the one hand, you have discrete events, on the other hand, continuous, as well as different time scales. Processing can take place in seconds or tenths of seconds, the temperature or the degree of humidity of an office do not change abruptly. By the way, the concepts are similar: some actions modify an environment, which must be monitored with appropriate sensors and you have to rely on a model to know how the environment will evolve and, with sensors capturing real data, you can compare what you are thinking is happening with what is happening

One of the advantages that digital twin promises is its applicability to BIM, an acronym for Building Information Modeling, a process based on 3D models that provide to professionals of architecture, engineering, and construction the know-how and tools for planning, designing, building and managing buildings and infrastructure more efficiently.

We could say that the BIM characterizes the building as it should be, while the digital twin means how the building is and will be. More in detail, the BIM was created to help the designer to rely on all the useful information for the construction of a building. However, it cannot provide real-time information, which is possible for the digital twin. The latter, relying on applied sensors IoT and functions of Artificial Intelligence, enables the development of the smart building, buildings able to respond immediately to the needs and desires of users. Information from data analysis in such buildings is automatically managed to improve user performance, enabling services and informing them. If we then add the simulative capability to BIM, through the connection to real sensors, we could have the digital twin of a building.

[20]

[21]

4. The simulation model

The concept of the model has been mentioned several times in the preceding sections; with the word model, a representation, abstract, and simplified of a real system and its interactions are indicated. A model represents a system from specific points of view obtained considering some characteristics of the project; models are built because it is simpler and cheaper than building a system directly. The models are useful for communication, for planning the construction of systems and for studying the restructuring of an existing system.

Simulative models, in most cases, are a simplified reconstruction of reality, with which it is possible to analyze the system in all (or many) of its states, through the use of specific software.

Moreover, the models can also be differentiated according to their static or dynamic nature; a static model is a model that does not evolve in time, while a dynamic model vice versa, is a model whose state and characteristics change over time. Among the dynamic models, which evolve, we can identify deterministic models and stochastic models. The distinction in these two categories lies in the model's behavior:

- stochastic models have behavior that evolves according to random variables tied to random distributions, which assume values within a range of values belonging to a distribution. The outputs of a stochastic model vary in the time, to varying of the inputs;
- deterministic models have behavior characterized by constants, whose value remains fixed over time and which determine fixed outputs.

A further classification can be made according to:

- continuous models, where variables vary continuously;
- discrete models, in which the value of the variables changes in well-defined instants of time.

4.1 Elements of a simulation model

Variables of state

First, we remind that a system is described in every instant of time by a set of variables that take the name of state variables. So, for example, about a queue system, it is a status variable the number of users present in the system in a precise instant of time. We also recall that there are discrete systems in which the variables change instantly at precise moments of time and continuous systems in which the variables vary with continuity concerning the time. It should be noted that the choice of a continuous or discrete model to be used is not necessarily obligatory by the type of system; it can be decided, for example, to build a discrete model for a continuous system, depending on the study to be carried out.

Events

An event is an instantaneous occurrence that changes the value of at least one of the status variables. The arrival of a user to a queue system is an event, as well as the completion of a service. There are external events (exogenous events) and internal events (endogenous events). For example, the start of the service to a user in a queue is an endogenous event, because it is internal to the system; a user's arrival to a queue system is an exogenous event.

Entities and attributes

Entities are individual elements of the system that need to be defined. An example of an entity is a user in a queue system. Entities may be characterized by attributes that provide a value of data assigned to the entity itself. Entities can be grouped into classes that are sets of entities of the same type or can be grouped according to attributes. If, for example, we consider men and women as users of a queue system, since entities are people, they can be grouped into two classes according to the attribute "sex."

Resources

Resources are elements of the system that provide a service to entities. An entity may require one or more resource units, and if this is not available, the entity shall stand in a queue until it becomes available, or take another action. If the resource is available, it is "captured" by the entity, "retained" for the time necessary and then "released". An example of a resource could be given by a worker who oversees the operation of a machine that cannot function without the worker himself; when the use of this machine is required, if the worker's resource is available then the execution of the work is carried out otherwise it is expected that there is resource (worker) available. The worker will be kept for the duration of the work and then released.

Activities and delays

An activity is an operation whose duration is known at the beginning of the execution of the activity itself. This duration may be a constant, a random value generated by a probability distribution, a number in input or calculated from other events occurring in the system. An example is the service time in a queue system. A delay is a period of indefinite duration, which is determined by the system's conditions. The time an entity spends in the queue before to seize the resource is a delay.

4.2 Discrete-event simulation

In our case study, we will consider discrete, dynamic, stochastic simulation models that are commonly called discrete-event simulation models. Many applications are well represented by models of this type, and approximating continuous variations with discrete variations, it is possible to use also discrete models to represent the behavior of continuous systems, simplifying the analysis.

A discrete-event simulation (DES) models the operation of a system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus, the simulation time can directly jump to the occurrence time of the next event, which is called next-event time progression.

So a "discrete event system" is an environment where changes in state (event) not only occur at precise and predefined time instances but take zero time to happen. It is assumed that nothing happens between two consecutive events or, instead, that there are no changes of state in this period of simulated time.

It is clear that, since these models are dynamic, it is necessary to record or keep the memory of the (simulated) time that proceeds. In particular, it will be necessary to define a time advancement mechanism to make the simulated time proceed from one value to another. The variable that in a simulation model provides the current value of the simulated time is called "simulation clock," and there are two ways to define its progress:

- progress of time to the next event,
- advancement of the time in preset increments where time is broken up into small time slices and the system state is updated according to the set of events/activities happening in the time slice. Because not every time slice has to be simulated, a next-event time simulation can typically run much faster than a corresponding fixed-increment time simulation.

Both forms of DES contrast with continuous simulation in which the system state is changed continuously over time based on a set of differential equations defining the rates of change of state variables.

The first is the most widespread and is the one to which we will refer to. In this case, the "simulation clock" is initialized to zero and is advanced at the time of the first among the future events; then, the system is updated, taking into account the event that occurred, the timing of future events is updated, and the procedure is repeated. Unlike fixed-increment time simulation, periods of inactivity are not considered. For instance, considering a queue system in which events are the arrival of a customer, the conclusion of service; both are events because they cause a change in the value of some state variables. The mechanism of advancing time follows, in this case, the occurrence of these two events in the chronological order in which they occur.

An example of discrete-event simulation

Let us see a simple example of how to make a simulation at discreet events. We consider for this purpose a queue system consisting of a queue and a single server and assume that the interarrival times are evenly distributed between 1 and 3 minutes and that also the service times are evenly distributed between 0.5 and 2 minutes. Let us see how we can simulate this system. Since it is a system regulated by two stochastic processes (arrivals and services) to generate events, it is necessary to generate random observations from the two probability distributions that regulate the two processes. Suppose you have the two lists that provide, respectively the generated randomly by the corresponding distribution and the service times also they generated randomly by the corresponding distribution:

Interarrival times	Service times
1.9	1.7
1.3	1.8
1.1	1.5
1.0	0.9
…	…

Table 3

Assuming that at time t = 0, no user is present in the system. By observing the sampled values shown in the two lists, the sequence of events is easily obtained:

Time t Events
1.9 arrives a user starts the service
3.2 a user arrives and queues
3.6 ends service and the first user in the queue starts the service
4.3 a user arrives and queues
5.3 a user arrives and queues
5.4 ends service and the first user in the queue starts the service
...

Limiting this simple simulation to time t = 5.4 (so that two users have entered and completed the service), we can calculate, for example, the average time of stay in the system: the first user remains in the system 1.7 minutes, the second 2.2 minutes and then the average value is 1.95. This estimate makes no sense because it is obtained from the particular sequence of random numbers of the two lists. So, if the example, on the one hand, wants to highlight the mechanism of a simulation to discrete events, On the other hand, it already points out a mistake that could be made in considering the results of a single execution as reliable and which had an arbitrary duration. On the other hand, it should also be borne in mind that if we are interested in assessing the system's performance measures, that is to say, when stable conditions have been reached, the system should not be considered during the initial transitional period. These issues are a crucial element of each simulation and will be considered in detail in the following case study of the thesis.

4.3 Queuing theory

As we know, queues are a collective every-day experience. Queuing theory deals with problems that involve queuing (or waiting). Typical examples might be:

- banks/supermarkets - waiting for service
- computers - waiting for a response
- production situations - waiting for the parts to be worked
- public transport - waiting for a train or a bus

Queue theory is considered a branch of the Operations Research and allows the formalization of queue models through which it is possible to represent the various types of waiting for queue systems that arise in practice. The formulas that are derived indicate how the relative systems should operate, and the average amount of waiting for that occurs in various circumstances. These models are beneficial for determining how a waiting queue system works and how it could be optimized. Interest issues generally concern costs. If a high service capacity is provided, the system manager will incur high costs, but if not enough is provided, there could be a very long wait, perceived as a cost by the customer. In designing queueing systems, we need to aim for a balance between service to customers (short queues implying many servers) and economic considerations (not too many servers).

Queue system

A queue system is a system composed of a non-empty set of servers, capable of providing a service, and a non-empty set of waiting areas (buffers) capable of accommodating customers who cannot be served immediately. When the demand and/or the capacity to provide the service are subject to randomness, temporary situations may occur in which the service provider cannot immediately satisfy the requests. Customers who do not find a free servant follow the queue and are served according to particular service disciplines.

System characterization

For the application of queue theory, it is required to create a model of the real situation that takes into consideration the fundamental aspects described below:

- the population of customers (entities): the set from which the entities arrive. It can be finite or infinite. The finite population can be easily identified in the manufacturing environment as it is common to divide the population into lots.
- The arrival process: the way customers arrive, and it is generally a stochastic process. It can be modeled starting from two parameters: the number of incoming customers and the time between the arrival of two subsequent customers.
- The queue: it is formed by the customers present in the buffer, waiting to be served. The buffer capacity can be finite or infinite. In the case of a finite-size buffer, this affects the capacity of the system, ie, the number of customers waiting. Customers arriving after the capacity is full are rejected.
- Servants (permanent entities): servants are the subjects who process clients in the queue. They can, therefore, include both human operators and automatic machines of the production line. They are in constant number, fixed at the project level, and can be arranged in series or parallel depending on whether the processing is simultaneous or for subsequent phases. There could also be a variability in the times that operators dedicate to customers.
- The service process: usually, it is also a stochastic process that defines the time in which the service is provided.
- The service discipline: specifies the next customer served among those waiting when a resource is released. The service disciplines usually considered are: 1) FCFS - First Come First Served; 2) FIFO - First In First Out; 3) LCFS - Last Come First Served; 4) LIFO - Last In First Out; 4) SIRO - Service In Random Order.

"Representing" a queue: Kendall's notation

The Kendall notation shows all the fundamental elements thanks to which it is possible to define a queue: A / B / c / K / m / Z

A: distribution of the arrival process;

B: distribution of the service process;

c: number of resources;

K: system capacity (default: infinite);

m: population size (default: infinity);

Z: service discipline (default: FCFS);

From the dynamic point of view, a queue consists essentially of two stochastic processes: the client arrival process (letter A) and the service process (letter B). In particular, A and B can be replaced by the following letters:

M: exponential distribution (Markoviana)

D: constant distribution (Degenerate)

Ek: Erlang distribution of order k

G: generic distribution

GI: generic distribution of independent events (for arrivals)

For example, M / M / 1 stands for M / M / 1 / ∞ / ∞ / FCFS: queue with Markovian arrivals and services, with a servant, with infinite system capacity, with arrivals from an infinite population, served based on FCFS.

In general, however, several parameters are used for a full description of a waiting line:

System Parameters
Number of Servers: ***s***
Arrival Rate (number per unit of time): **λ**
Service Rate (number per unit of time): **μ**
Utilization Factor (ratio between the time spent in service and the total time available): $\boldsymbol{\rho}$

Performance Measure
Number of Entities in the System: **L**
Number of Entities in the Queue: **Lq**
Number of Entities in Service: **Ls**
Time Spent in the System: **W**
Time Spent in the Queue: **Wq**
Time Spent in Service: **Ws**

Formulas:

In general, the results available from queueing theory are for steady-state conditions

The expected average value of the interarrival time distribution: $\boldsymbol{E(A) = \frac{1}{\lambda}}$

The expected average value of the service rate distribution: $\boldsymbol{E(S) = \frac{1}{\mu}}$

The utilization factor also represents the probability that a server will be busy at any point in time:

$$\rho = \frac{\lambda}{s * \mu} = \frac{E(S)}{s * E(A)}$$

The average time an entity spends in the system:

$$W = \mathbf{Wq} + \mathbf{Ws} = \frac{1}{\mu - \lambda}$$

$$W = \mathbf{Wq} + \mathbf{E}(S)$$

The average number of entities in the system:

$$L = \mathbf{Lq} + \mathbf{Ls} = \frac{\rho}{1 - \rho}$$

The average number of entities in the queue:

$$\mathbf{Lq} = \frac{\lambda^2}{\mu(\mu - \lambda)} = \frac{\rho^2}{1 - \rho}$$

The average time spent waiting in the queue:

$$\mathbf{Wq} = \frac{\lambda}{\mu(\mu - \lambda)} = \frac{\rho}{\mu(1 - \rho)}$$

Little's Law

If a queue is stable, on average, as many clients as they come in, they have to go out. For a queue M / M / 1, the output speed is therefore λ. Little's Law states that the long-term average number of customers in a stable system L is equal to the long-term average effective arrival rate, λ, multiplied by the average time a customer spends in the system, W.

$$\mathbf{L} = \lambda * \mathbf{W}$$

$$\mathbf{Lq} = \lambda * \mathbf{Wq}$$

Example

Suppose we are in a supermarket with ten customers per minute and suppose every cashier serves a customer every 2 minutes. How many cashiers should I arrange so that the average total waiting time (waiting in queue + more service in cash) is less than 5 minutes?

We define:

$\mu = 2$: average service rate $\Rightarrow 1 / \mu = 0.5$: expected service time

$\lambda = 10$: average arrival rate $\Rightarrow 1 / \lambda = 0.1$: time expected between two arrivals

unknown: s numbers of servants

At this point, it is essential to define the so-called utilization factor

$\rho=\lambda/(s\mu)$

which expresses the ratio between the average service time and the average time between two arrivals. A system is defined stable if, on average, it has the potential to serve customers faster than they arrive. From which the so-called stability condition is obtained: $\rho < 1$

Therefore:

If it must be $(10 / s * 0.5) < 1$

$\Rightarrow s = 20$

So with 20 boxes available, there would be the certainty of having a system able to manage the queue, but not to guarantee that the average waiting time is less than 5 minutes.

The average waiting time in a system with s resources is equal to:

$Ws = s / (\mu * s-\lambda)$

By imposing the constraint:

$Ws < 5 \Rightarrow s / (0.5 * s-10) < 5 \Rightarrow s > 33.33$

Hence, given this average time of arrival of the customers, and this average service time, the number of cashiers guaranteeing an average residence time in the system, fewer than 5 minutes is 34.

5. The life cycle of a simulation project

The main difficulties in the use of simulation are related to the design phase of the model and the analysis phase of the simulation experiments because an error in one of these two phases can result in too considerable uncertainty of the results and a failure of the simulation itself.

The third is to build a model that is a good approximation of the real system, without being an exact representation of this, but which takes into account the central processes which characterize the functioning of the system and which allow to obtain all the data useful for the analysis on the system that you want to do.

Consensus exists between the people involved in the development and maintenance of simulation models, that simple models are preferable to complex models. Despite it, in many projects, the simulation models usually are large and complex. It is necessary to emphasize that the excess of complexity in the models not only has an impact on the computational performance; it also affects other aspects, such as the time needed for the model development, its maintenance, verification, and validation.

Although it seems a very intuitive concept, it does not exist a definition or measurement of complexity accepted as a standard by the scientific community. Some authors relate, for example, the complexity of the model with "the level of detail" and others with "the spread of the system." Some of the advantages of working with simple models are:

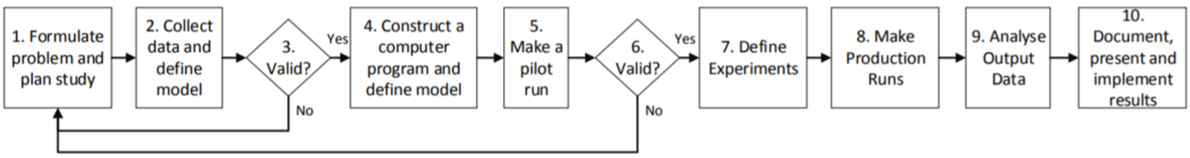
- They are easier to implement, validate, and to analyze.
- It is more comfortable and, in a certain way, less painful, to reject a simple model that has, for example, a design error than a complicated model in which a considerable number of hours of expert personnel have been invested.
- It is easier to adapt a simple model than a complex model if the conditions or hypotheses of operation on the real system change.
- The overall project life cycle time is usually smaller.

A simulation project is dynamic by nature. The results that are obtained as it is developed, expose new problems as well as inherent limitations to the studied system, this can force to reconsider the initial project orientation. Moreover, the motivation of the client can also change throughout the project, as a consequence of the obtained results or by external factors to the own project. To be successful in such a dynamic environment, it is necessary to use the correct methodology.

Although the following set of phases, it can seem that the development of a simulation process is a sequential process, actually is not thus. For example, if the obtained model of simulation does not surpass the validation phase, it could be necessary to modify the conceptual model as well as the simulation model.

5.1 Phase Description

To build a model, there is, therefore, a need to follow "guidelines" that are clear, shared, and repeatable. As described by Law&Kelton, a typical simulation process can be built through iterative processes:



The DES process, adapted from Law & Kelton (1991).

5.1.1 Formulation of the problem

A kickoff meeting(s) for the simulation project is (are) conducted, with the project manager, the simulation analysts, and subject-matter experts (SMEs) in attendance. The following things are discussed at this meeting:

- The overall objectives of the study (precise, reasonable, comprehensible, and measurable).
- The specific questions to be answered by the study. Without such specificity, it is impossible to determine the appropriate level of model detail.
- The performance measures that will be used to evaluate the efficacy of different system configurations. Different performance measures will sometimes dictate different levels of model detail.
- The scope of the model.
- The system configurations to be modeled. This information is necessary to determine the generality that must be built into the simulation computer program.
- The time frame for the study and the required resources.

Simulation projects generally take more time than initially estimated, because the system's logic turns out to be more complicated than thought and because there are delays in getting the required information and data. Also, significant difficulty in many projects is the decision-maker misunderstanding of the amount of time and resources required to perform the study.

The specification of objectives is one of the most important tasks of a simulation project. All modeling and analysis activities should be focused on the objectives. If the objectives are not transparent or are small concrete, there exists the danger of not approaching the problem correctly and being incapable of responding to the generated expectations. Consequently, it is necessary, in the initial phase of any simulation project, to identify the objectives and to formalize them so that they are precise, reasonable, comprehensible, and measurable. These objectives will be a guide throughout the project. Thus, as the study proceeds and a better understanding is obtained, this information should be communicated to the decision-maker who may reformulate the problem.

5.1.2 Data collection

Collect information on the system structure and operating procedures. In general, it is recommended to question all the information and data available. Which is the source? When was obtained? How was gathered? Has this one sense? We have insufficient data, or is it excessive?. To obtain good results, it is an indispensable condition having good data. Unfortunately, in many cases, this is not possible. Even so, an answer to the raised questions is required and is necessary to carry out reasonable hypotheses in collaboration with the end-user. If the data is limited or its quality is doubtful, it is advisable to be prudent at the time of concluding the base of the simulation results. Even in the cases in which there are problems with the data, the acquired knowledge, and the results obtained in the simulation study are valuable information for decision making.

At this stage, all the activities necessary for data processing are foreseen to make them suitable for use within the model. Data may come from different sources, both from business databases and direct field measurements. No single person (or document) is sufficient. Thus, it will be necessary for the simulation analysts to talk to many different SMEs to gain a complete understanding of the system to be modeled. Data collection is very often an iterative process, which takes place throughout the development of the model.

Design of the conceptual model

Document the model assumptions, algorithms, and data summaries in a written *conceptual model* (or "assumptions document"). This is a *critical* activity that is often skipped – verbal communication is very prone to errors.

The temptation to initiate the construction of the simulation model immediately should be avoided. This option generally leads to simulation models with multiple lagoons and onerous maintenance. For this reason, it is advisable to formulate or to specify the simulation model being used at a level of abstraction (conceptual model) superior to the level of the simulation code. The conceptual model specifies the more critical structural relations of the system that is tried to simulate and, consequently, constitutes a means of dialogue and coordination between the different departments or involved groups.

The conceptual model should include the following:

- An overview section which contains the overall project goals, the specific issues to be addressed, and the performance measures of interest.
- A process-flow or system-layout diagram (if appropriate).
- Detailed descriptions of each subsystem and how they interact.
- Simplifying assumptions were made and why. A simulation model should be a simplification or abstraction of the real system, with just enough detail to answer the questions of interest.
- Summaries of model input data – technical details and complicated mathematical/statistical calculations should be in appendices. The conceptual model should be readable by the *decision-maker* as well as by the analysts and the SMEs.
- Sources of essential or controversial information, so that this information can be confirmed by an interested party.

5.1.3 Conceptual-model validation

Perform a structured walk-through of the conceptual model before an audience that includes the project manager, analysts, and SMEs. This critical activity, which is called *conceptual-model validation*, is very often skipped.

More specifically, it should be examined whether real system performance measures are well approximated by the measurements generated by the simulation model. This is very difficult to perform, especially at the design stage when the real system does not exist.

- It helps ensure that the model's assumptions are correct and complete.
- Fosters interaction among members of the project team – having members of the project team read the conceptual model on their own is recommended but is *not* sufficient.
- Promotes ownership of the model, which can help lessen political problems.
- Takes place *before* "programming" begins to avoid significant reprogramming later.
- If errors or omissions are discovered in the conceptual model, which is virtually always the case, then the conceptual model must be updated before proceeding at programming.

5.1.4 Construction of the model

Program the conceptual model in either a general-purpose programming language (e.g., C or C++) or a commercial simulation-software product. Several advantages of a programming language are familiarity, greater program control, and lower *software purchase cost*. On the other hand, the use of a commercial simulation product will reduce "programming" time and *overall project cost*. There are two main types of commercial simulation-software products: general purpose (e.g., Arena, Extend, SIMUL8, and SLX) and application-oriented (e.g., AutoMod, Flexsim, Pro- Model, SIMPROCESS, and WITNESS). Verify (debug) the computer program.

Often, the effort concentrates more on the construction of the model than in the resolution of the problem. Obtaining a running model becomes erroneously a high-priority objective. The dominant motivation should be the understanding of the problem and the obtaining of solutions. To advance more quickly in the attainment of these objectives is recommendable to construct in the first place one or several simplified models that characterize the most essential parts of the system.

Since we are dealing with stochastic systems, to formulate a model you need to know the probability distributions of the quantities of interest. To generate various scenarios representative of how a system works, a simulation must generate random observations from these distributions. For example, in queue systems there is a need for the distribution of inter-travel times and service times; in the management of stocks, the distribution of the demand for products and the distribution of time between an order and the receipt of the goods are necessary; in the management of production systems with machines that may occasionally fail, you will need to know the distribution of time until a machine fails and the distribution of repair times.

Generally, it is only possible to estimate these distributions by, for example, observing similar existing systems. If, from the analysis of the data, we see that the form of this distribution approximates a standard type distribution, the standard theoretical distribution can be used by performing a statistical test to verify whether the data can be represented well by that probability distribution. If there are no similar systems from which observable data can be obtained, other sources of information shall be used: machine specifications, machine instruction manuals, experimental studies, etc. The construction of a simulation model is a complex process. In particular, concerning discrete event simulation, the construction of a model includes the following steps:

(a) Definition of the status variables.

(b) Identification of the values that can be assumed by the variables of state.

(c) Identification of possible events that change the status of the system.

(d) Simulated time measurement, “simulation clock”, which records the flow of simulated time.

(e) Development of a method to randomly generate events.

(f) Identification of event-generated status transitions.

5.1.5 Pilot case

Once the model is realized and validated, there is the first execution of the same one; in this step is executed a pilot execution for the verification of the dynamic behavior of the simulation model realized.

You need to decide how to conduct the simulation. Often a simulation is a process that evolves during its realization and where the initial results help to lead the simulation towards more complex configurations. There are also statistical issues:

- determination of the length of the system transient before steady-state conditions, from which data start to be collected if system performance measures are desired;
- the determination of the simulation length (duration) after the system has reached equilibrium. It should always be borne in mind that simulation does not produce exact values of the performance measures of a system because each simulation can be viewed as a statistical experiment that generates statistical observations on the performance of the system. These observations are then used to produce estimates of the performance measures, and, of course, increasing the duration of the simulation can increase the accuracy of these estimates.

The output of the simulation provides statistical estimates of the performance measures of a system. The fundamental point is that each measure is accompanied by the confidence interval within which it may vary. These results may immediately show a better system configuration than the others, but often more than one candidate configuration will be identified. In this case, further investigation may be necessary to compare these configurations.

5.1.6 Verification and validation

Figure 31

In the simulation field, the experience recommends supposing that all models are incorrect unless the opposite is proven. One of the main dangers of the simulation is "to forget the real world and to accept without repairs the results of the model."

In an engineering and simulation context, to ensure that a product, service, or system complies with the specifications and, as a consequence, to make strategic decisions or operational being based on the results, it is necessary to verify and to validate the simulation model.

Verification means the assessment of the product under development to determine that the specified requirements are met. At this stage, we do not evaluate the actual product but the specifications, plans, drawings, and procedures.

Instead, validation refers to the finished product and assesses whether the requirements and specifications are met. Validation is used to demonstrate that the finished product can do what it was designed and designed to do.

Regarding simulation, in the validation phase, we check, for example, that the model solves the right problems, is based on correct assumptions, and follows the appropriate physical laws, ensuring the correctness and accuracy of the result. The validated model, therefore, appears to be applicable only in the specific context for which it was created.

The verification of the model, instead, allows characterizing errors whose correction will not go to modify the specifications but only how they are implemented. These include, for example, programming errors to ensure that the model meets the validated requirements and behaves as intended.

In summary, the V&V process makes it possible to compare what the model does with the actual system behavior (validation) and what the model predicted (verification).

Validation is a difficult task since there is not a standard way to solve validation problems.

If there is an existing system, then compare performance measures from a simulation model of the existing system with the comparable performance measures collected from the actual existing system. If results validation is successful, then it also lends credibility to the simulation model.

Regardless of whether there is an existing system, the simulation analysts and SMEs should review the simulation results for reasonableness. If the results are consistent with how they perceive the system should operate, then the simulation model is said to have face validity.

Sensitivity analyses should be performed on the programmed model to see which model factors have the most significant impact on the performance measures and, thus, have to be modeled carefully.

5.1.7 Experimentation and analysis

It consists of experimenting with the model to carry out inferences that allow making decisions with greater security. In this stage, techniques such as the reduction of the variance or the design of experiments are often used. In general, the most important added value of a simulation study is not the final results obtained with the model. The most valuable result is the insight knowledge acquired in the analysis process that gives justified qualitative and/or quantitative arguments in favor of or against the different raised design options.

For each system configuration of interest, decide on tactical issues such as simulation run length, length of the warmup period (generally necessary if the steady-state behavior of a system is of interest), and the number of independent model replications. A significant pitfall here is to make one replication of the simulation model of some arbitrary length and then to assume that the resulting output statistics are, in fact, the actual performance measures for the model. We recommend that a confidence interval be constructed for a performance measure of interest. Analyze the results and decide if additional experiments are required.

Starting from the real situation, that is from the model that represents the system in its current state - “As-Is” - we pass to the analysis of experimental operating solutions - “What-If” - evaluating, thanks to the use of the simulator, both the changes in system behavior and the changes in performance that these solutions determine. Using the analysis of “What-If” it is possible:

- determine the response to the change in the system;
- search for the system’s expected performance;
- search for the optimal value of a system variable;
- determine the sensitivity of the system to changes;
- compare alternative system configurations.

During the study of a system, the attention is usually focused on some aspects specific such as:

- the characteristics of the inputs;
- the characteristics of the transactions which mainly influence the flow through the process;

- the bottlenecks;
- the use of resources and conflicts for their use.

5.1.8 Documentation and implementation

It is essential to maintain an updated document that reflects the state of the project. Therefore, the document will evolve, and it will become mature in parallel with the simulation project. The objectives pursued with the documentation are:

1. To show the state of the project at a given moment. In this manner, all the technical or directive personnel who are related to the project have up to date information on its progress.
2. To inform about the whole project (final document).
3. To facilitate the reusability of the model in the cases in which a possible interest in its future use is anticipated. It is recommended to collect in the documentation the following information: introduction, objectives, hypothesis, physical description of the system, description of the conceptual and simulation models, verification and validation, analysis of the conducted experiments, and conclusions.

Taking decisions as a result of a simulation study is understood as implementation. A simulation analyst needs to interact with the appropriate managers regularly. If the manager or decision-makers understand and agree with the model's assumptions, they are more likely to accept the model as valid and use the results to make decisions.
(AM Law et al. 2000)

6. The case study Ratti S.p.A.

6.1 Introduction of change in the textile industry

The textile and clothing industries have always been considered, in common sense, labor-intensive and with low use of technology due to the high intensity of work and the reduced investments made in the field of research and development. Textile and clothing companies, mainly small and medium-sized enterprises, are characterized by multiple activities, such as the production of raw materials and the creation of finished products. In recent years, however, things are taking a different direction: there is an acceleration regarding technological development and a change in innovation models. More and more open innovation models are being developed, in which internal knowledge is exploited to accelerate development processes and external knowledge to expand distribution markets. This depends both on the ability to collaborate with companies from different sectors and on the ability to exploit investments in research and development within the industry. The role of Information Communications Technology (ICT) has brought about a change both in the production processes and in the ways of selling and using consumers. In recent years there has been an increase in productivity in all parts of the production chain; due to the crisis; however, some companies have been forced to transfer their production plants to areas where labor is available at low cost (Iacobucci D. and Perugini F., 2018).

Besides, a factor that is becoming increasingly important today is the issue of environmental sustainability: to try to reduce emissions and, therefore, waste, and it is necessary to have an efficient production process. For this reason, the concept of Industry 4.0 with the associated enabling technologies must also be introduced in these artisan businesses.

The textile industry includes diverse constituents such as raw material, yarn, weaving, dyeing, and finishing. The finishing department is one of the last processing section for textile products. Here, various processes are being applied to enhance the features of textile goods, for instance, appearance-related ones such as dyeing, printing, polishing; handling related ones such as softening, hardening, usage properties related ones such as easy to iron, flame retardant, and shrink-proof finishes.

These sections of integrated textile mills are the ones that need the utmost attention; hence they accommodate complex processes and contain various operations that are hard to recover and which entail high costs in case of any error. The complexity of the production imposes to employ the techniques that enable to facilitate the decision-making mechanism.

Demand input is the principal fundamental input parameter for preparing the production plans and control of the stocks. For that reason, as the realist demand forecasts will ensure the validation of the plans, it is necessary to pay due attention to this issue. Hence textile mills mostly follow the strategies to protect the potential customers, they know about their customers and realize their demands leaning against the forecasting methods based on experience and intuition or they make their forecasting, taking in to account the sales volume of a defined product group within an appropriate period (3 months/annual) following average demand approach. The demand in the textile sector is not constant; therefore, factors such as seasonal influences and trends would be a more reliable approach. The essential aspect of demand forecasting, which is essential to reckon with, is the tendency of demands concerning fashion (trend) and seasonal changes.

Therefore, the prime element in the textile sector is to accept that the demand is not constant.

Usually, the costs of tops dyed fabrics are generally much higher than the costs of fiber dyed fabrics. Because, the number of top dyed fabric production processes higher than the number of fiber dyed fabric production processes, and their reprocess (reversing of the process) rates are also higher.

If there was the risk of failing to catch a deadline, or there were any resources related to bottle-necks, subcontractor production is a widely employed solution.

In such mills, the complexity of the production planning imposed to set up a planning model.

(Emel Ceyhun et al., 2014)

6.1.1 Simulation in the textile sector

Simulation is the separation of the model setting operation into small parts and recomposing them in a way that enables them to show their mutual interactions and in their natural order. It is an experimental study to execute the trials and to forecast the error times of the procedures on the purpose of designing the model of the real system and operating the system with this model.

There are numerous studies, for example, work-time scheduling for production planning under variable demand, customer satisfaction, reducing the number of stops, elimination of the bottlenecks, shortening the length of deadlines, cost minimization, etc.

(Emel Ceyhun et al., 2014)

Once a simulation model is accurately programmed, any machine change, various manufacturing policies, and other "what-if' scenarios can be quickly evaluated. And, it will provide detailed data such as machine utilization, WIP inventory, and production cycle time. These results can answer questions about resource availability, detect bottlenecks, and determine storage requirements. The probabilistic, interactive, and dynamic nature of the manufacturing system makes computer simulation a more suitable tool than analytical techniques to solve this kind of problem.

Any unbalanced process or bottle-neck will reduce manufacturing capability. Once a problem happens in any manufacturing process, a solution has to be found very quickly to solve the problem without delaying production.

The simulation model can be used in two ways. One way is to use it to schedule production. Since it takes only a few minutes to simulate one week of production, it is swift to do scheduling work, which makes it possible to test different schedules to find a good, if not optimal, schedule.

Another way to use the simulation model is to allocate resources for different production requirements. Because any order change will cause the corresponding adjustment in the related processes, potential problems in terms of bottle-neck or unbalanced facility utilization need to be identified in advance to make any change quickly and smoothly without reducing productivity. Resources (such as equipment and human operators) can be reallocated easily by adding or reducing the capacity of that resource in the simulation model. The consequences of any change will be reflected by the simulation result.

Historic manufacturing data and sales forecasts were used to design simulation scenarios that covered typical manufacturing situations in the company.

(Jingjun Sun et al., 1991)

As a demonstration that the textile industrial realities are changing, in the next section, the case study relating to Ratti S.p.A., a textile company that has decided to undertake the path towards the introduction of the principles of Industry 4.0 will be presented.

In the following paragraphs, the company will be presented, and the work that has been done in these 6 months will be illustrated and discussed.

6.2 Presentation of the company

The company Ratti S.p.A. was founded by Antonio Ratti in Como in 1945, with the name of "Tessitura Serica Antonio Ratti," to create and market silk fabrics and scarves. In 1954 the industrial activity for the printing of silk fabrics started. The Guanzate (CO) plant was inaugurated in 1958, where production is still taking place, from the yarn to the finished product through the weaving, dyeing, printing and finishing stages. In 1961 and 1974, the lines of fabrics for women's clothing and fabrics for furnishings were introduced respectively. In 1975 the company began exporting its fabrics, opening the offices in Paris and New York, while in 1989, it was listed on the Milan stock exchange. In 1995 he opened, at the Metropolitan Museum of Art in New York, one of the largest and most advanced structures in the world in terms of technology for the study and conservation of fabrics, the "Antonio Ratti Textile Center." In 1999 the Guanzate (CO) plant was renewed, and only a year later, in 2010, the Ratti S.p.A. company is acquired by the Marzotto Group. Today Ratti S.p.A. is one of the major producers of printed, plain and yarn-dyed fabrics, jacquard for clothing, neckwear, shirts, beachwear, underwear, and furnishings. It manufactures and distributes accessories for men and women for international luxury brands. Ratti S.p.A. internally develops the complete processing cycle: from the creative phase inherent in the design and design of the fabric to the actual production through the stages of weaving, dyeing, printing, and finishing. The mission of Ratti S.p.A. consists of the constant search for beauty, which, according to the company, goes hand in hand with the study, experimentation, and adoption of innovative and cutting-edge production techniques. The annual production exceeds four million meters of fabric, and the export has reached about 70% of the total turnover.

Ratti S.p.A., over the past few years, it has been implementing an integrated management system in which quality, the environment, safety, and social responsibility must go hand in hand. By quality we mean, the continuous improvement of business processes to meet the needs of internal and external customers; environment means respect for the ecosystem with particular attention to the theme of recycling, the reduction of consumption, the materials and products used; safety means the guarantee of safety of people and working environments; finally, social responsibility regards people, communities and all society as a whole. To implement an integrated production system, Ratti S.p.A. has recently embarked on the evolution process towards the Smart factory. In this way, we will move from a centralized system to a decentralized one thanks to the progressive introduction of advanced ERP and MES systems at company level together with the creation of a network for the interconnection of data that will replace the exchanges of information that still occur in large part starts in paper form, by telephone and email.

We speak of a distributed IT system when at least one of the following two conditions is verified:

- the applications, which cooperate, reside on several processing nodes (distributed processing);
- the unitary information assets are hosted on several processing nodes (distributed database).

In general terms, therefore, a distributed system is made up of a set of logically independent applications that collaborate for the pursuit of common objectives through a hardware and software communication infrastructure. [22]

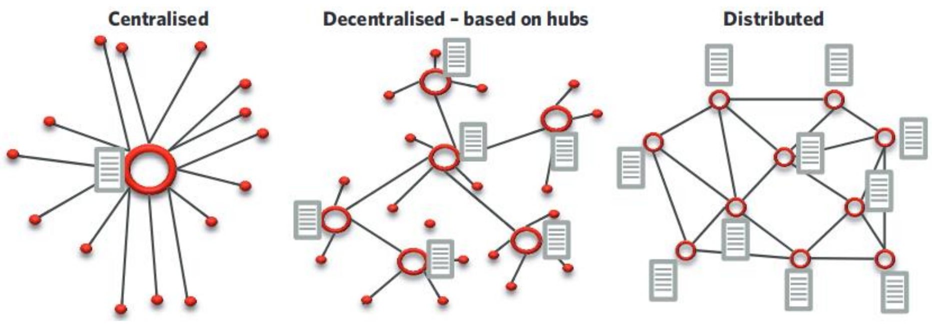


Figure 32

Initially, the planning process was based only on the knowledge and experience of the physical operator, who had to be trained for the use of the new enabling technologies typical of Industry 4.0. Over time, some scholars have argued that centralized and autonomous control was efficient and that a decentralized control system instead led to higher levels of complexity in decisions. However, with the new concept of interconnection and intelligent machine, the need arose to change this thought because the existence of intelligent objects and distributed control is changing the role of the operator in managing the production system. The production manager is in a condition where he decides only if he has a right amount of data from intelligent objects. In a sense, the decision-maker is short-sighted in that he makes choices based on what is communicated to him by the intelligent machines connected to the network (Bendul J. C. et al., 2019).

Most of the employees and operators who work in this industrial reality have in-depth knowledge and experience gained in the field over the years. Precisely for the fact that most of the knowledge belongs to the operators, the company must undertake a path of the introduction of Industry 4.0 so that everyone, even the newly hired staff, can be aware of the processing parameters and information needed to perform the work better. Thanks to the interconnection that involves all departments, operators will have visibility over the entire process, thus managing to have better planning and management of the workload. Being Ratti S.p.A., an artisan company, the operator can never be replaced entirely by intelligent machines and objects typical of the Smart factory but can be assisted and supported by these technological interconnections in making decisions.

6.3 Organizational structure

Currently, the corporate organizational structure is divided into four levels: the first level is made up of six business poles, the second by groupings of operating divisions, the third by operating divisions, and the last by reporting divisions. Each pole has an organizational and business manager who reports directly to the underlying levels. Each organizational division has its customers and supplier's data; this information is transmitted at a general level to transfer the data to the administration that deals with accounting and cost monitoring and to allow reporting analyses. The Luxury pole follows the segment of the fashion market with high-brand customers. We tend to produce printed fabrics for clothing and accessories, yarn-dyed fabrics for clothing and textile accessories. It is a production mainly based on the order. The Carnet pole follows the market of tailors who buy ready-made fabrics from the warehouse and the packagers. The fabrics are mainly purchased from Marzotto group companies and produced internally. The Collections pole follows the medium segment of the fashion market for which it is mainly produced on order, printed and yarn-dyed fabrics for clothing and textile accessories such as stoles, scarves, scarves, ties, etc. The Studio pole follows the licensing market; that is, it deals with the production and distribution of textile accessories under license from specific brands. Production is both on order and for the warehouse. This pole also manages private customers, who have no known clothing lines. The Industries pole follows the fast fashion market for which it produces printed fabrics for clothing and accessories to order. The Furniture pole follows the furniture fabrics market for which it produces printed fabrics and accessories to order.

6.4 Description of information systems

To date, in Ratti S.p.A., there is a complex ERP architecture composed of different information systems based on AS400. In particular:

1. SIR: customized system to support the printer.

2. Gtex-Porini: a vertical market system for textile companies, used in the weaving department.

3. Stealth: a customized market system for the clothing business and the management of finished garments and textile accessories.

4. Carnet: customized system serving the stock service.

5. SAP: a system used in administrative, management control, and plant maintenance processes. It is also used to cover purchases of chemicals and dyes.

The ERPs present is supported in the operational processes by departmental sector systems and/or specific department components.

6.5 Description of the Ratti production process

As previously reported, the company is today one of the world's largest manufacturers of packaged products for men and women, such as ties, scarves, and scarves. The entire production cycle is carried out within the company through the processes of weaving, dyeing, scouring, plating, printing, steaming, washing, finishing, quality control, and packaging of the finished product.

The first activities relating to the creation of the drawing, the definition of the order, and the inclusion in the customer master data in the SIR information system, are carried out by the technical office. The launch of the order is then carried out, and the paper print order sent to the office responsible for production planning which, registers the order on the Microsoft Access Database, checks the references and communicates the feasibility analysis of the processing. Once the order is acquired, it is evaluated and dated by the Dating information system, so that the fabric can be blocked in the system and reserved for processing via MRP. Following the printing of the order confirmation, production proceeds. After the warehouse has received the order, it can prepare the fabric for subsequent processing, depending on whether the reels are ready for printing or need further processing to prepare for printing. In particular, if the material supplied by the suppliers is raw and if the printing is carried out with the traditional technique, the fabric passes to the purge; on the other hand, if the printing takes place through inkjet technology, the fabric must first be plated. In the purge department, the rolls of fabric to be processed are inserted into the machine of the same name and are subjected to one of the two types of baths provided according to the characteristics of the fabric. This process is intended to clean the fabric of any residual slag. Once "purged," the fabric is brought to the plating department to undergo flattening. Plating and flattening are carried out by the same machine as what changes is the product that is used. In particular, in the case of flattening, water is used, while in the case of plating, a particular product specified on the recipe is used based on the type of fabric. Once the fabric has completed the pre-printing activities, we proceed with the printing activity, which can be of two types, inkjet or traditional, depending on the specific order. To ensure longer life of the printed design and to clean it of any residues, the fabric is introduced first into the steaming machine and then into the washing machine. Washing can be of two types, rope or comprehensive, depending on the characteristics of the fabric. The washed fabric is then checked in the intermediate quality control department and taken by the operators to the finishing department where the processing of the same name is carried out and sent to the final quality control before being transferred to the packaging and finished products department. During the finishing, there is also a test activity regarding some fabrics, to verify the conformity of the fabric. Only after the test has passed can the fabric advance to the next final quality control process.

The company's production process is artisanal, and therefore people's skills, knowledge, and skills are of fundamental importance. For this reason, it is complicated to replace operators, especially when they have been in the company for years. However, with ever-increasing production volumes, and the request for customization, it is essential to try to have accurate production planning that involves a higher degree of flexibility, efficient use of resources and optimization of time.

6.6 Job Shop Scheduling

Scheduling is one of the essential activities in production planning because, if carried out efficiently, it is what allows us to obtain an optimization of production. Scheduling plays a fundamental role in the manufacturing process since it has a direct impact on both efficiency and production costs. Precisely because of the importance of this phase, the research pays attention to the issue of efficient scheduling since 1956 (Zhang J. et al., 2019).

As anticipated, unlike traditional scheduling, which can be centralized or semi-distributed, the typical scheduling of the Industry 4.0 environment is decentralized or distributed and is supported by the key technologies typical of the Smart factories illustrated above.

Over the years, the concepts of Advanced Planning and Scheduling (APS) and Smart Distributed Scheduling (SDS) have been introduced precisely to highlight the characteristics of the new production environment: advanced, smart, and distributed. In particular, thanks to the technology always more innovative, Advanced Planning and Scheduling represents a revolutionary step in that it takes into account numerous constraints for the realization of an optimal production plan both at the company and inter-company level.

The parameters to which APS refers are for example, the availability of materials, the capacity of the machine, the timing and needs of customers, the levels of safety stocks, the distribution requirements, the efficient sequencing of setups, etc. (Lin L. et al., 2012).

Given that the application case treated below is inherent to a textile company that has an organization by departments, we will pay particular attention to the typical scheduling of Job Shop production.

Job-shop scheduling model (JSP) The Job Shop (JSP) scheduling model concerns the determination of the operating sequences on the machines of the different departments, to minimize the makespan (Cheng R. et al., 1996). The makespan is a technical term used to indicate the time that elapses between the moment of release of the first piece in production and the moment of completion of the last piece in production in the last machine.

7. The Ratti Simulation Project

For the development of the project, I will use the life cycle process proposed by Law & Kelton as a reference scheme and guideline.

7.1 Formulation of the problem

The general objective of the project is to try to reproduce the behavior of a part of the production process to see if it will be possible to apply the simulation when product tracking is implemented with RFID. To date, therefore, this project remains experimental because the lack of specificity in many data, as we will note in the critical issues, and also of a specific scheduling method make the maximum accuracy of detail useless. The aim, however, remains to simulate the finishing department with real data that reproduce its behavior in an approximate but truthful way. In the end, after validation, some solutions will be sought for possible future ideas regarding scheduling logic.

To carry out the simulation, the acquisition of data obtained from the company information system was of great importance. Although they have often been presented with many gaps, it was possible to create datasets thanks to the use of the R software in order to make them useful for the study. A three-year production span was taken as the analysis period.

7.1.1 Finishing department

The finishing department was defined as a starting point to develop the simulation study because despite being positioned downstream of the production process, in this area, the products remain long and with numerous queues. The room for improvement is, therefore, relatively high compared to other departments.

The textile finishing operations are a part of the "fabric ennobling" operations for which we mean the set of treatments aimed at transforming the raw fabric into semi-finished products suitable for subsequent processing, or in finished fabric ready for the manufacture of articles.

The finishing (or finishing) of fabric includes all those treatments to which the fabrics are subjected at the end of the ennobling operations. These treatments are intended to improve their appearance, hand, properties, also according to the possible fields of use.

Finishing, therefore, means the set of chemical, physical, and mechanical treatments to which the fabrics are subjected to give them specific properties for the use for which they are intended.

[23]

The chemical structure of the textile fibers, whether natural, artificial, or synthetic, determines for them some properties that are naturally present also in the manufactured articles that are produced from them. Therefore there will be more tenacious fibers (linen, hemp, silk, nylon, polyester) than others (wool, viscose, acrylic); others that tend to deform under stress (cotton, viscose) compared to those that recover the initial appearance after deformation (wool); still others that burn easily (cellulose), slowly and self-extinguish (wool, silk) or burn and melt (synthetic). These and other characteristics contribute to defining, for a textile, those positive or negative properties from the use for which it will be destined. In this perspective, the judgment is formulated from different points of view: wearability, hand, mechanical resistance, hydrophilicity, washability, deformability, fire resistance, and others.

For the realization of the finishes, depending on the type of textile substrate (staple, yarn, or fabric), we use:

- Mechanical means through the application of physical principles such as friction, temperature, pressure, tension, and others.
- Chemical media after application of natural and/or synthetic chemicals, which are more or less permanently bond to the fibers.
- Combination of mechanical and chemical means through the use of both mechanical and chemical processes.

(Giovanna Baglio, Ottobre 2007)

In the particular case of the finishing department of the Ratti company, the procedures for carrying out the process depend on the recipe associated with the order. The recipe is defined by a series of parameters that clarify the various procedures to be followed.

Orders are, in fact, subject to specific processes characterized by phase schedule. Machinery or activities (such as sewing to connect the production flow) are required to carry out the phases. From here on, to simplify understanding, only the term machines will be used since their distinction does not affect the behavior of the model. Having more phases than machines means that the procedures in individual machines vary by phase. As will be seen in the paragraph of data analysis, the processes don‘t follow the same number of phases, and the sequence of these last ones cannot be changed. Therefore is kept a macro view on what is happening within the finishing department, while the technical operation of the phases is explained as it is not of extreme relevance for the study.

The fabric that arrives at the finishing department is accompanied by a sheet for each order containing its processing specifications such as for example

• order identification with barcode

• a process with the various phases

• processing machine and recipes

• if necessary, a subdivision of the order into color or design variants and associated sizes.

Whenever a new product has to undergo processing with a machine, the operator reads the recipe from the processing sheet with which the product must be processed. If the machine already has the parameters set with the values compatible with the recipe, the product can be directly inserted into the machine. If, on the other hand, the machine is set with different parameters, the operator will change them via the machine's HMI.

The variation of the process parameters involves a setup time. They will not be considered in the study because they are irrelevant to the other phase times. Furthermore, the setup status is often not recorded in the system, so it is not possible to trace it back. They are not explicitly declared by the operator, who should take note of it to update the information system.

Finally, it was found that most of the machine parameters related to a job can vary, with the same recipe, at the operator's discretion. In fact, an attempt is made to keep as much continuous fabric at the machine inlet as possible, that is until a substantial process parameter change is required, due to a recipe change. Specific approximations have therefore been considered.

An implementation of a CPS system could, therefore, considerably support the control of all parameters.

Mapping of the department with its legend (image on page 149)

7.1.2 Ward critical issues

During some interviews with the operators and some inspections in the company, the following operational issues were found:

- Lack of a pre-established procedure that defines which operator and which department (whether finishing or intermediate quality control) must print the finishing processing note to then advance to the system.
- During the intermediate quality control, the system often advances the initial total meters despite the operator having the possibility to cut the defective fabric meters. The operator manually reports on the processing bill the defective meters cut but the system continues to advance an incorrect quantity.
- The remake order is filled in manually by programming, which also takes care of blocking the cut fabric at the intermediate quality control.
- Lack of warehouse demarcation.
- Lack of coil position assignment. It is the operator who, based on the reference on the bubble and his experience, knows where the coil could be positioned.
- Failure to measure the length by the Bruckner machine present in the finishing department, since the operators do not reset the count based on the orders, but reset it only when strictly necessary.
- Manual compilation of a paper table by the operator at the end of the processing concerning the characteristics of the fabric. This is an activity that takes time and is often carried out superficially as operators do not have time to fill in the table precisely and rigorously.
- Problems in communicating the test result: compliance or non-compliance is communicated via e-mail to the manager of the finishing department. It is the latter that, based on the reading of the e-mail, takes care of the removal of the reel that has passed the test and transports it to the final quality control department. The department manager relies on reading the e-mail or not to understand if the fabric is still finishing or is in the next department.
- The scheduling of finishing activities is entirely managed by the department head who, based on his experience and urgencies, defines the processing sequence.
- Emergency management problems as there is no centralized system that makes all departments aware of problems or any urgent changes.

As a consequence related to the critical issues listed above, some problems arise in the traceability of the information that we will find in the following paragraph on data analysis. They will, therefore, influence the way in which we will reason in the following steps.

7.1.3 The problem's focus

As we have already anticipated, the textile sector has numerous application difficulties in industrial automation since it is characterized by numerous phases where attention to detail makes the difference, particularly in the luxury market where the Ratti company mainly competes.

To summarize what has been said so far, despite the high production, one of the biggest problems is represented by the production of limited lots, sometimes even single reels of a few meters, with specific requests to be respected, which limits automation in the absence of specific technologies.

In addition, the order schedule is often changed during the process based on remakes, delays, or other priorities that are decided at the moment.

Even though the company is going to implement RFID technology soon, traceability is currently difficult to perform, although each product is characterized by specific identification.

Consequently, it is difficult to follow a precise schedule that allows maintaining complete control over the progress of orders.

At this moment, the logic that is used in the finishing department is the following:

The insertion in the various machines is performed by trying to agglomerate orders with similar recipe characteristics, such as the setting of the technologies or the type of additives used.

The problem is that the scheduling is done at the moment by the department head based on his experience and the material ready for advancement in the finishing phase.

However, whenever a "problem" occurs, for example, following an urgent request, this logic is interrupted. Consequently, once the problem has been resolved, it restarts with the same reasoning that further modifies the previous planning program since orders that were in the vicinity of progress could now be postponed.

After carrying out interviews with the various department operators, it was noted that the setup times are not very high, both as regards the stitching to join the fabric spools and for the replacement of additives in the machine.

Given that the main reason for which this department was chosen is the presence of many queues that distinguish the finishing department as a department store, one should try to create a new scheduling logic to optimize the flow thanks to the use of simulation.

Obviously, before doing this, it is necessary to analyze the data and try to recreate a model of the department.

It was, therefore, spontaneous to think about the first hypothesis of maintaining a fixed program in the progress, also following urgent changes. The difference in timing can be simulated in the two different theories on setting up the work.

7.2 Data collection

The data used for the development of the project were provided after the first meetings once the finishing department was chosen as the object of study. In particular, the engineer Luigi Riva, responsible for technical development, was charged with supporting data with the clarification and procurement of information. All the data were obtained from the information system, while the elucidation of the flows and of the various production dynamics was acquired thanks to the inspections carried out in the company during these 6 months.

For this reason, the data collection/analysis phase takes place in parallel with the construction of the conceptual model with continuous development of knowledge.

The company would seem to have never done a data analysis job, in fact, it will be shown. Currently, there are numerous problems regarding data management.

To complete the data collection and analysis phase has been used software r. Obviously, as this thesis does not mainly deal with data analysis, the most relevant results will be clarified with the relative descriptions, without however explaining the meaning of the codes. In any case, all the scripts with the various notes will be present in the R file attached to the thesis. In this way, it will be possible to test the coding work done using the original databases.

R is an integrated suite of software facilities for data manipulation, calculation, and graphical display.

It includes:

- an effective data handling and storage facility,
- a suite of operators for calculations on arrays, in particular, matrices,
- an extensive, coherent, integrated collection of intermediate tools for data analysis,
- graphical facilities for data analysis and display either on-screen or on hardcopy, and
- a well-developed, simple, and useful programming language that includes conditionals, loops, user-defined recursive functions, and input and output facilities.

It is becoming the reference not only for the academy: Bank of America, Facebook, Ford, NewScientist, The New York Times, FDA are just some of the companies that use R to manage their data.

Note that all the files provided were in excel format, and to obtain the datasets necessary for the modeling, numerous set-up operations were carried out through R.

In particular, two final datasets will be obtained in which only the variables considered to be relevant for the study compared to all those available will be exposed. To do this, in many situations, filters have been applied based on certain conditions, which will also be explained in the notes of the scripts.

The first dataset obtained from the crossing of the company files is the one concerning the orders with information such as codes, the type of product, the dates of entry and exit to the department, the quantities in meters of fabric per order, the customers and the processes to which must be subjected. The highlighted rows of each table presented below contain the names of the variables used, which have not been modified to facilitate the reading of the reports to the company.

Each order is identified by a code and three attributes, such as RIGA, VAR, and COL. These will influence the processes associated with it throughout the production flow. In particular, in the finishing department, a particular type of process is associated with each combination of code and line. As you can see in the tables, thanks to the R each process has been converted into a numerical code since with the arena we cannot use variable characters. The column relating to the arrival dates in the ward has been transformed as a numerical time evolution since, in this case too, Arena is not able to read the date format. Unlike reality, however, the increase in time will take place without considering weekends and holidays as Arena works with this logic.

The columns highlighted in blue are the numerical data representing the input variables that will be inserted in our simulation model.

Table 4

Order Code	Attribute 1	Attribute 2	Attribute 3	Meters In	Cliente	Arrival Date	Arena Date	Process	Arena process
DAORD	DARIGA	DAVAR	DACOL	DAQTMT	DACLIE	DATE	Date code	PFFASE	Process Code
1701011	1	1	1	19	C01835	09/01/2017	1	FIB111	16
1701011	1	2	1	19	C01835	09/01/2017	1	FIB111	16
1701004	2	1	1	21,8	C01835	09/01/2017	1	FIG111	28
1701004	2	2	1	21,8	C01835	09/01/2017	1	FIG111	28
1701025	1	1	1	19	C01835	10/01/2017	2	FIA001	8
1701005	1	2	11	24,5	C01835	10/01/2017	2	FIM001	33
1701005	2	2	11	24	C01835	10/01/2017	2	FIM001	33
1701019	1	1	11	25	C01835	10/01/2017	2	FIM001	33
1701019	2	1	11	25	C01835	10/01/2017	2	FIM001	33
…	…	…	…	…	…	…	…	…	…

The second dataset obtained is that relating to the phase details where all the types of processes are explained, showing the phases associated with them. It also defines the machine to be used and the processing time per meter of fabric. This time was found thanks to a specific algorithm built by the company's programmers.

Table 5

Process	Arena process	Order sequence	Phase	Machine	Machine process time per m (h)
FFASE	Process Code	SFNRSQ	SFCDOP	SOMACC	SOORTR
FI0AIR	1	10	FICU01	CUCI	0.0006944444
FI0AIR	1	20	FIRA01	RAM	0.0013888889
FI0AIR	1	30	FIAI01	AIRO	0.0083333333

FI0AIR	1	40	FIRA05	RAM	0.0006944444
FI0AIR	1	50	FIRU01	RUOTA	0.0555555556
FI0AIR	1	60	FIMA01	EXT	0.0000000000
FI0MGL	2	10	AFFAL D	EXT	0.0000000000
FI0MGL	2	20	FICU01	CUCI	0.0006944444
FI0MGL	2	30	FIRA08	RAM003	0.0010416667
FI0MGL	2	40	FIMA01	EXT	0.0000000000
…	…	…	…	…	…

In total, we have 45 processes, each characterized by a specific sequence of activities. The latter are 32 in total, which can also be interpreted as workstations, whose combination defines a specific type of process. Obviously, the sequence in which they are presented cannot be changed. As anticipated, each station has a machine associated with it. In total, we have 15 machines.

It can be seen that some machine times associated with the variable SOMACC = EXT are equal to zero. They represent all the phases that take place in other machines outside the department but which, from a theoretical point of view defined by the company, are related to the finishing processes. Since it was always upstream or downstream of all processes, it was therefore decided that these phases should not affect the finishing department, thus canceling their processing time. The processing times for each machine are not fixed but vary according to the type of phase they are working on. This is because each order has its own recipe.

Below are the tables with the details of what has been explained so far.

Table 6

Processes	
PFFASE	Code
FI0AIR	1
FI0MGL	2
FI0NCR	3
FI0TEF	4
FI0VLL	5
FI1FGX	6
FI2SSA	7
FIA001	8
FIA002	9
FIA003	10
FIA111	11
FIA222	12
FIA333	13
FIB001	14
FIB003	15
FIB111	16
FIB222	17
FIC001	18
FIC111	19
FID111	20
FIE001	21

FIE111	22
FIF001	23
FIG001	24
FIG002	25
FIG003	26
FIG004	27
FIG111	28
FIG112	29
FIH001	30
FIL001	31
FIL002	32
FIM001	33
FIN001	34
FIN003	35
FIN004	36
FIP001	37
FIQ001	38
FIT001	39
FIV001	40
FIV002	41
FIV004	42
FIX001	43
FIY001	44
FIZ001	45

Table 7

Phases		**Machines**	**Process Time (h)**		
SFCDOP	SODELU	SOMAC	SOORTR (h)	SOORTR (min)	SOORTR (sec)
AFFALD	OPERAZIONE ESTERNA	EXT	0.0000000000	0	0
FESGRX	OPERAZIONE ESTERNA	EXT	0.0000000000	0	0
FIAI01	AIRO 1OOO	AIRO	0.0058333333	0,35	21
FIAIRA	AIRO 1OOO	AIRO	0.0058333333	0,35	21
FIAIRB	AIRO 1OOO	AIRO	0.0058333333	0,35	21
FICAL1	CALANDRA COMERIO	COM	0.0004861111	0,029167	1,75
FICAL2	CALANDRA COMERIO	COM	0.0004861111	0,029167	1,75
FICL01	CALANDRA RAMISH	RAMISH	0.0007291667	0,04375	2,625
FICU01	TAGLIACUCE MARROW	CUCI	0.0004861111	0,029167	1,75
FIMA01	OPERAZIONE ESTERNA	EXT	0.0000000000	0	0
FIPA01	PALMER A CATENA	PALMER	0.0009722222	0,058333	3,5
FIRA01	RAGGRUPPAMENTO MACCHINA SOCD RG	RAM	0.0009722222	0,058333	3,5
FIRA04	RAGGRUPPAMENTO MACCHINA SOCD RG	RAM	0.0009722222	0,058333	3,5
FIRA05	RAGGRUPPAMENTO MACCHINA SOCD RG	RAM	0.0004861111	0,029167	1,75
FIRA06	RAGGRUPPAMENTO MACCHINA SOCD RG	RAM	0.0019444444	0,116667	7
FIRA08	RAMEUSE 3 BABCOCK 1996	RAM003	0.0007291667	0,04375	2,625
FIRM01	RAMEUSE 3 BABCOCK 1996	RAM003	0.0009722222	0,058333	3,5
FIRM02	RAMEUSE 3 BABCOCK 1996	RAM003	0.0009722222	0,058333	3,5
FIRM03	RAMEUSE 3 BABCOCK 1996	RAM003	0.0007291667	0,04375	2,625
FIRM05	RAMEUSE 3 BABCOCK 1996	RAM003	0.0004861111	0,029167	1,75
FIRM06	BARCA LAVAGGIO GENERICA	BRCGEN	0.0009722222	0,058333	3,5

FIRM08	RAMEUSE 3 BABCOCK 1996	RAM003	0.0007291667	0,04375	2,625
FIRM22	RAMEUSE 4 TTM	RAM004	0.0009722222	0,058333	3,5
FIRMP	CILINDRINO CON VAPORIZZATORE	CIL	0.0004861111	0,029167	1,75
FIRMSP	RAMEUSE 3 BABCOCK 1996	RAM003	0.0007291667	0,04375	2,625
FIRMTE	RAMEUSE 3 BABCOCK 1996	RAM003	0.0019444444	0,116667	7
FIRT01	RADDRIZZ. A RUOTA DITTA BIANCO	RUOTA	0.0004861111	0,029167	1,75
FIRU01	RADDRIZZ. A RUOTA DITTA BIANCO	RUOTA	0.0388888889	2,333333	140
FISAN1	SANFOR BRUCKNER	SANFO R	0.0007291667	0,04375	2,625
FISN01	SANFOR BRUCKNER	SANFO R	0.0486111111	2,916667	175
FIVD01	DECATIZZO CONTINUO	DEC	0.0004861111	0,029167	1,75
LAVLG A	LAVAGGIO LARGO ARIOLI	LAVEX T	0.1111111111	6,666667	400

Table 8

Machines	
SOMACC	SMDELU
AIRO	AIRO 1OOO
BRCGEN	BARCA LAVAGGIO GENERICA
CIL	CILINDRINO CON VAPORIZZATORE
COM	CALANDRA COMERIO
CUCI	TAGLIACUCE MARROW
DEC	DECATIZZO CONTINUO
EXT	OPERAZIONE ESTERNA
LAVEXT	LAVAGGIO LARGO ARIOLI
PALMER	PALMER A CATENA
RAM	RAGGRUPPAMENTO MACCHINA SOCDRG
RAM003	RAMEUSE 3 BABCOCK 1996
RAM004	RAMEUSE 4 TTM
RAMISH	CALANDRA RAMISH
RUOTA	RADDRIZZ. A RUOTA DITTA BIANCO
SANFOR	SANFOR BRUCKNER

7.2.1 Data validation and reconstruction

Data analytics is the science of examining raw data with the purpose of drawing conclusions about that information. Data analytics are used in many industries to allow companies and organizations to make better business decisions. Data Validation and Reconstruction is a promised tool of Data Analytics, which allows testing if the raw data is reliable or not. In the positive case, this raw data is stored as validated data, and, on the contrary case, the raw data is rejected and replaced by an estimated or reconstructed data. Once all the data are validated, useful information could be derived for system management tasks.

(J. Quevedo et al., 2016)

As can be seen from reading the codes in the study applied with R, the cleaning data process was very complicated and time-consuming. The cause is obviously due to the bad management of the information from the information system.

In this paragraph, some of the problems faced after the data collection phase will be shown, explaining the appropriate hypotheses applied to continue the study.

Since we are talking about a computer language, it has been preferred to keep the codes and the relative notes in the R file instead of making the report so that they could be used. In fact, the original CSV sheets will also be provided to run the program.

So below, I will just explain some reasons carried out to remedy the problems encountered.

1. For some orders, I don't have the process specifications

In the beginning, the process to follow which was associated with the combination of order code and RIGA attribute was not specified in the list of orders. To obtain this information, another database was used where there should have been the details of all orders regarding the processes to be used. Crossing the two datasets and combining them based on common elements, some process information was missing.

In fact, by working with the set operations, a list of order codes was obtained, which did not have the process detail.

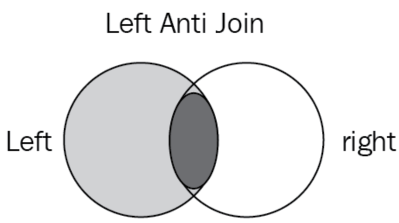


Fig. 33

```
> nrow (Nomatchcodes)
[1] 1211
> head(Nomatchcodes)
   DAORD
1 1701197
2 1701771
3 1702139
4 1701325
5 1701894
6 1701243
> tail(Nomatchcodes)
      DAORD
1206  1930187
1207  1932728
1208  1931437
1209  1932128
1210  1930370
1211  1932675
```

Fig. 34

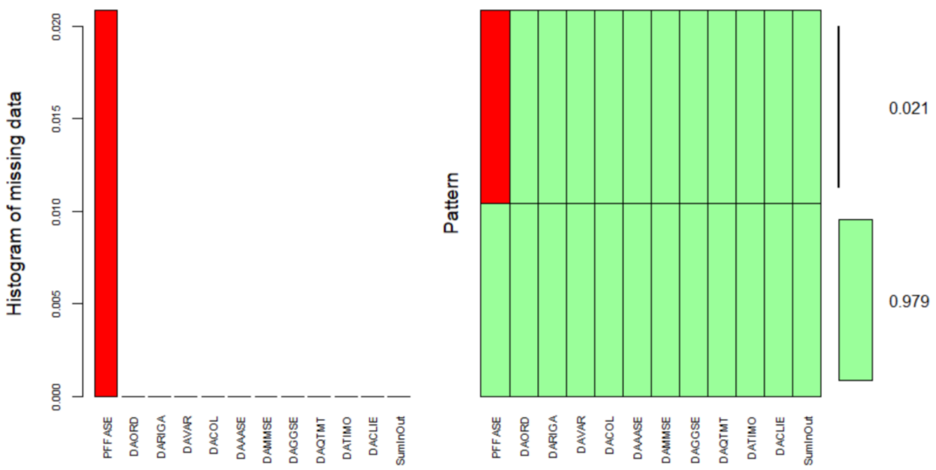
To solve the problem, the technique of imputing missing values was used so that the data set could be completed; this method is more effective than deletion since no data is sacrificed.

In this case, in fact, the failure to combine all the elements of the tables derives from an incomplete selection or filter errors when data was extracted from the information system.

Mistakes of this type are common when working with large databases. However, having a close relationship between the order code and line combination, it was not difficult to trace the respective missing processes. Obviously, this presupposes that there are no further types of processes or, at least, not very different.

Usually, a maximum safe threshold for missing data is 5% of the total for large datasets.

Fig. 35 Missing values graphs



The function 'missForest' in this package is used to impute missing values, particularly in the case of mixed-type data. It uses a random forest trained on the observed values of a data matrix to predict the missing values. It can be used to impute continuous and/or categorical data, including complex interactions and non-linear relations.

2. Some processes don't have phase details

Similarly to the previous situation, to obtain the information of the phases, such as the machines to be used and the corresponding execution time, crossing the various files, some details were missing.

In this case, these phases were not present in my phase detail datasets, so it was not possible to trace them.

However, I have not decided to eliminate the lines since being our primary objective; the calculation of the simulation time would have had a worse effect than considering less precise times.

I, therefore, opted not to consider these two types of the process, trying to find the phases that could best replace them based on all the other information. To do this, I used the imputation explained above.

3. Sometimes the process type changed with the same order type.

These repetitions were due to process updates that duplicated the same order in the system. Despite the repetitions, however, in the details, there were other attributes as a reference to find the process to associate correctly. Then set operations were applied to trace the definitive list.

Specifically, PFTIPO and PFLIVE are the two attributes that described the latest system update. So to find the real processes to be associated, it was necessary to follow the following order of preference: C-P48, C-P45, P-P48, P-P45.

Below is a part of the code used.

```
processesCP48 <- filter(unicprocesses, PFTIPO == "C", PFLIVE=="P48")
codCP48<-processesCP48[!duplicated(processesCP48[c("PFNROR","PFRGOR")]),]
REST<-anti_join(unicprocesses, codCP48, by=c("PFNROR","PFRGOR"))
processesCP45 <- filter(REST, PFTIPO == "C", PFLIVE=="P45")
codCP45<-processesCP45[!duplicated(processesCP45[c("PFNROR","PFRGOR")]),]
REST1<-anti_join(REST, codCP45, by=c("PFNROR","PFRGOR"))
processesPP48 <- filter(REST1, PFTIPO == "P", PFLIVE=="P48")
codPP48<-processesPP48[!duplicated(processesPP48[c("PFNROR","PFRGOR")]),]
REST2<-anti_join(REST1, codPP48, by=c("PFNROR","PFRGOR"))

listprocesses<-rbind(processesCP48,processesCP45,processesPP48)
listprocesses<-select(listprocesses, PFTIPO, PFLIVE, PFNROR,PFRGOR,PFFASE)
listprocesses <-rename(listprocesses,DAORD = PFNROR, DARIGA = PFRGOR)
```

Fig 36

The fundamental concept that must be conveyed by showing the image above is not the meaning of this complex code but the fact that having an information system that correctly tracks and processes all the information dramatically simplifies the study of data analysis.

4. Some orders get in but do not get out from the department, or the opposite

In the initial order dataset, as already explained and shown in fig 37. the dates of entry and exit from the department were present. Specifically, each row is equivalent to the entry or exit date. In particular, the attribute DATIMO = 1 means entry while DATIMO = 3 exit.

It was therefore checked that in a number of orders of the same type, it had entered and exited.

For this to happen, the average (Var1) of the incoming and outgoing DATIMO attributes must be 2 for each type of order. Below the results table:

Var1	Freq
2	64111
1.66666666666667	947
1.5	200
1.8	173
1.4	75
2.33333333333333	57
1.33333333333333	46
1.85714285714286	30
1.57142857142857	26

Fig 37

It can be seen that in most cases, there is consistency between the number of inputs and outputs. However, there are situations where orders are agglomerated or separated on exit, so it is not possible to associate them with the dates of incoming orders.

Since a suitable method for validating the model would be to compare the real output dates with the simulated ones to trace the output times, I used linear regression on the part of the complete dataset to then predict the release dates of the remaining orders.

This part will be explained in the validation phase.

5. **For some orders there are differences in meters between the inputs and outputs or vice versa, sometimes vast quantities**

Having the quantities of incoming meters, it has been researched the presence of possible disparities (Var1).

Var1	Freq
0	65839
-42	35
42	33
10	28
9	27
-41	25
-40	25
38	22

Figure 38

```
> head(tablesumordered)
   Var1 Freq
1 16102    1
2  6757    1
3  6193    1
4  3446    1
5  2490    1
6  1645    1
> tail(tablesumordered)
     Var1 Freq
244 -1291    1
245 -4096    1
246 -4623    1
247 -5039    1
248 -5670    1
249 -6178    1
```

Figure 39

Again most were optimal cases. However, for a limited number of orders, the differences were high. These lines probably represent remakes that have not been registered in the system. It was, therefore, decided to eliminate them.

7.2.2 Graphical analysis

Once the data has been collected, the first thing to do is an exploratory analysis beginning to create some charts to understand how the dataset is structured and what kind of relationship can exist between the variables.

Descriptive analysis is useful because it allows us to learn from past behaviors and to understand how they might influence future results.

Moreover, thanks to the graphical analysis, as you will see, it is possible to obtain information even if you do not have technical details regarding the resources and the logic used.

Frequency by type of process in the production

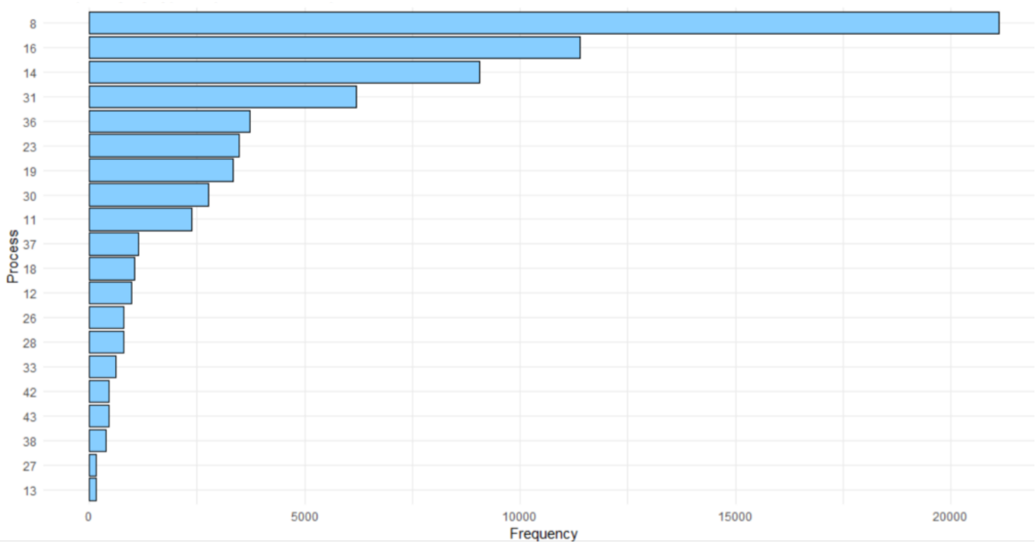


Figure 40

The first graph represents the frequency of the various types of processes in the finishing department during the three years analyzed. Only the first 20 processes were shown in order of frequency. You can immediately notice how there is a significant disparity in frequency and how the n8 process remarkably detaches the others.

Frequency by type of phase among the processes

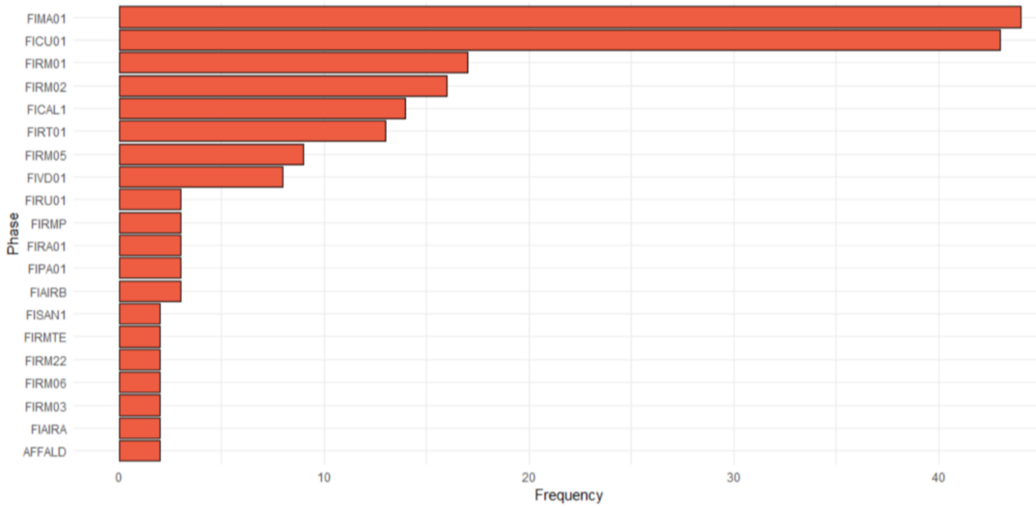


Figure 41

The second bar graph shows the frequency of the phase types by merely considering the list of processes. Again only the top twenty positions are shown. This chart is limiting since it is not calculated based on the orders that are processed. It is not sure that the most common phrases in the various processes are also the most used ones. It is, therefore, interesting to compare it with the graph that describes the frequency of the phases that were used during the three-year time cycle.

Frequency by type of phase in the production

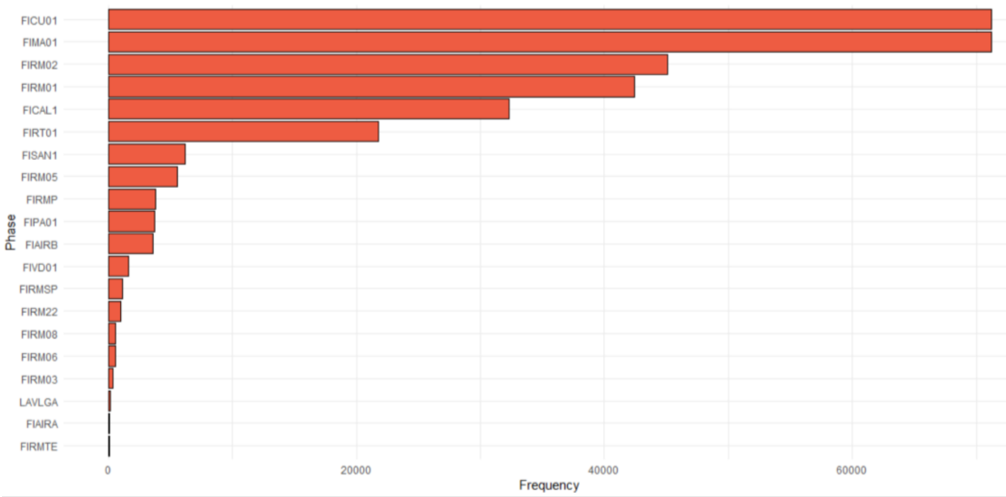


Figure 42

You immediately notice how many positions have changed and how even some phases have disappeared from the top twenty positions. This graph is undoubtedly more truthful and tells us that the FICU01 and FIMA01 phases are the most frequent in the finishing department. Note that FIMA01, as can be seen in the phase detail table, is part of the group of activities associated with external machines, which work outside the department, as explained above. Consequently, although it is prevalent, it will not affect the timing and queues.

Frequency by type of machines in the production

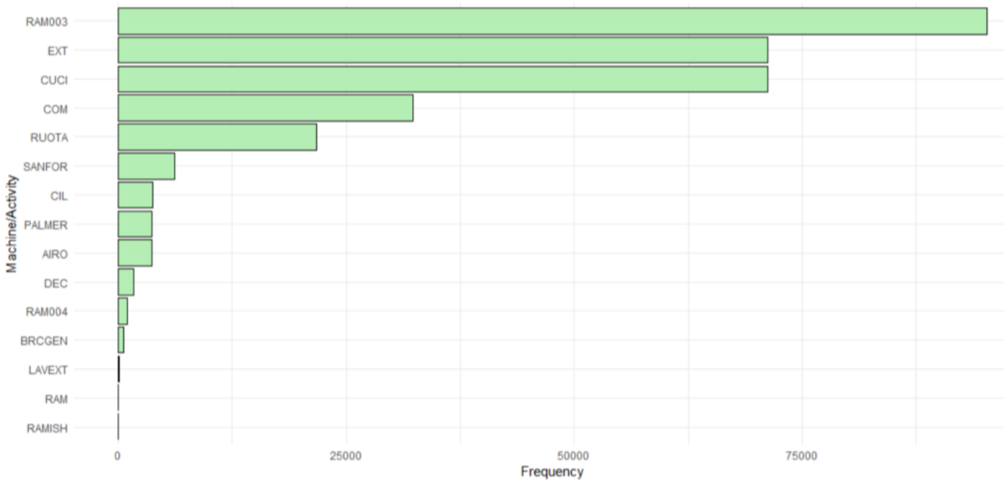


Figure 43

The graph above describes the frequency of use of the machines in the finishing department. It can be observed that the difference between the use of the first machines at the top and the remaining ones is high. This suggests that some machines are present in most processes, and their failure could block numerous orders. The group of EXT machines ranks second but is irrelevant to the model. Also, in this case, as in fig. 43, the graph can be confusing since the machines at the top of the ranking list are not necessarily the most problematic due to the possible problems related to queues. In fact, just for the reason that all the machines are unitary, a long working cycle could have more significant effects than the frequency. In the next graph, it is therefore presented how the duration of the processes can influence this list.

Total process time over the three years by type of machine

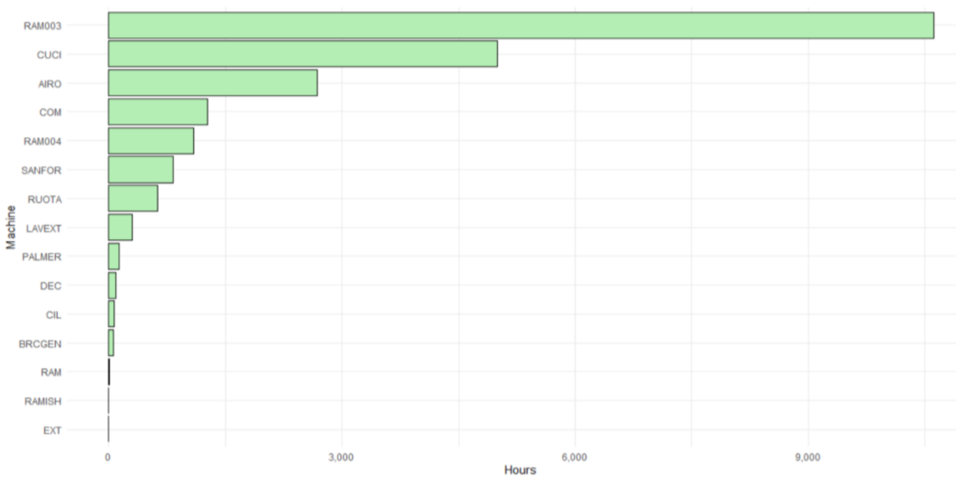


Figure 44

You immediately notice how the EXT group collapsed at the bottom of the standings since its times are zero. The first two positions on the list remain unchanged, and this definitively explains that they are the most critical machines to be kept under control. In the rest of the list, there are numerous changes of position, so it was correct to check the timing.

If you consider the number of working days in the three years, it is practically always in use considering two 8-hour shifts. By dividing the total working hours of RAM003 (about 10600) by the days considered in the study (716), a rough estimate of daily use can be calculated (14.8). There could, therefore, be bottleneck problems. The model will be able to confirm.

Quantity produced over time

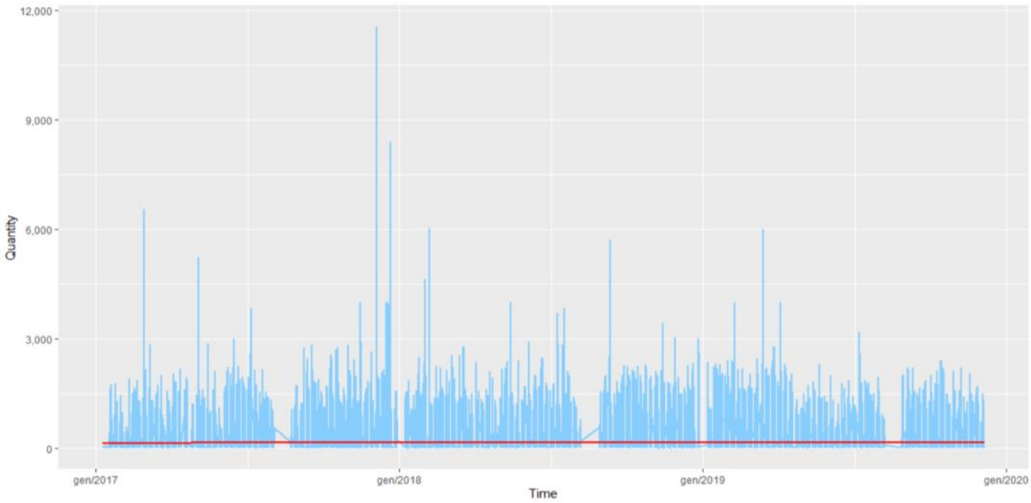


Figure 45

A graph relating to the meters of fabric worked in the three-year time frame. There are very high peaks compared to the linear regression of the total quantity worked per day. These peaks need to arouse attention because using the arena student version since orders concentrated in a short period can create problems. While if they were large orders, one should be careful of possible bottlenecks. There are also some periods of inactivity certainly linked to the holidays.

Total quantity by type of process

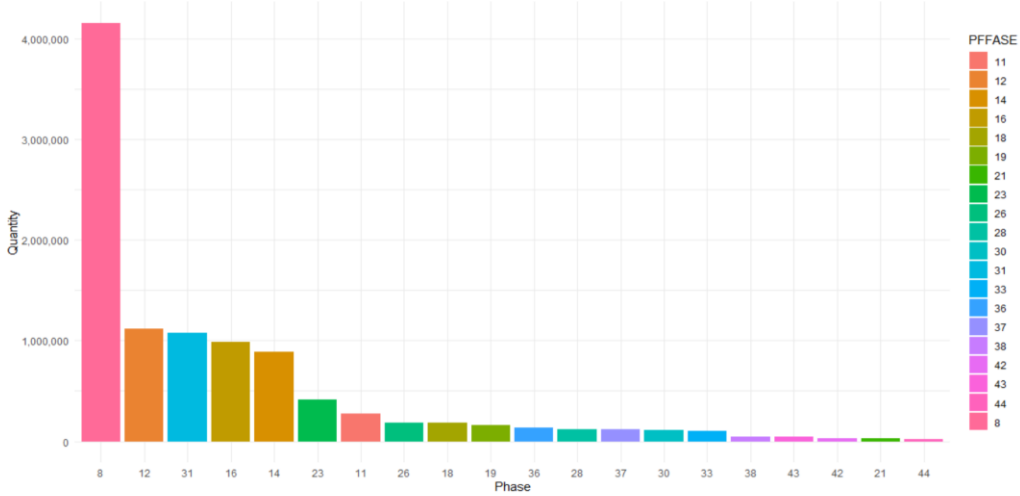


Fig. 46

Similarly to what has been done previously, the total amount of fabric in meters for the respective processes is shown by associating them with specific colors. It would be appropriate to understand if the quantities of meters of fabric processed affect the ranking of the processes in fig 46. In fact, it is not said that a process that occurs frequently is also expensive from a temporal point of view. For example, the presence of activities belonging to the EXT machine group, i.e., upstream and / or downstream of the process, could considerably lower the total process time. So taking a look at the chart, you can see that the first place remains unchanged. In addition to being the most frequent, the n8 process is also the one in which the majority of meters of fabric pass. In fact, it represents almost the sum of all meters worked through the other processes. The rest of the ranking, as you could imagine, changes considerably, and the disparity increases. For example, process 12 gains 9 positions. This may mean that the phases within it are very time-consuming or that it is made up of numerous phases.

Box plot by type of process

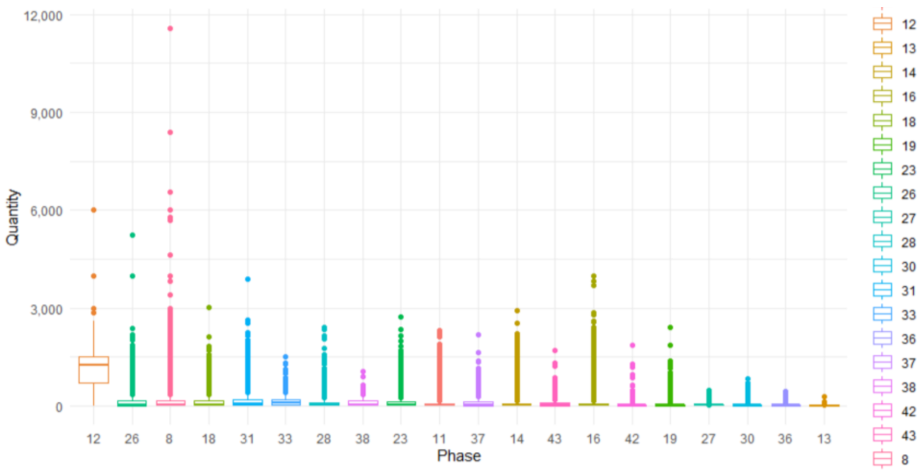


Figure 47

It is also interesting to note how the distributions represented by the box plots evolve for the quantities of meters entering each process. As in the previous graph, each process is associated with a color and ordered according to a ranking with respect to the medians.

If a lot is characterized by a high number of meters, it could block the machines belonging to a similar process for a long time, thus also influencing their queues, slowing down other orders. It is not convenient to break a lot both for set-up times and because it goes against the logic of the company that tries in every way to maintain a continuous production cycle.

You immediately notice that the process n12 detaches the others for the length of the worked lots. The distribution of the lengths of its lots is indeed much broader and higher than other processes. This could mean that it is a particular procedure that is applied only when orders of large meters are available. The low number of outliers compared to the other processes also confirms this idea. On the contrary, the process n16, as seen in the previous graph, is among those that produce the most and is characterized by relatively smaller orders. This could describe it as a specific process for small/medium size orders.

It would also be interesting to compare the costs associated with the use of the machines to obtain further information, going into detail of these logics. Unfortunately, this information was not available. In general, we can observe that the presence of outliers characterizes most of the processes. Process n13 appears to be the one most in control but probably because the number of lots worked and relatively low. In fact, in the previous graph, it was not present in the ranking of the first 20.

Quantity produced overtime for the primary processes

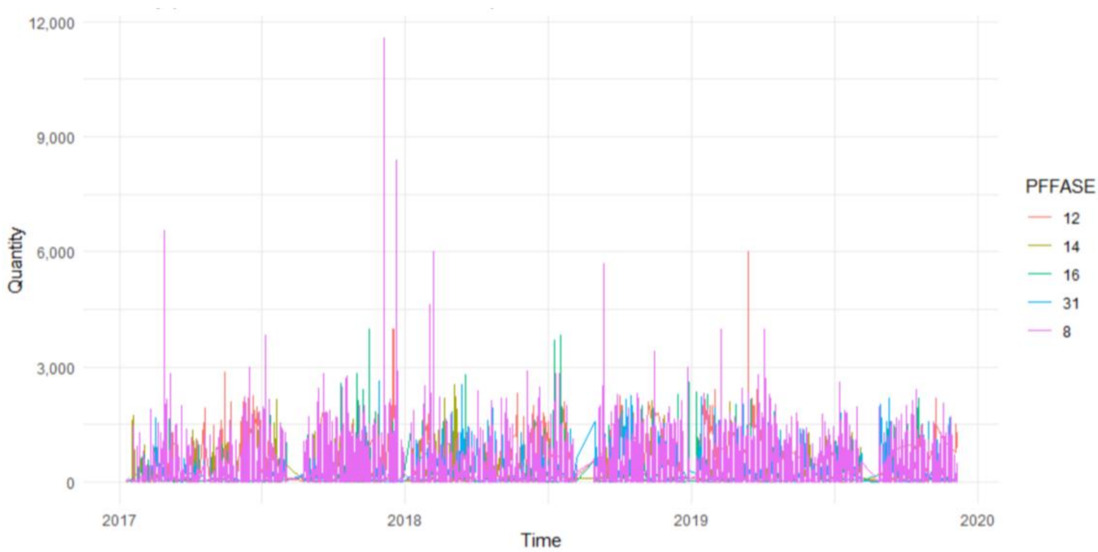


Figure 48

This graph is the same as in fig. 48, but considering only the first five processes in order of total meters worked. Here too, the same colors associated with the processes in the previous graphs have been kept. This graph, although from the first point of view is not extremely clear, it is advantageous to understand how the peaks of incoming meters associated with the related processes evolve. Predominant as you could predict the prevalence of the fuchsia color, which also has the highest peaks. One in particular at the end of the year 2017, probably characterized by substantial orders. It is, however, observed that the presence of peaks is also present for the other colors, although in a lesser way.

Difference between input and output

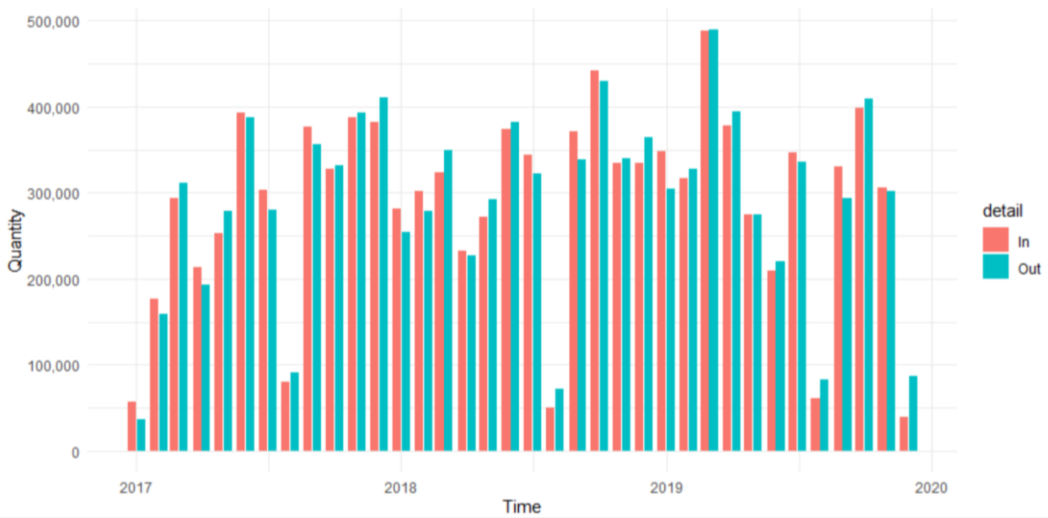


Figure 49

The last graph shows the total monthly quantity entering and leaving the department. In fact, in the order file obtained by the company, there were also the dates of leaving the department. It can be seen that the trend in the number of orders follows a relatively constant development over the three years. However, it is interesting to note that the difference between the monthly number of incoming and outgoing orders continues to vary between negative and positive. This is because it represents the recovery of late orders. During holidays, the difference is always negative as imaginable. In the previous and subsequent months, on the other hand, it is positive assuming that we are trying to move forward or recover. These logics could also influence the model.

7.3 Design of the conceptual model

To build the conceptual model has been used the Petri Nets logic, which is one of several representations for modeling dynamic systems with discrete events. They define the evolution of event-driven systems and represent an excellent approach to learn to model systems by constructing them graphically before to use any computer software for simulation and analysis.

It is easily modifiable, modular, well interpretable and can represent systems with infinite states with a finite number of nodes.

A Petri Net is a collection of directed arcs connecting places and transitions. An arc can join only nodes of different types, therefore nodes with transitions and vice versa. Places are graphically represented by circles and transitions by rectangles.

Each seat can contain one or more tokens represented by dots; if the tokens that may be inside the seat have a limited number, it is represented outside (above or below) the corresponding seat. Each arc can be associated with a weight, positive integer (if the writing is omitted, the weight is considered unitary).

Distribution of tokens on the set of places on the network is called marking. Transitions act on incoming tokens according to a rule, called firing rule.

A transition is enabled when the number of tokens in each of its input places is at least equal to the arc weight going from the place to the transition. An enabled transition may fire at any time. When fired, the tokens in the input places are moved to output places, according to arc weights and place capacities. This results in a new marking of the net, a state description of all places.

The transition can be immediate if the time associated is zero or timed, whether we have a time function.

To translate the logic of the Petri Nets into the construction of a simulation model, first of all, we need to understand what its graphic components refer to.

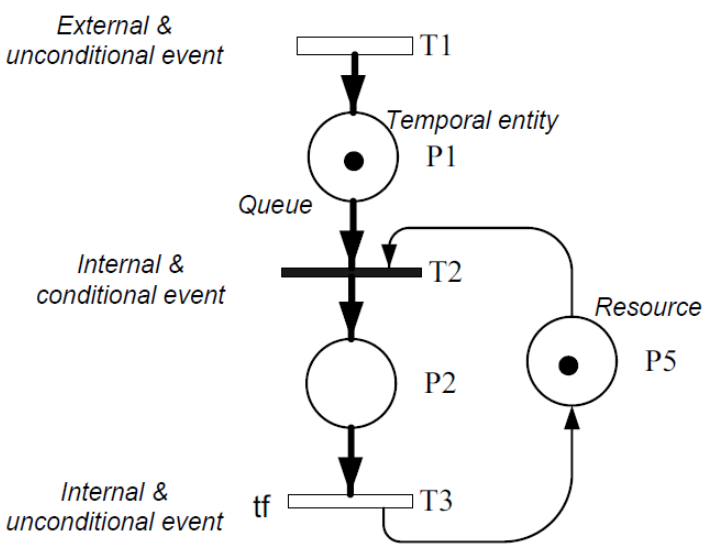


Figure 50

Entities

Entities are the sets of system components, such as machines, parts, equipment, or clients. Entities can be grouped into two categories:

- Resources or permanent entities: As the name indicates, the main characteristic of these entities is that their number does not increase or decrease during the simulation. In general, they are used to describe how activities are executed. A resource defines who or what executes the activity. Examples of resources include machines, transportation units, and operators.
- Temporal entities: The main characteristic of these entities is that they are created and destroyed throughout the simulation. In general, they are used to describe the objects that are processed in the system, for example, the parts, clients, or documents.

Petri nets do not distinguish explicitly between resources and temporal entities. This is part of the semantics of the net.

Attributes

Attributes allow the characterization of the entities. Each attribute corresponds to a property (for example, price, priority, size). Attributes store important information and are essential for controlling the flow of entities through the system.

Activities

Activities are the tasks or actions that take place in the system. One of their essential properties is the duration, which is needed so that the simulator can determine the moment at which the activity will finalize. In the previous example of a simple workstation with one machine, the activity begins whenever the system contains a free resource (machine) and a temporal entity (part) that is available to be processed. Note that the beginning and the end of activity coincide with the firing of a transition in the Petri net.

Events

In discrete event simulation models, the state variables can only change the value as a result of an event. Therefore, an event can be defined as an instantaneous action (i.e., does not consume time) that can change the value of a state variable in the modeled system.

Usually, more than one activity begins or ends with each event. An initial classification allows us to differentiate two types of events:

- Conditional events: Events that are activated when one or more conditions are fulfilled.
- Unconditional events: Events that are planned for execution and do not depend on logical conditions. They are activated after a specific (usually stochastic) time interval.

Events also can be classified as:

- Endogenous or Internal Events: Events caused by conditions in the model; for example, the end of an operation.
- Exogenous or External Events: Events external to the model; for example, the arrival of a part at the model.

It is very important to bear in mind that the global state of the model, like the state of each of its attributes, can only change in response to an event. This is the characteristic that allows simulators to advance the simulation time and to manage events in such a way that the evolution of state variable values describes the behavior of the system.

Queues

These structures are a collection of entities (in general, temporal entities) ordered in a logical form, for example, clients in a FIFO waiting line. The entities in the queue undergo a delay of unknown duration. In Petri nets, queues do not appear explicitly, but those places occupied by temporal entities that are delayed waiting for restricted resources are usually queues.

The Petri Nets Model

Consensus exists between those involved in the development and maintenance of simulation models that simple models are preferable to complex models. Despite this, the simulation models used in many projects are large and complex. It is important to emphasize that excessive complexity not only has an impact on computational performance but affects other aspects, such as the time needed for development, maintenance, verification, and validation of the model. (Fonseca i Casas, 2014)

Table 9

Table c		**Iteration number**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Type of process	**1**	5	10	1	10	14	7	0	0	0
	2	7	5	11	7	0	0	0	0	0
	3	7	5	11	4	3	6	7	0	0
	4	5	14	10	10	10	13	14	7	0
	5	5	11	7	0	0	0	0	0	0
	6	7	7	0	0	0	0	0	0	0
	7	10	15	7	0	0	0	0	0	0
	8	5	11	7	0	0	0	0	0	0
	9	5	11	7	0	0	0	0	0	0
	10	5	11	11	7	0	0	0	0	0
	11	5	11	11	7	0	0	0	0	0
	12	5	12	7	0	0	0	0	0	0
	13	5	8	11	7	0	0	0	0	0
	14	5	11	4	7	0	0	0	0	0
	15	5	4	7	0	0	0	0	0	0
	16	5	11	11	4	7	0	0	0	0
	17	5	12	4	7	0	0	0	0	0
	18	5	14	11	4	14	7	0	0	0
	19	5	14	11	11	4	14	7	0	0
	20	5	11	11	4	7	0	0	0	0
	21	5	11	1	11	7	0	0	0	0
	22	5	11	11	1	11	7	0	0	0
	23	5	11	1	11	7	0	0	0	0

	24	5	11	4	6	7	0	0	0	0
	25	5	11	6	7	0	0	0	0	0
	26	5	11	7	0	0	0	0	0	0
	27	5	11	11	7	0	0	0	0	0
	28	5	11	11	4	6	7	0	0	0
	29	5	11	11	6	7	0	0	0	0
	30	5	14	11	11	4	14	7	0	0
	31	5	11	15	7	0	0	0	0	0
	32	5	15	4	7	0	0	0	0	0
	33	5	11	7	0	0	0	0	0	0
	34	5	14	14	9	3	7	0	0	0
	35	5	14	14	9	4	14	7	0	0
	36	5	14	11	14	9	4	3	7	0
	37	5	11	7	0	0	0	0	0	0
	38	5	11	7	0	0	0	0	0	0
	39	5	11	0	0	0	0	0	0	0
	40	5	6	7	0	0	0	0	0	0
	41	5	6	11	7	0	0	0	0	0
	42	5	6	11	7	0	0	0	0	0
	43	5	11	2	11	7	0	0	0	0
	44	5	11	2	1	11	7	0	0	0
	45	5	1	11	4	7	0	0	0	0

For this reason, since in the project there were different types of orders, different processing times in the same stations and also different schedules of the various process within the department, I opted for a compact Petri Nets model to make coding flexible and agile also in Arena. Obviously, in addition to the model, I defined the various tables to recall the specific values for any iteration, based on the variables referring to the entities. In this way, using cycles in the model, each time I could increase the index of certain variables to be able to get different values from the tables in the following iterations.

Below are the tables that have been used in the model with the relative explanations.

Table c

The first table is named “c” and is related to the schedule of the machines according to the iteration number and the type of process. When the values are equal to zero it means that the order is not processed and as we will see it has deviated toward the end of the model base on a specific condition.

Table tfc

The second table is named "tfc" and is related to the various processing times (h) to perform 1 m of fabric. The values are based again on the various iteration (vi) and the type of job (ty). All decimal values were kept to maintain agreement with the units of measurement. Obviously this table is closely linked to the first one as the scheduling of the times follow the same development of the machines in fact they are perfectly superimposable.

Table 10

Table tfc		Iteration number							
		1	2	3	4	5	6	7	8
Type of process	1	0.0004861111	0.0009722222	0.0058333333	0.0004861111	0.0388888889	0.0000000000	0.0000000000	0.0000000000
	2	0.0000000000	0.0004861111	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	3	0.0000000000	0.0004861111	0.0009722222	0.0004861111	0.0004861111	0.0004861111	0.0000000000	0.0000000000
	4	0.0004861111	0.0388888889	0.0009722222	0.0009722222	0.0019444444	0.0007291667	0.0388888889	0.0000000000
	5	0.0004861111	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	6	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	7	0.0009722222	0.0486111111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	8	0.0004861111	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	9	0.0004861111	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	10	0.0004861111	0.0009722222	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	11	0.0004861111	0.0009722222	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	12	0.0004861111	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	13	0.0004861111	0.1111111111	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	14	0.0004861111	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	15	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	16	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	17	0.0004861111	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	18	0.0004861111	0.0004861111	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000
	19	0.0004861111	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000
	20	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	21	0.0004861111	0.0009722222	0.0058333333	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	22	0.0004861111	0.0009722222	0.0009722222	0.0058333333	0.0004861111	0.0000000000	0.0000000000	0.0000000000
	23	0.0004861111	0.0009722222	0.0058333333	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	24	0.0004861111	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	25	0.0004861111	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	26	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	27	0.0004861111	0.0004861111	0.0009722222	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	28	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000
	29	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	30	0.0004861111	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000
	31	0.0004861111	0.0009722222	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	32	0.0004861111	0.0007291667	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	33	0.0004861111	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	34	0.0004861111	0.0004861111	0.0004861111	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000
	35	0.0004861111	0.0004861111	0.0004861111	0.0009722222	0.0004861111	0.0004861111	0.0000000000	0.0000000000
	36	0.0004861111	0.0004861111	0.0009722222	0.0004861111	0.0009722222	0.0004861111	0.0004861111	0.0000000000
	37	0.0004861111	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	38	0.0004861111	0.0007291667	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	39	0.0004861111	0.0019444444	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	40	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	41	0.0004861111	0.0004861111	0.0019444444	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	42	0.0004861111	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	43	0.0004861111	0.0009722222	0.0009722222	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000
	44	0.0004861111	0.0009722222	0.0009722222	0.0058333333	0.0004861111	0.0000000000	0.0000000000	0.0000000000
	45	0.0004861111	0.0058333333	0.0004861111	0.0004861111	0.0000000000	0.0000000000	0.0000000000	0.0000000000

Explanation of logic (image on the end)

From the first point of view, it can be observed how the model can be divided into two parts. The first is for reading the orders and their respective attributes while the second is for finding the processing time for each phase (cycle).

There are no static distributions in the model to describe the arrival intervals. In fact, orders enter the model according to a list organized by days.

The model starts with the creation of an entity from state P1, which will be the first and last to be created. In fact, a solution was used that simply requires an entity to activate the model.

In the immediate transition T1, the first entity acquires the attributes of the first line in the list. Obviously, one line is read at a time.

When it arrives in the transition timing T2, the entity suffers a delay according to the function tf1.

Our model starts with the creation of an entity without the attribute. Since the system variable var CurrentTime at time 0 equal to 0, the entity does not suffer any delay.

After the immediate transition T3, the "Max" resource is associated with the entity, which is used to control the limit number of resources in the model. In fact, this Petri net was designed with the same reasoning for the construction of a model in the arena with the student version in which there is a maximum limit of resources is 150. Each time, in fact, there will be more than 148 entities in the circuit, the entities they will have to wait for an available Max resource to continue the journey. After the transition T3, the varCurrentTime variable equal to tnow was also updated. Tnow is a System variable that is always updated to the current System time and increases by itself. Being on the first lap still on day 0 (as per Arena logic) varCurrentTime remains unchanged.

In transition T4, the circuit undergoes separation in two ways. One continues towards the second part of the Petri net while the other returns to the P1 state. Obviously, the entity is also separated, keeping the same attributes and associated resources.

When the splitted entity returns to state P1, as explained above, the creation of a new entity is not necessary in fact; it will be updated with new attributes, characterizing a new order, after transition T2. In this way, we will have a completely new entity with the attributes of the second row, and so on.

Clearly, in the transition time T2, we will have a delay only when the day attribute is increased. This will mean that we will have moved on to orders for the second day. This was the only way to give a daily time block to the orders on the list. When the orders of the first day are finished, and the tnow system variable will be updated to the following day, the entities relating to this specific day will have finished waiting.

Continuing the flow after transition T4, the entity is assigned the vi attribute, which has a value of 0.

In state P5, we have a decision situation. If the value of table c associated with the attributes ty e there is equal to zero, the entity is diverted towards the exit of the model, while if the value is different, it can continue to be processed.

If we assume we are in the second case, the entity arrives in transition T6 where the resource is assigned but from the set of machines. The resource ma will correspond to a value from table c based on the attributes ty and vi. The resources included in the set machines are the set of all the machines in the department that have unit value.

Once the machine is occupied, the entity undergoes the processing time in the transition timed T7. This time is equal to the result of the function tf2 or the multiplication between the value in the tfc table associated with the attributes ty and vi, and the value of the attribute m. As seen in the part of the given analysis, the result of this operation is equivalent to the product between the time required by the machine to produce one m of fabric and the relative quantity of meters.

When the processing phase is finished, after the transition T8, the resource can be released. At this point, before returning to the P5 state, the vi attribute that characterizes the next step in the phase scheduling is increased. If the result of the decision is still different from zero, the entity will continue in its process; otherwise, it will go to state P9.

Before finally concluding its path, the entity releases the Max resource after the T10 transition. Therefore, if there are more than 148 entities queued in the System, it will leave its space to another entity to enter the process.

7.4 Construction of the model

For the construction of the simulation model will be used, Arena. This paragraph will start with a sort of software manual where the working environment, the main modules of the flowchart, and the data modules are presented. Once learned, all these notions about how to analyze the real system, how to implement a model, and how the simulation software in question works, will be faced a real application.

7.4.1 The software Arena

The arena is a discrete event simulation and automation software developed by Systems Modeling and acquired by Rockwell Automation in 2000.

Arena software allows bringing the power of modeling and simulation to business. It is designed for analyzing the impact of changes involving significant and complex redesigns associated with supply chain, manufacturing, processes, logistics, distribution and warehousing, and service systems. Arena software provides the maximum flexibility and breadth of application coverage to model any desired level of detail and complexity.

With Arena, you can:

- model your processes to define, document and communicate
- simulate the future performance of your system to understand complex relationships and identify opportunities for improvement
- visualize your operations with dynamic animation graphics

➢ analyze how your system will perform in its “as-is” configuration and under a myriad of possible “to-be” alternatives so that you can confidently choose the best way to run your business

Typical scenarios include:

- detailed analysis of any type of manufacturing system, including material handling components
- analysis of sophisticated customer service and customer management systems
- analysis of global supply chains that include warehousing, transportation, and logistics systems
- predicting system performance based on key metrics such as costs, throughput, cycle times, and utilizations
- identifying process bottlenecks such as queue build-ups and over-utilization of resources
- planning staff, equipment, or material requirements

Arena is used by companies engaged in simulating business processes. Some of these firms include General Motors, UPS, IBM, Nike, Xerox, Lufthansa, Ford Motor Company, and others.

7.4.2 The Arena environment

As soon as the Arena software is "launched", the following screen will appear:

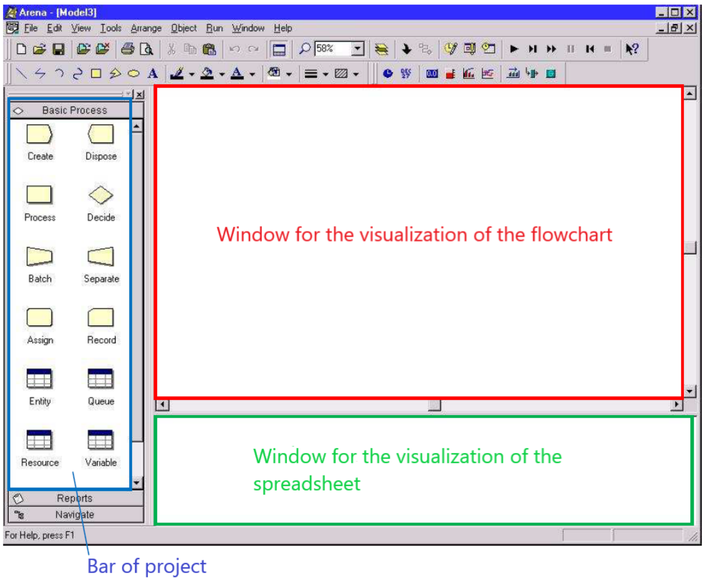


Figure 50

To model the process in the Arena, you work in three central regions of the application window.

The Project Bar houses panels with the main types of objects with which you work:

- The Basic Process, Advanced Process, and Advanced Transfer panels: contain the modeling forms, called modules, which are used to define the process. The eight shapes in the "Student" version are: "Create", "Dispose", "Process", "Decide", "Batch", "Separate", "Assing", "Record".
- The Reports panel contains the reports available for viewing simulation results.
- The Navigate panel allows you to view different views of the model.

In the model window, there are two principal regions: the flowchart view window, which contains all the model graphics (objects, links between them, animation, etc.) and, further down, the spreadsheet flowchart window that shows data models, for example, times, costs and other parameters.

You can also change the "Run" settings of the model: by clicking with the left mouse button on "Run," present in the "menu bar" ("Menu bar"), a drop-down menu opens on which you must click on "Setup ...";

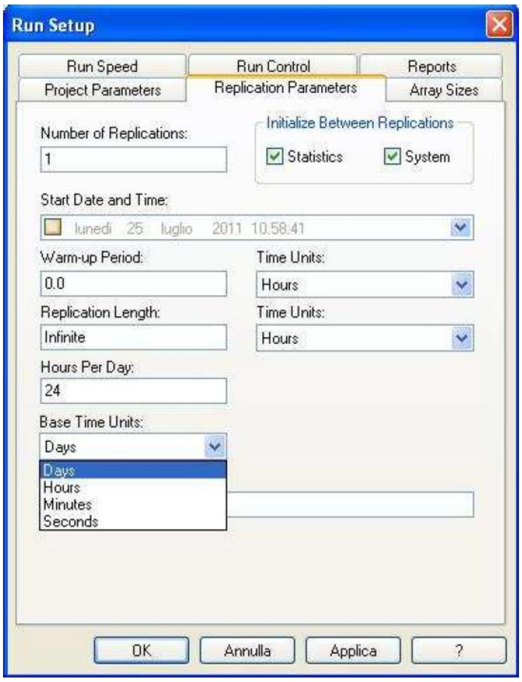


Figure 51

This window presents, in the upper part, a whole series of "tabs" of what can be set.

In particular, we find "Replication Parameters": through it, you can set the values you want, and that best describes the model; you can set the time during which you want the model to be replicated by putting a value in the space dedicated to "Replication Length" and the unit of measurement by changing it from the drop-down menu on the right of the value just set at the same height. Further down there is another important parameter to set which is "Base Time Unit," ie, it allows you to choose the unit of measurement of time for the model: the possible options to choose from are "Day", "Hours", "Minutes", "Seconds".

7.4.3 The model

The arena model is the translation of the conceptual model built with the Petri nets logic and will have a very similar structure. Then the settings will be explained with more considerable attention without going into the details of the logic that has already been taken care of in the part of the conceptual model.

Clearly, the complete model was not built from scratch. I started with a simple model assuming simplifications and then progressively improved it adding new data and features. Below is the model:

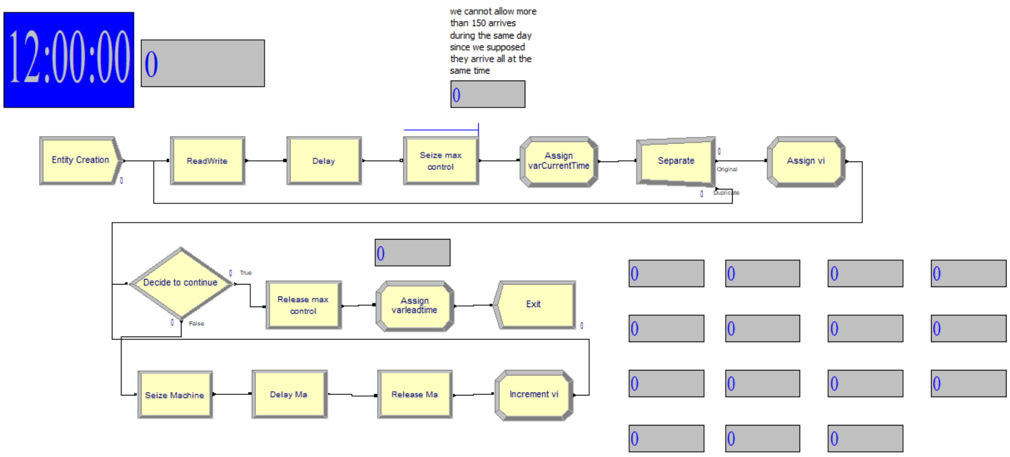


Figure 52

Flowchart

The flowchart modules are the set of objects that are inserted (by dragging the mouse) into the model window to describe the simulation process.

All the information needed to simulate a process is stored in forms.

There are two types of modules inside the Arena:

• FLOW-CHART modules which, linked together, describe the system dynamically

• DATA modules, for the static description of the problem.

First, all the elements that make up the model and its operation will be explained.

<u>DATA modules</u>

The data modules are the set of objects in the view of the model spreadsheet that allows defining the characteristics of the process elements. They set values and conditions for the entire model and are not affected by entity flows or connections. The Basic Process panel contains the following data modules: Entity, Queue, Resource, Variable, Schedule, Set. To use a data module, click on it with the left mouse button, and then you can proceed with changing the characteristics in the Visual spreadsheet.

- Entity: used to define entities, it is possible to define the name, cost of staying in the system, and other initial costs such as waiting costs, transfer.
- Queue: used to define the queues; different management modes are possible, FIFO (first in first out), the first element that enters is the first element that leaves the queue, LIFO (last in first out) the last element that enters is the first to exit. Finally, it is possible to prioritize the element that enters.
- Resource: used to define resources; we can establish a fixed capacity of resources or variable through the schedule.
- Variable: used to define global system variables, they can be vectors or matrices.
- File: used with the ReadWrite module to manage arrivals read from an Excel file. The name of the file is defined (the same entered in ReadWrite), the type and path of the file, and, within Recordsets, the name of the Excel cells from which to extrapolate the arrival times.
- Set: The most common situation is the selection of an available resource from a resource pool. The Sets module provides the basis for this functionality. Arena sets are groups of similar objects that can be referenced with a common name (the name of the set) and a set index. The objects that make up a set are called members of the set. The members of a given set must all be of the same type of object, such as resources, queues, images, etc. Almost all types of Arena objects can be collected in one set, depending on your modeling needs. An object can also reside in more than one set.
- Advanced Set: specifies queue sets, storage sets, and other sets and their respective members. A set defines a group of similar elements that may be referenced via a common name and a set index. The elements that make up a set are referred to as the members of the set. Two sets may be specified within a Seize or material-handling-type module. Storage sets may be used in the Store and Unstore module. Other sets may include sets of attributes or other miscellaneous elements.
  (Rockwell Automation Arena Users Guide User Manual)

<u>FLOW-CHART modules</u>

- "Create" module

This module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time interval between one arrival and another. Entities leave the form to be "processed" through the system. The number that is at the bottom right of the module image indicates the number of entities created.

Details:

- Name: identifier of the module;
- Entity Type: type of the entity created;
- Type: generation mode (with exponential, constant or distributed inter-arrival times according to a probability distribution);

- Entities per Arrival: number of the arrival group;
- Max Arrivals: total number of entities generated;
- First Creation: an instant of arrival of the first entity.

- "ReadWrite" module

Use a remote file on your computer (Excel spreadsheet) to read the arrival times of the entities in the system. Within the model, the Create module will, therefore, have the only function of creating the entity. When it reaches the ReadWrite module, it 'reads' its arrival time and stores it within a specific attribute, defined within the module.

Details:

- Name: identifier of the module;
- Type: defines the type of file that Arena will have to query to know the arrival times of the entities;
- Arena File Name: name of the above file. The name must be the same that appears in the DATA File module associated with this FLOW-CHART module;
- Recordset ID: identification that must match the one specified in the DATA File module, which is associated with the name of the Excel cells from which to extrapolate the arrival times;
- Assignment: this field defines the attributes to which the values read from the Excel file are assigned.

- "Assign" module

This module is used to assign new values to variables, to entity attributes, to entity types, entity images, or other system variables. Multiple assignments can be done with a single "Assign" module. The assignment operation occurs when an entity crosses the form.

Details:

- Name: the unique identifier of the module;
- Assignments: specifies the assignment to be made each time an entity crosses the form.

- "Process" module

This module is intended as the central processing method in simulation. Options are available for collecting and releasing resources. Besides, there is the possibility of using a submodel and specifying a hierarchical logic defined by the user. The processing time is assigned to the entity and can be considered an added value, not an added value, of transfer, of waiting, or other. The associated cost will be added to the appropriate category. The bottom number, below the image, indicates the number of entities currently underway in the process.

Details:

- Name: identifier of the module;
- Type: standard processing or subModel;
- Action: type of processing;
- Delay: processing time is required, but no resources;
- Seize Delay: processing time is required and a resource that is allocated, but not released;
- Seize Delay Release: processing time and a resource that is allocated and released is required;
- Delay Release: processing time is required, after which a previously allocated resource is released;
- Priority: priority level of the entities that pass through the module;
- Resources: resource or set of resources used for processing;
- Delay Type: distribution used to generate processing times;
- Units: the unit of time measurement.

- "Seize" and "release" modules

If you want to anticipate or delay the capture or release of resources, respectively, you can use the seize and release modules separately from the processing module.

- "Separate" module

This form can be used both to copy an incoming entity into multiple entities and to divide a previously grouped entity. Rules are also specified for the distribution of costs and times for duplication. Rules for assigning attributes to member entities are also specified. When dividing existing lots, the representative temporary entity, which was formed, is disposed, and the original ones that made up the group are recovered. Entities proceed sequentially from the form in the same order in which they were originally added to the batch. When entities are duplicated, the specified number of copies are made and sent by the form. The original entities also leave the form.

Details:

- Name: identifier of the module;
- Type: type of separation (Duplicate Original, Split Existing Batch)
- Percet Cost to Duplicates: allocation of times and costs of the incoming entities of the outgoing duplicates;
- # of Duplicates: number of duplicates.

- "Decide" module

This module allows decision-making processes in the system. It includes options for making decisions based on one or more conditions (for example, if the entity type is Gold Card) or based on one or more probabilities (for example, 75%, it is true, 25%, false). Conditions can be based on attribute values, variable values, entity type, or an expression. There are two exit points from the "Decide" module when the specified type is either "2-way chance" or "2-way condition". There is an exit point for "true" entities and one for "false" entities. When instead there is "N-way chance" or the type of condition is specified, there are multiple exit points, one for each condition or probability and one for the "else" exit. The number of entities that come out of each type (true/false) is displayed for the “2-way chance” possibility or only for the condition modules.

Details:

- Name: identifier of the module;
- Type: decision on condition.

- "Dispose of" module

It represents the destruction of an entity once the whole system has been covered. The form is generally preceded by the collection of statistics. The number at the bottom right of the image represents the number of entities that have been resolved.

7.4.4 Ratti S.p.A Model settings

The model that has been built can be divided substantially into two parts, where there are cycles that characterize the compact modeling logic that has been used.

The model will then be explained in pieces. First, the part that defines the arrival times of the entities with their respective attributes and then the part where the various simulation times in the department are calculated.

Run setup

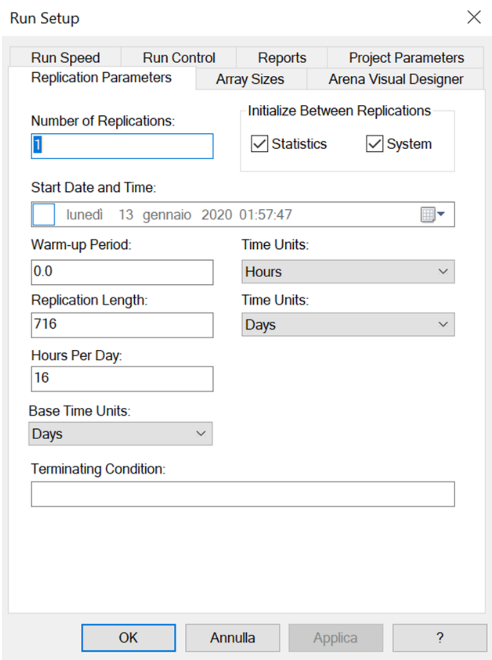


Figure 53

As can be seen from the figure 53, it has been set as a unit of time days since the list of input orders is organized according to this criterion. Also, the company works on two 8-hour daily shifts so 16 hours of activity per day have been set. The length replication is the same as the last input time value of the input list. This list, as has already been explained, is ordered incrementally according to the dates without considering the periods of inactivity such as weekends or holidays. This criterion indeed exactly describes the logic with which arena works.

DATA modules

- Entity: the only entity used is the one to activate the model, as explained in the Petri net. It was decided to keep the generic name of Entity 1.
- Resource: the list of resources is represented by the set of machines in the finishing department. As seen in the Petri net, we also have the MaxControl resource, which has the function of limiting the entry of entities into the process.

Table 11

Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	AIRO	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
2	BRCGEN	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
3	CIL	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
4	COM	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
5	CUCI	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
6	DECC	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
7	EXT	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
8	LAVEXT	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
9	PALMER	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
10	RAM	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
11	RAM003	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
12	RAM004	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
13	RAMISH	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
14	RUOTA	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
15	SANFOR	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
16	maxControl	Fixed Capacity	146	0.0	0.0	0.0		0 rows	☑

- Variable: the varCurrentTime variable and the c and tfc matrices have already been explained in the Petri net. The varleadTime variable will instead be used to plot the traversal period in the system. They both have an initial value equal to 0. The model also uses the tnow system variable which automatically evolves following the running time of the simulation.

Table 12

Variable - Basic Process

	Name	Comment	Rows	Columns	Data Type	Clear Option	File Name	Initial Values	Report Statistics
1	varCurrentTime				Real	System		1 rows	☐
2	c		45	9	Real	System		352 rows	☐
3	tfc		45	8	Real	System		316 rows	☐
4	varleadTime				Real	System		0 rows	☐

- *Queue*: as regards the queues, a relative queue has been created for each resource. Since queues cannot have the same resource name for ease of understanding, a lowercase q was simply added to each name. All queues created to follow the First In First Out logic.

Queue - Basic Process

	Name	Type	Shared	Report Statistics
1	AIROq	First In First Out	☐	☑
2	BRCGENq	First In First Out	☐	☑
3	CILq	First In First Out	☐	☑
4	COMq	First In First Out	☐	☑
5	CUCIq	First In First Out	☐	☑
6	DECCq	First In First Out	☐	☑
7	EXTq	First In First Out	☐	☑
8	LAVEXTq	First In First Out	☐	☑
9	PALMERq	First In First Out	☐	☑
10	RAMq	First In First Out	☐	☑
11	RAM003q	First In First Out	☐	☑
12	RAM004q	First In First Out	☐	☑
13	RAMISHq	First In First Out	☐	☑
14	RUOTAq	First In First Out	☐	☑
15	SANFORq	First In First Out	☐	☑
16	maxControlq	First In First Out	☐	☑

Table 13

- *File*: the order reading file is called input and is in txt format. It was obtained by joining excel sheets through set operations or filters and then converted and extracted most appropriately thanks to the R software. Obviously, the address from which to upload the file must be specified.

File - Advanced Process

	Name	Access Type	Operating System File Name	Structure	End of File Action	Initialize Option	Comment Character
1	input	Sequential File	C:\Users\Lorenzo\Desktop\arena\input.txt	Free Format	Dispose	Hold	No

Below is a part of the file

input - Blocco note di Windows

File Modifica Formato Visualizza ?

```
1701011,0,16,19
1701011,0,16,19
1701004,0,28,21.8
1701004,0,28,21.8
1701025,1,8,19
1701005,1,33,24.5
1701005,1,33,24
1701019,1,33,25
1701019,1,33,25
1701006,1,33,22.4
1701006,1,33,23.4
1701004,1,28,28.6
1701009,1,11,23.9
1701009,1,11,24
```

Set: a set of resources called "machines" was created and made up of all the machines in the department. To create this group, the same name was called. The index to the left of each name characterizes the numerical code with which the machine is represented in table c. Thanks to R, it was easy to encode all the names and maintain concordance in all the settings.

Table 16

Set - Basic Process

	Name	Type	Member Definition Method	Members
1	machines	Resource	Manual List	15 rows

Members

	Member Type	Resource Name
1	Single Element	AIRO
2	Single Element	BRCGEN
3	Single Element	CIL
4	Single Element	COM
5	Single Element	CUCI
6	Single Element	DECC
7	Single Element	EXT
8	Single Element	LAVEXT
9	Single Element	PALMER
10	Single Element	RAM
11	Single Element	RAM003
12	Single Element	RAM004
13	Single Element	RAMISH
14	Single Element	RUOTA
15	Single Element	SANFOR

Advanced set: also in this case the same logic was followed to create the set of resources but for the queues. This setting is very useful in order to view the queues of the various machines in the arena report.

Table 17

Advanced Set - Advanced Process

	Name	Set Type	Member Definition Method	Members
1	machines.Queue	Queue	Manual List	15 rows

Members

	Queue Name
1	AIROq
2	BRCGENq
3	CILq
4	COMq
5	CUCIq
6	DECCq
7	EXTq
8	LAVEXTq
9	PALMERq
10	RAMq
11	RAM003q
12	RAM004q
13	RAMISHq
14	RUOTAq
15	SANFORq

The functioning of the model

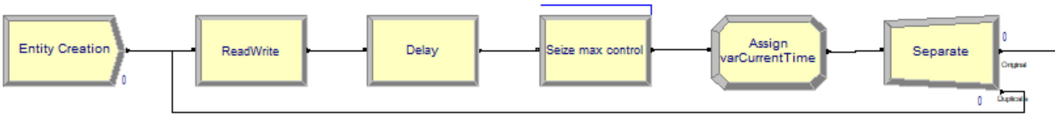


Figure 50

The first part of the circuit, as repeated several times, serves both to correctly read all the input data that will be processed in the model and to maintain a limited number of queues in the system so that it does not crash due to the student version of Arena.

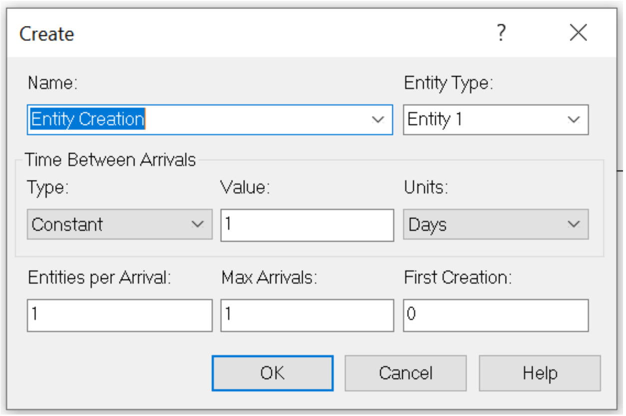
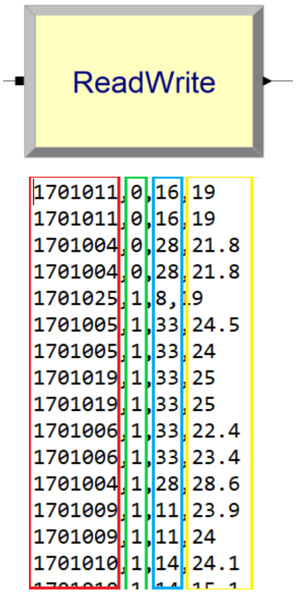
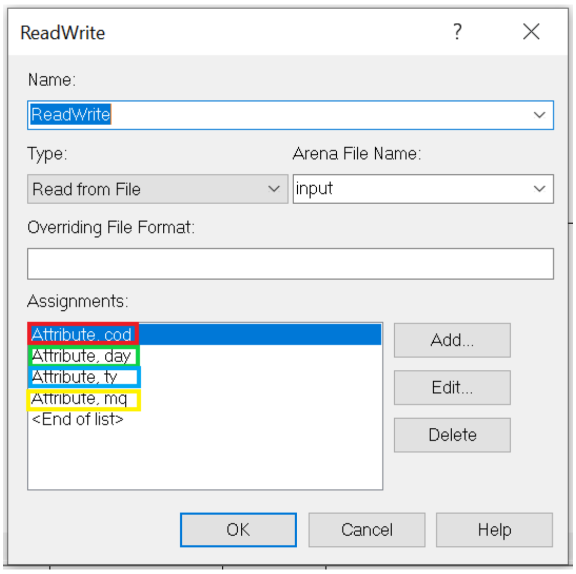


Figure 51 – A e B

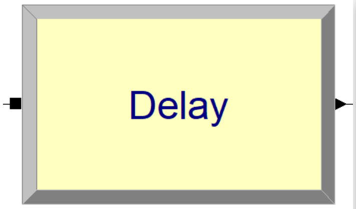
In the create module, the creation of a single Entity 1 was set at time 0 or at the start of the simulation. Although only one entity is created, the system will continue to create new ones thanks to the separate module that will be seen below.

Figure 52 – A e B





With the ReadWrite module, the file to be selected for reading the information is selected. The module has the purpose of associating to each column of the file a specific attribute thanks to the assignment's function. The order in which the attributes are created must be the same as the columns to be associated.



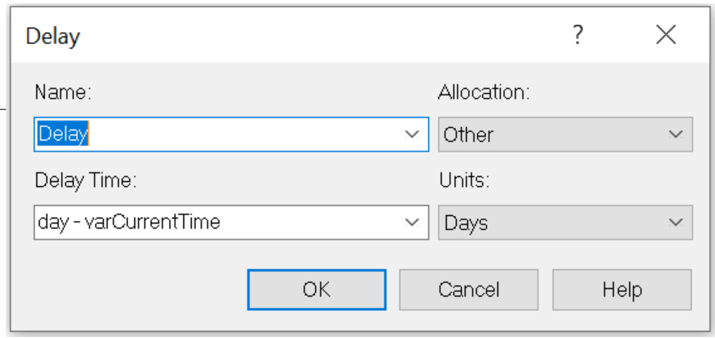


Figure 53 – A e B

With the delay module, we define the function to determine how long a given entity should wait before entering the system. It can proceed only when the period given by the Delay Time function has ended. Taking, for example, the first lines of the reading sheet that represent the orders:

```
1701047,3,16,45.89
1701120,3,8,90
1701050,4,16,39.4
1701159,5,8,12
1701159,5,8,12.4
1701159,5,8,12
1701175,5,8,5.5
1701175,5,8,5.5
1701175,5,8,5.5
1701159,5,8,12.3
1701185,5,8,20
1701088,5,8,40.7
```

Consider, for example, a random row. At time 0 the selected code will have to wait for a period of 8 days. While if we were on the second day of the simulation, it would still have 6 days of waiting. Obviously, having the days as a unit of time and working with discrete events, it is assumed that all orders with the same day attribute enter the system at the same time.

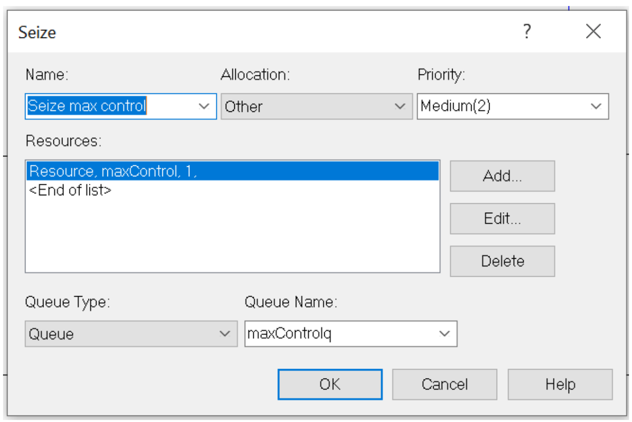


Figure 14 – A e B

With the seize module, we associate the maxControl resource with entities that have ended the waiting period. If all maxControl resources are already occupied, it means that the queue limit lock is active, and they will have to wait until a resource is freed. The module automatically proposes the name of the queue to be associated and has been kept as such.

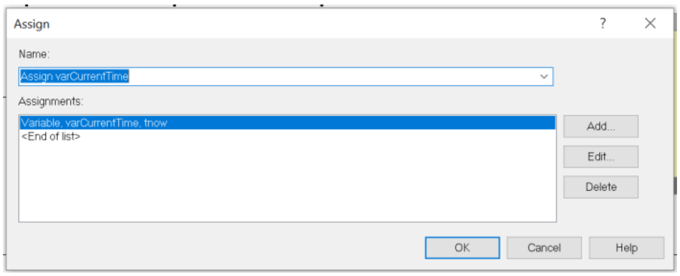
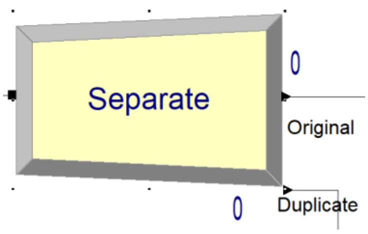


Figure 55 - A e B

Thanks to the seize module, we associate a new value to the varCurrentTime variable, which is the value of the variable on the tnow system.



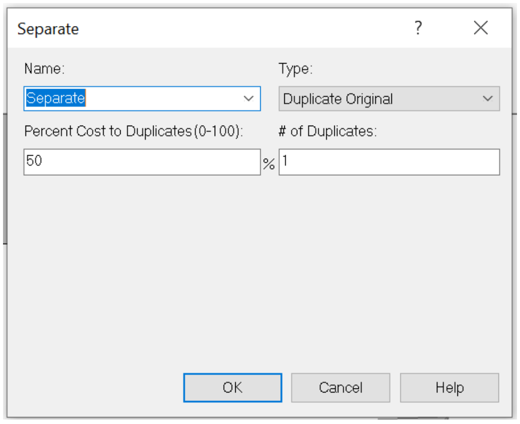


Figure 56 – A e B

With the separate module, the starting entity is duplicated to create a continuous cycle that allows reading from the input sheet. Clearly, having to split the entity into two other equal ones, we set the percentage of cost equal to 50%.

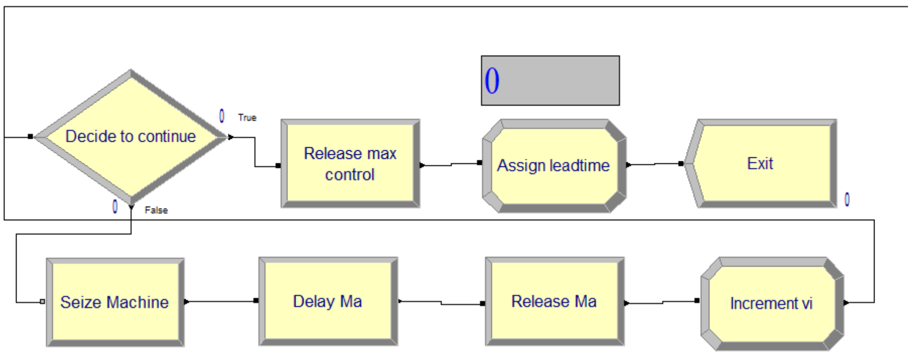


Figure 57

In the second part of the model, instead, there is the cycle that allows entities to follow their scheduling through continuous iterations until they complete the related process. An additional form has also been added for information purposes to show the crossing time in the system.

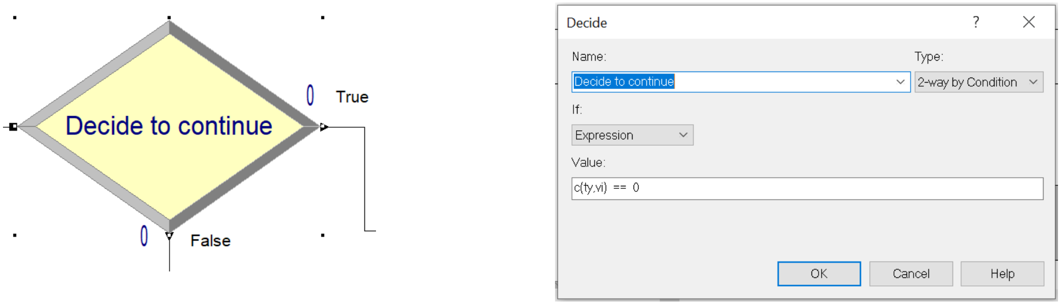
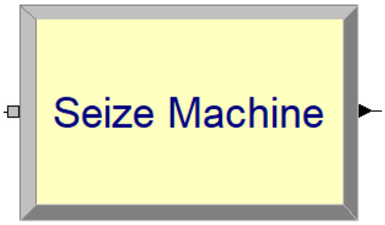


Figure 58 – A e B

With the decision module, the ability to direct the entity to different deviations in the system has been applied thanks to the setting of certain conditions. In particular, the 2-way typo was used since only two outputs from the module were needed. Then applying the expression condition and constructing it to your liking, whenever the value c (ty, vi) is different from zero, the entity continues to iterate following the direction false, while otherwise, it follows the direction correct since the condition is respected.



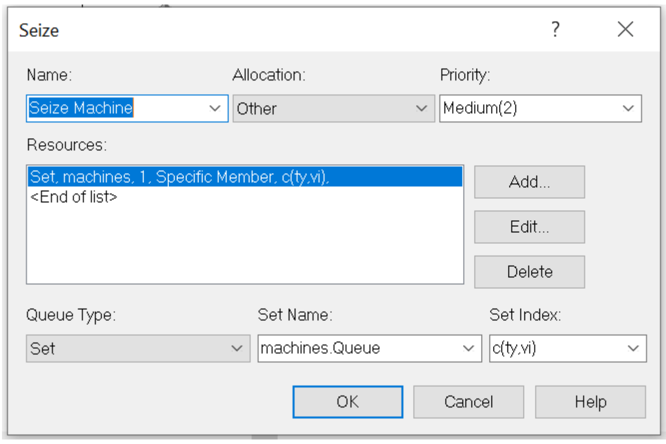


Figure 59 – A e B

Each time the entity enters the cycle, the first thing to do is to associate the machine necessary to process the specific phase of the current iteration. It is then defined to seize to capture a specific machine from the resource set using the "specific member" selection rule. The matrix c will return based on ty and vi the representative code of the machine to be associated. Each time you use a resource set, you can also analyze how individual queues behave. To do this, it is therefore necessary to create a set of queues through the advanced sets then and with the set index the criterion with which the queue-resource association takes place is defined.

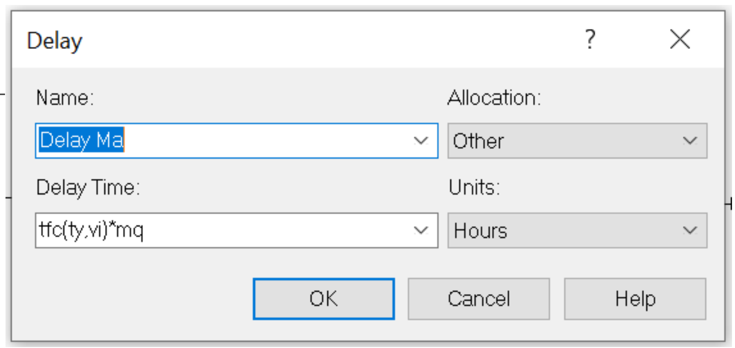


Figure 60 – A e B

Once the machine has been correctly associated with carrying out the phase, the entity is ready to be processed. The processing time is then calculated using the delay module according to the formula shown in the figure 60 B. The value relating to the time to process one m of tissue is obtained from the tfc table, as already seen, while the m attribute linked to the entity characterizes the number of meters to be worked. The resultant of their product will give the necessary time to conclude the phase. Virtually despite only one delay module, multiple entities can be processed simultaneously.

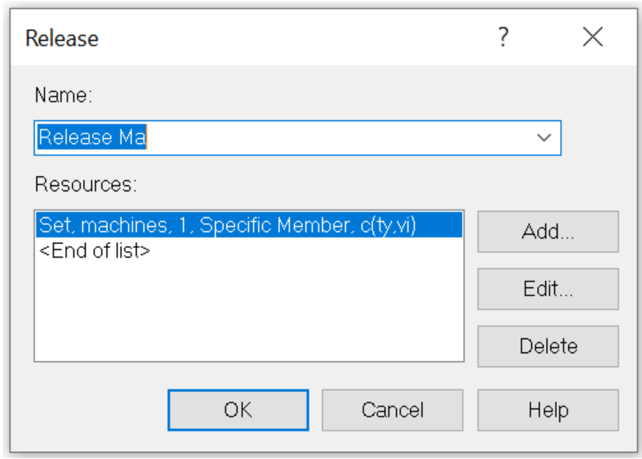
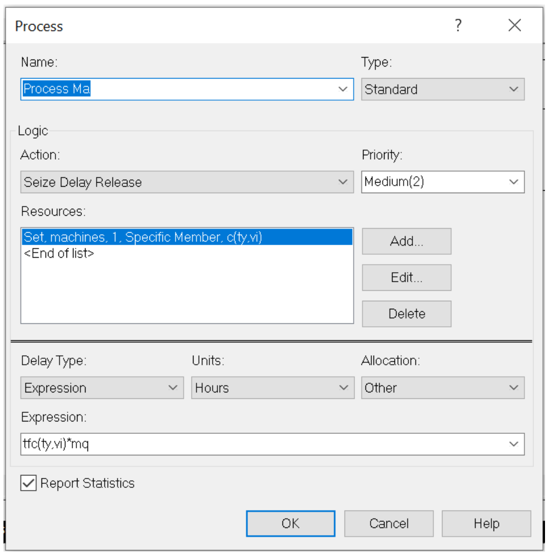


Figure 61 – A e B

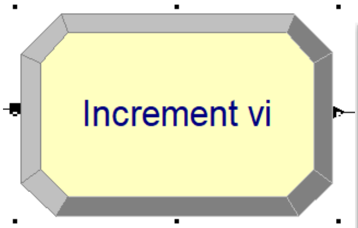
The release module has the task of freeing the resource from the entity and follows the same reasoning as the seize module.

It would also have been possible to put the last three modules in a single process module since their actions occur sequentially, and the orders do not follow particular logic of capture or release of the machine.

Figure 62



In fact, a piece when it enters the system if the resource is available, simply waits in the queue while when it is finished being worked on it does not need to capture the machines of the next phase. This reflects reality, in fact the size of the department is relatively large and the orders move between the various positions with trolleys. When a job has to wait for a car to free itself, it waits in the queue on the trolley. The carriages are moved by the department operators, but to simplify the model, the times relating to movements have not been calculated. They could be considered in a future and improved version of the model.



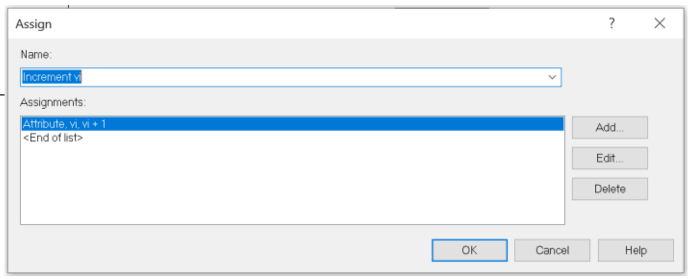


Figure 63 A, B

The assign module has the task of increasing the iteration variable vi. If this action were not carried out, the same order would continue to be processed in the same phase without ever leaving the system.

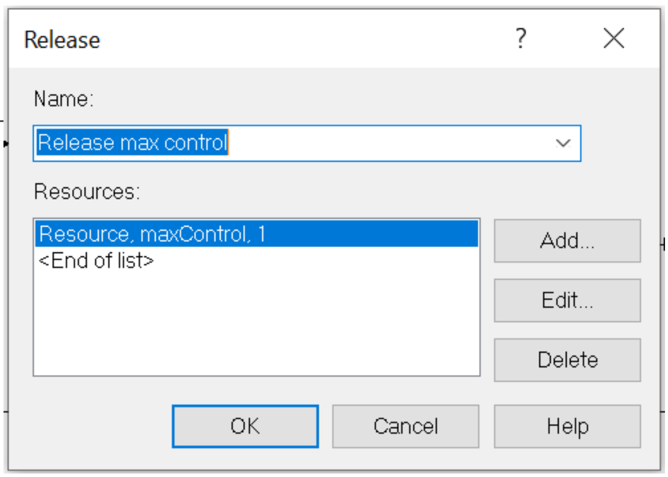
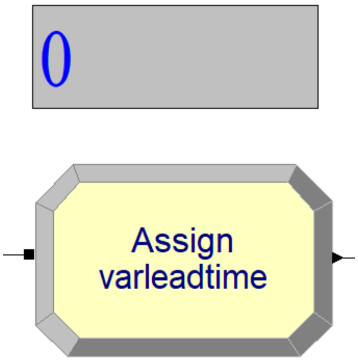


Figure 64– A e B

Once the entity has finished the process and is diverted by the decision maker, it must free the maxControl resource that has been seized all the time. The system in this way can block the entry of entities if there are already a number greater than 148. It was therefore possible to overcome the obstacle of the limit of the student version.

However it is necessary to pay attention because with this setting the actual total crossing time in the department could be influenced. In fact, if it is assumed that the model is able to manage a greater number of entities without large queues, the entry of the order may be delayed and therefore also its exit.

For this reason, before the dispose we decided to add an additional module to show the lead time of each outgoing order. Using the assigned module, we associate the result of the difference between the entry time (day attribute) and the exit time (tnow) to the varleadTime variable.



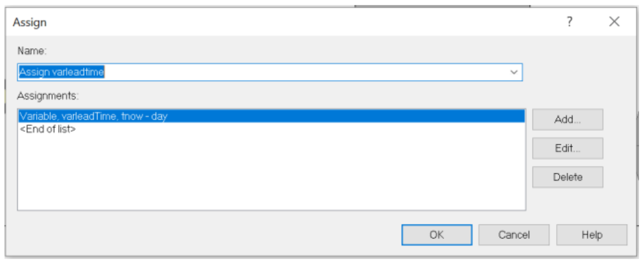


Figure 65– A e B

Keeping under control the lead time variable and the system queues with the use of real-time graphic representations, it was noticed that when maxControl always touched the limit of 148 occupied resources, the queues of the machines were also high. Consequently, the lead time increased.

When maxControl decreases, the other values are also reset. Checking that the lead time does not grow excessively, its total average is around 3 days with some higher peaks. This reflects the normal behavior of the stationing period of the orders in the department.

7.5 Validation process

The next step that needs to be addressed is that of model validation and probably represents the most complicated part of managing in a situation like this. In fact, in order to be validated, a model must correctly describe the situation for which it was created, and this already presupposes initially high accuracy of the data and setting variables.

Obviously, having reasoned from the beginning with high levels of supposition, assuming numerous behaviors, the biggest mistake would be to try to validate it by looking at the results. In fact, precisely for this reason, if the model were perfect, we would most likely not have a coincidence in the outputs since the inputs are not the same. Therefore, by nature, validation assumes that the model is always wrong and that the opposite must be proven.

We must observe his behavior and check that he does not follow strange, non-logical attitudes. Before validating it with other situations, such as the real one of the project, it should be validated with the theoretical hypotheses of itself.

This is a very long phase and probably still originates in the construction phase. In fact, we never start from a complete model, but we try to complete its characteristics through different validations. For this reason, most of the time, the first modeling is incorrect and must be improved by facing numerous changes: what the experts in this sector call playing with data.

In any case, given that the initial objective of this project was to conclude a simulation project applied to a real case, we will continue to hypothesize that the information used is correct, however self-conscious of the contrary.

There could be various ideas to try to validate it, and indeed, the more hypotheses are validated, the more we move away from the possible errors that could represent it.

Among the various information provided by the interviews with the operators, one of the most important concerned the average crossing time in the department. It has been found that an order resides typically about three days in the department. Here we immediately find an example that clarifies how looking only at the results could be wrong evaluation. In fact, observing the model implemented, the lead time varied from values equal to zero and other very high ones. In this case, even if the approximate average of all lead times were equal to three days, it would not be true because its standard deviation is too high.

Another validation method could be the comparison between real department release dates with simulated ones. To do this, the model was further modified so that it could also provide output information. Adding another readwrite block before dispose configures the following settings.

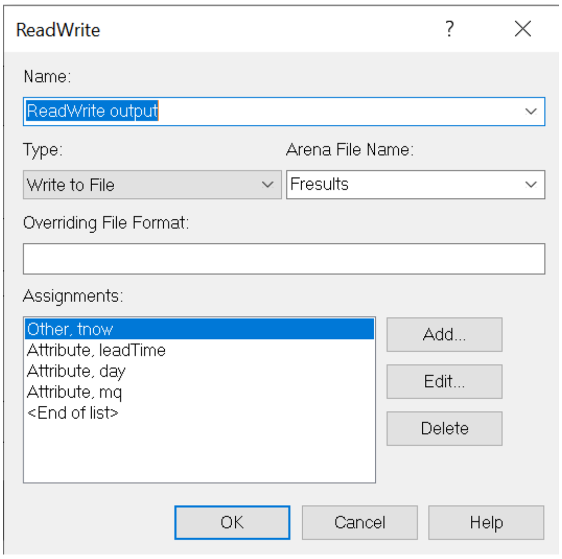


Fig. 66

Now we will output all the information necessary to compare it with the real one.

But we do not forget that in the original dataset, there were not all the output dates for the problems related to the data explained in the previous chapters. Prediction techniques were then applied to obtain the missing results. The codes and results of the prediction are shown in the R file.

Indeed, another method to try to validate the model may consist of comparing the graphic values of the arena report with those carried out in the data analysis part.

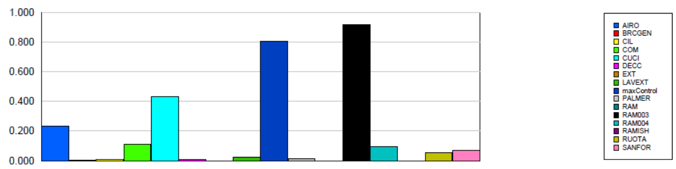
For example, if we look at the various utilizations of the machines of the model, we see that they reflect very well the graph of the total quantities of hours spent by type of machine. The risk of bottleneck for RAM003 is always high.

Fig. 67

Usage

Scheduled Utilization

	Value
AIRO	0.2331
BRCGEN	0.00532196
CIL	0.00605637
COM	0.1104
CUCI	0.4322
DECC	0.00838773
EXT	0.00
LAVEXT	0.02611218
maxControl	0.8061
PALMER	0.01121270
RAM	0.00027222
RAM003	0.9162
RAM004	0.0941
RAMISH	0.00000138
RUOTA	0.05501229
SANFOR	0.07188818



The total number seized, on the other hand, is reflected in the graph on the frequency of the various types of machines in production.

For completeness, we also show the result of the waiting times.

Fig. 66

Usage

Total Number Seized	Value
AIRO	3691.00
BRCGEN	580.00
CIL	3761.00
COM	31885.00
CUCI	70341.00
DECC	1667.00
EXT	70240.00
LAVEXT	149.00
maxControl	70395.00
PALMER	3710.00
RAM	42.0000
RAM003	94041.00
RAM004	983.00
RAMISH	1.0000
RUOTA	21560.00
SANFOR	6144.00

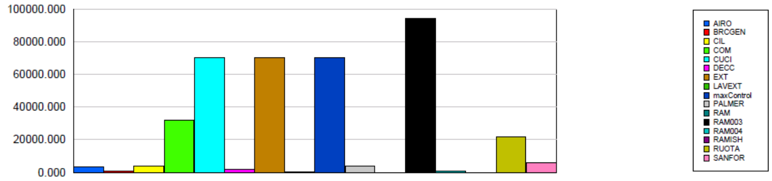


Fig. 68

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
AIROq	0.1126	(Correlated)	0.00	1.8879
BRCGENq	0.00152381	0.000673793	0.00	0.07085555
CILq	0.00062635	0.000164806	0.00	0.01215278
COMq	0.00159468	0.000240777	0.00	0.0986
CUCIq	0.1041	(Correlated)	0.00	1.4081
DECCq	0.00066776	0.000322918	0.00	0.05977951
EXTq	0.00	0.000000000	0.00	0.00
LAVEXTq	0.3471	(Insufficient)	0.00	2.3732
maxControlq	0.00701788	(Correlated)	0.00	0.6681
PALMERq	0.00294071	0.000713500	0.00	0.03554687
RAM003q	0.8071	(Correlated)	0.00	3.0237
RAM004q	0.1188	(Correlated)	0.00	0.8688
RAMISHq	0.00	(Insufficient)	0.00	0.00
RAMq	0.00039667	(Insufficient)	0.00	0.00482526
RUOTAq	0.00263987	0.001685195	0.00	0.4544
SANFORq	0.00400731	0.001273027	0.00	0.4371

As could be imagined, the RAM003 detaches other resources in a big way while in second place is LAVEXT. Indeed, this situation suggests that since the graph of the frequency and that of the hours in which it was used in production during the two-year period, there was no particular concern. This is probably due to the fact that having a very high process time, a few large orders in a short time are enough to create queues. In fact, his maximum waiting time exceeds two days.

These types of observations could be very useful in controlling the flow within the finishing department. In fact, having to aim to maintain a continuous flow in production without exceeding the queues, thanks to the simulation, Ratti S.p.A could try to maintain the optimal utilization value by keeping waiting times under control.

To conclude, the testing phase will make more sense to be developed when the implementation of RFID is finally completed. At that point, perhaps the model will have increased its effectiveness to make the best use of the new techniques. Currently, in fact, due to the lack of specificity, it is not appropriate to face further steps but rather to focus on the values of industry 4.0 that have been treated in the literature section.

8. Conclusion

This project started from far away from touching all the main points of the new enabling technologies that are distinguishing this rapid leap into the future that no longer seems so far now.

In the end, however, we came to a conclusion, almost like a journey that is not destined to stop just like this project, which will still have some time to be perfected. The main objective was to map the main pillars of industry 4.0 with particular attention to simulation, the meeting point between the now consolidated technologies and those that are about to turn the whole industrial vision

The digital twin, just like a brother, will accompany this revolution that has just begun for a long time. But the simulation will still be there because although it can already be considered an ancient technology, it is the basis of everything that surrounds us. Indeed, it is a transparent process that silently controls everyday life. Nothing is nowadays left to chance, and those who are aware of it will always be one step ahead of everyone. There is still a lot of confusion about how to deal with real industrial development, and many companies do not understand that it is a long path, just like this thesis. To be able to get far, you have to start from afar because without the "base," development does not take place. By now, almost everyone wants to ride the wave of development, but doing it too quickly can be counterproductive. As a simulation project, you have to follow specific steps, and you cannot skip steps; otherwise, the risk of error is too high.

We live in a world where industrial risk, for those who know how to manage it, no longer exists, managing to foresee everything. The simulation does and will always do this, supporting every type of decision. This is not to say it is more important than other subjects, but it is undoubtedly the one that has the most contacts between the numerous technologies.

The intention of this thesis was to try to facilitate the understanding of numerous definitions and methodologies that are now used without even knowing their meaning, and to do so, the use of simulation has been taken advantage of. For example, data analysis work was carried out, which characterized a large part of the reflections. R, a beneficial software at the base of the knowledge, has managed to incorporate exceptionally well with Arena. These two tools were the basis of the real study undertaken for the Ratti company. The latter represents the typical example of a different reality where patience in waiting for this slow transformation will bring great results. With what I have tried to convey with this thesis, I do not expect to improve the situation in the short term, but I hope to have been convincing in showing that this is the right way to go.

9. Bibliography and References

- Humayed, J. Lin, F. Li, B. Luo, 2017, Cyber-Physical Systems Security – A Survey,Ieee Internet Things J. 4 (6) (1802–1831)
- A.J.C. Trappey, C.V. Trappey, U.H. Govindarajan, J.J. Sun, A.C. Chuang , 2016, A Review Of Technology Standards And Patent Portfolios For Enabling Cyber-Physical Systems In Advanced Manufacturing Ieee Access, 4 , Pp. 7356-7382
- Ahmadzai Ahmadi, Chantal Cherifi, Vincent Cheutet, Yacine Ouzrout , 2017 A Review Of Cps 5 Components Architecture For Manufacturing Based On Standards
- Alberto Segura Components Majid Bayani School Of Informatics National University Of Costa Rica Heredia, Costa Rica School Of Informatics National, 2017, Internet Of Things Simulation Tools: Proposing Educational
- Am Law, Wd Kelton, Wd Kelton (2000) Simulation Modeling And Analysis Mcgraw Hill
- Babiceanu Rf, Seker R ., 2016, "Term That Describes Large Volumes Of High-Speed, Complex And Variable Data, Which Require Advanced Techniques For The Acquisition, Storage, Distribution, Management And Analysis Of Information"
- Boschert S., Rosen R. Digital Twin – 2016, The Simulation Aspect, In Mechatronic Futures, Hehenberger P., Bradley D. Eds. Cham: Springer International Publishing, 59-74.
- Ch Chakradhara Rao, Mogasala Leelarani, Y Ramesh Kuma, 2013, Cloud: Computing Services And Deployment Models
- Chen, D.; Vernadat, F.B. Enterprise Interoperability, 2003, A Standardisation View; Springer: Boston, Ma, Usa; Pp. 273–282
- Chiara Cimino, Elisa Negri, Luca Fumagalli , 2019, Review Of Digital Twin Applications In Manufacturing
- Christos Koulamas, Athanasios Kalogeras , Nov 2018, Cyber-Physical Systems And Digital Twins In The Industrial Internet Of Things
- D. Rossetti, 2015, Simulation Modeling And Arena, Manuel
- Dr. Andreas H. Glas, Prof. Dr. Florian C. Kleemann (June 2016) The Impact Of Industry 4.0 On Procurement And Supply Management: A Conceptual And Qualitative Analysis
- E. Blunck E H. Werthmann, 2017, «Industry 4.0 – An Opportunity To Realize Sustainable Manufacturing And Its Potential For A Circular Economy,» Diem
- E. Hofmann, M. Rüsch, 2017, Industry 4.0 And The Current Status As Well As Future Prospects On Logistics, Computers In Industry 89 23–34ieee, 104 (5)
- E. Hofmann, M. Rüsch, 2017, Industry 4.0 And The Current Status As Well As Future Prospects On Logistics, Computers In Industry 89, 23–34
- E. Hozdić, 2015, Smart Factory For Industry 4.0: A Review Int. J. Modern Manuf. Technol., 7 (1)
- Elisa Negri, Luca Fumagalli, Marco Macchi,2017, A Review Of The Roles Of Digital Twin In Cps-Based Production Systems
- Emel Ceyhun Sabir, Esma 2014, Batuk Modeling Of Textile Dyeing-Finishing Millproduction Cost And Time Under Variabledemand Conditions With Simulation
- F. Pérez, E. Irisarri, D. Orive, M. Marcos And E. Estevez, 2015, A Cpps Architecture Approach For Industry 4.0, 2015 Ieee 20th Conference On Emerging Technologies & Factory Automation (Etfa), Luxemburg 1-4

- Fei Tao , Qi Q, Liu A, Kusiak A. , 2018, Data-Driven Smart Manufacturing. J Manuf Syst ;48(Part C):157–69.
- Fei Tao Et Al. , 2019, Engineering 5 653–661
- Fei Tao, Qinglin Qi, Lihui Wang, A.Y.C. Nee, 2019, Digital Twins And Cyber-Physical Systems Toward Smart Manufacturing And Industry 4.0: Correlation And Comparison
- Franco Landriscina, 2014, Simulation And Learning, A Model-Centered Approach
- Gandomi A., Haider M., 2016, Beyond The Hype: Big Data Concepts, Methods, And Analytics, International Journal Of Information Management, Volume 35, Issue 2, April 2015, Pages 137-144
- Giovanna Baglio, Tessuti E Finissaggi Produrre Con Qualità Per Un Mercato Di Qualità – Cciaa – Como – 25 Ottobre 2007
- Igor Halenar Martin Juhas Bohuslava Juhasova Dmitrii Borkin 2019, Virtualization Of Production Using Digital Twin Technology
- Industry 4.0: The Future Of Productivity And Growth In Manufacturing Industries April 09, 2015, Michael Rüßmann, Markus Lorenz, Philipp Gerbert, Manuela Waldner, Jan Justus, Pascal Engel, And Michael Harnisch
- International Organization For Standardization: Geneva, Switzerland , 2015, Iso/Iec. Iso 16100-6:2011(E): Industrial Automation Systems And Integration—Manufacturing Software Capability Profiling For Interoperability; International Organization For Standardization: Volume 2011
- J. Meierhofer & S.S, September 2019, 2nd Smart Services Summit, Zürich, 50 Ed.. West An Architectural Approach For Service Value Creation With The Digital Twin Dominique Heller And Jürg Meierhofer, Zurich University Of Applied Sciences Shaun West, Lucerne University Of Applied Sciences And Arts
- J. Posada Et Al. (2015) Visual Computing As A Key Enabling Technology For Industrie 4.0 And Industrial Internet, Ieee Comput. Graphics Appl. 35 (2) (2015) 26–40. 10.1109/Mcg.2015.45
- J. Quevedo, J. Pascual. S. Espin And J. Roquet, 2016, Data Validation And Reconstruction For Performance Enhancement And Maintenance Of Water Networks,
- J. W. Strandhagen, E. Alfnes, J. O. Strandhagen E L. R. Vallandingham, 2017, «The Fit Of Industry 4.0 Applications In Manufacturing Logistics: A Multiple Case Study,» Springer
- Jehn-Ruey Jiang, 2018, An Improved Cyber-Physical Systems Architecture For Industry 4.0 Smart Factories
- Jingjun Sun Prof. James A. Chis Ph.D. , 1991, Pe Computer Simulation Of Textile Facilities "
- Jonathan Eyre Chris Freeman, 2018, Immersive Applications Of Industrial Digital Twins
- Kemmerer, S.J., 2009, Manufacturing Interoperability Program: A Synopsis, National Institue Of Standards And Technology; Technical Report For Nist Interagency/Internal Report (Nistir)-7533: Gaithersburg, Md, Usa.
- Kosankeaf.Vernadatbm.Zelm, 2015, (International Organization For Standardization: Geneva, Switzerland
- Koulamas And Athanasios Kalogeras, 2018, Cyber-Physical Systems And Digital Twins In The Industrial Internet Of Things Christos
- L. Negri, L. Fumagalli, And M. Mac- Chi, Sept. 2017, “A Review Of The Roles Of The Digital Twin In Cps-Based Production Systems,” Procedia Manufacturing, Vol. 11, Pp. 939–948

- L. Rentzos, S. Papanastasiou, N. Papakostas, G. Chryssolouris, 2013, Augmented Reality For Human-Based Assembly: Using Product And Process Semantics, Ifac Proceedings Volumes 46 (15),98–101
- Lee E. A., Seshia S., 2017, A. Introduction To Embedded Systems: A Cyber-Physical Systems Approach, 2nd Ed. Cambridge, Massachusetts: Mit Press,
- Lee J., Bagheri B., Kao H.-A., A 2015, Cyber-Physical Systems Architecture For Industry 4.0-Based Manufacturing Systems, Manufacturing Letters; 3:18-23
- Liang-Jie Zhangjia Zhanghong Cai, 2007, Services Computing Pp 89-113, Service-Oriented Architecture
- Luigi Manca Roberto Grugni Ramin Mirzazadeh Digital Twin A Digital Copy Of Reality That Enables You To Simulate And Find Answers In A Risk-Free And Secure Environment
- M Wollschlaeger, R Schrieber , 2013, "Iec 62890: Life-Cycle Management For Systems And Products Used In Industrial-Process Measurement, Control, And Automation (Working Document),"
- M. Andulkar, D.T. Le, U. Berger , 2018, A Multi-Case Study On Industry 4.0 For Sme's In Brandenburg, Germany Proceedings Of The 51st Hawaii International Conference On System Sciences
- M. Andulkar, D.T. Le, U. Berger, 2018, A Multi-Case Study On Industry 4.0 For Sme's In Brandenburg, Germany Proceedings Of The 51st Hawaii International Conference On System Sciences
- M. Roma – Sistemi Di Servizio E Simulazione – Sapienza Università Di Roma – A.A. 2015-201
- M.N.O. Sadiku, Y. Wang, S. Cui, S.M. Musa, 2017, Industrial Internet Of Things, Int. J. Adv. Scientific Res. Eng. (Ijasre)
- Martin Kunath Et Al. / Procedia Cirp 72 (2018) 225–231, Integrating The Digital Twin Of The Manufacturing System Into A Decision Support System For Improving The Order Management Process
- Martin Kunath Et Al. 2018 / Procedia Cirp 72 225–231
- Martin Kunath Et Al., 2018, Procedia Cirp 72 -225–231
- Martin Kunath Et Al., 2018, Procedia Cirp 72 225–231
- Michael Grieves And John Vickers, 2018, Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior In Complex Systems
- Michael Grieves, 2015, A Whitepaper "Digital Twin: Manufacturing Excellence Through Virtual Factory Replication
- Min Xu, Jeanne M. David & Suk Hi Kim (2018) The Fourth Industrial Revolution: Opportunities And Challenges
- Mohd Aiman Kamarul Bahrin, Mohd Fauzi Othman, Nor Hayati Nor Azli, Muhamad Farihin Talib (2016) Industry 4.0: A Review On Industrial Automation And Robotic
- Mohd Aiman Kamarul Bahrin, Mohd Fauzi Othman, Nor Hayati Nor Azli, Muhamad Farihin Talib (2016) Industry 4.0: A Review On Industrial Automation And Robotic
- P Sharma, 2016 Discrete-Event Simulation
- P. Bocciarelli, A. D'ambrogio, A. Giglio, E. Paglia,2017, A Bpmp Extension For Modeling Cyber-Physical-Production-Systems In The Context Of Industry 4.0, 2017 Ieee 14th International Conference On Networking, Sensing And Control (Icnsc), Calabria 599–604
- Philipp Gerbert , Markus Lorenz , Michael Rüßmann , Manuela Waldner , Jan Justus , Pascal Engel , Michael Harnisch, 2015, Industry 4.0: The Future Of Productivity And Growth In Manufacturing Industries

- Philipp Gerbert , Markus Lorenz , Michael Rüßmann , Manuela Waldner , Jan Justus , Pascal Engel , Michael Harnisch, 2015, Industry 4.0: The Future Of Productivity And Growth In Manufacturing Industries.
- R. Harrison, D. Vera, B. Ahmad Engineering , 2016, Methods And Tools For Cyber-Physical Automation Systems Proc.
- Rainer Müller Ing. Prof.Dr, Dipl.-Wirt.-Ing. (Fh) Matthias Vette M.Eng1, Dipl.-Ing. Dipl.-Wirt.Ing. Leenhard Hörauf, Dipl.-Ing. Christoph Speicher And Kruttika Jatti M.Sc , 2016, Concept And Implementation Of An Agent-Based Control Architecture For A Cyber-Physical Assembly System
- Resman, M.A,*, Pipan, M.A, Šimic, M.A, Herakovič, N.A, 2019, A New Architecture Model For Smart Manufacturing: A Performance Analysis And Comparison With The Rami 4.0 Reference Model
- Riccardo Palmarini, John Ahmet Erkoyuncu, Rajkumar Roy, 2017, An Innovate Process To Select Augmented Reality (Ar) Technology For Maintenance, Procedia Cirp, Volume 59
- S. Madakam, R. Ramaswamy, S. Tripathi, Internet Of Things (Iot): A Literature Review, J. Comput. Commun. 3 (2015)
- Shafto M., Conroy M., Doyle R., Glaessgen E. H., Kemp C., Lemoigne J, Wang L., 2010, Draft Modeling, Simulation, Information Technology & Processing Roadmap - Technology Area 11. Washington, Dc: National Aeronautics And Space Administration
- Shao Seung-Jun Shin Sanjay Jain, 2014, Data Analytics Using Simulation For Smart Manufacturing Guodong Systems Integration Division The George Washington University Engineering Laboratory 2201 G Street Nw National Institute Of Standards And Technology Gaithersburg, Md – 20899, Usa Funger Hall, Suite 415 Washington, Dc- 20052, Usa
- Shiyong Wang, Jiafu Wan, Di Li, 2016, Implementing Smart Factory Of Industrie 4.0
- Sino-German, 2018, Alignment Report For Reference Architectural Model For Industrie 4.0/ Intelligent Manufacturing System Architecture Industrie 4.0/Intelligent Manufacturing Standardisation Sub-Working Group
- T. Stock, G. Seliger, 2016, Opportunities For Sustainable Manufacturing In Industry 4.0
- Tc 65 “Iec 62890, 2013, Life-Cycle Management For Systems And Products Used In Industrial-Process Measurement, Control, And Automation (Working Document)
- V. Alcácer, V. Cruz-Machado (2018) Scanning The Industry 4.0: A Literature Review On Technologies For Manufacturing Systems
- Willliam M. D., 2014, Industrie 4.0 - Smart Manufacturing For The Future. Berlin: Germany Trade & Invest)
- Yang Liu, Yu Peng, Bailing Wang, Sirui Yao, And Zihe Liu Review, 2017, Cyber-Physical Systems
- Yang, W.; Tan, Y.; Yoshida, K. & Takakuwa, 2017, Digital Twin-Driven Simulation For A Cyber-Physical System In Industry 4.0 S. Daaam International Scientific Book Pp. 227-234 Chapter 18
- Fonseca i Casas,2014, Formal Languages for Computer Simulation: Transdisciplinary Models and Application

10. Sitography

[1]*https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/topics/industry-40.html*

[2]*https://www.esa-automation.com/en/industry-4-0-the-importance-of-automated-and-interconnected-production/(Jul 2017)*

[3] https://www.pwc.com/gx/en/industries/industries-4.0/landing-page/industry-4.0-building-your-digital-enterprise-april-2016.pdf

[4]https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4future_productivity_growth_manufacturing_industries.aspx

[5]https://www.nist.gov/cyberframework

[6]https://www.bcg.com/it/publications/2015/engineered_products_project_business_industry4_future_productivity_growth_manufacturing_industries.asp

[7] https://new.siemens.com/global/en/products/automation/industry-software/plant-engineering-software-comos/virtual-reality-training.html

[8] https://realpars.com/automation-pyramid

[9] https://www.copadata.com/it/industrie/soluzioni-automazione-industriale/cross-industry-insights/end-game-automation-pyramid

[10] https://realpars.com/automation-pyramid/

[11] https://www.centrosoftware.com/differenza-tra-erp-e-gestionale

[12] https://www.challenge.org/insights/digital-twin-history/

[13] https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital twins-are-entering-mai

[14] https://www.entrepreneur.com/article/333645

[15] https://www.ge.com/digital/iiot-platform

[16] https://www.corrierecomunicazioni.it/cyber-security/siemens-un-digital-twin-processo industriale

[17] https://new.siemens.com/global/en/company/stories/industry/the-digital-twin.html

[18] https://cambashi.com/siemens-goes-all-in-on-digital-twin/

[19] https://blogs.sap.com/2017/09/09/digital-twin-implementation/

[20] https://www.ny-engineers.com/blog/how-digital-twins-can-make-buildings-smarter

[21] https://www.e-zigurat.com/blog/en/digitalization-lighting-industry-bim-vison-digital-twin/

[22] https://icomalta.com/distributed-ledger-technology/

[23] https://www.cibitex.it/textile-finishing/

11. Imagines

Fig2: Di Fei Tao, Meng Zhang, A.Y.C. Nee, 2019, Digital Twin Driven Smart Manufacturing

Fig 3:Mehmet Dogar, Andrew Spielberg, Stuart Baker, Daniela Rus, 2018, Multi-robot grasp planning for sequential assembly operations

Fig4 : https://simulatemore.mscsoftware.com/shaping-smarter-simulation-with-artificial-intelligence/

Fig 8: https://www.fairinstitute.org/blog/nist-maps-fair-to-the-csf-big-step-forward-in-acceptance-of-cyber-risk-quantification

Fig 9: https://robertgreiner.com/windows-azure-iaas-paas-saas-overview/

Fig 10: V. Alcácer, V. Cruz-Machado, 2019, Scanning The Industry 4.0: A Literature Review On Technologies For Manufacturing Systems

Fig 11a: Elvis Hozdić, 2017, Smart Factory For Industry 4.0: A Review

Fig 11b: https://www.semanticscholar.org/paper/A-rapid-control-prototyping-platform-methodology-Kastner-Jan%C3%9Fen/cdc8a166a43477c3376c62e29bb524c674959ace

Fig 15: https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018/

Fig 16: The Digital Twin concept is the next wave in modeling and simulation (Rosen et al., 2015, p. 568).

Fig 17: Aidan Fuller, Zhong Fan, Charles Day, 2018, Digital Twin: Enabling Technology, Challenges and Open Research

Fig 19: https://www.plm.automation.siemens.com/global/es/webinar/closed-loop-digital-twin/64502

Fig 20: https://www.lanner-america.com/es/blog-es/sdn-se-muestra-prometedor-en-la-industria-4-0/

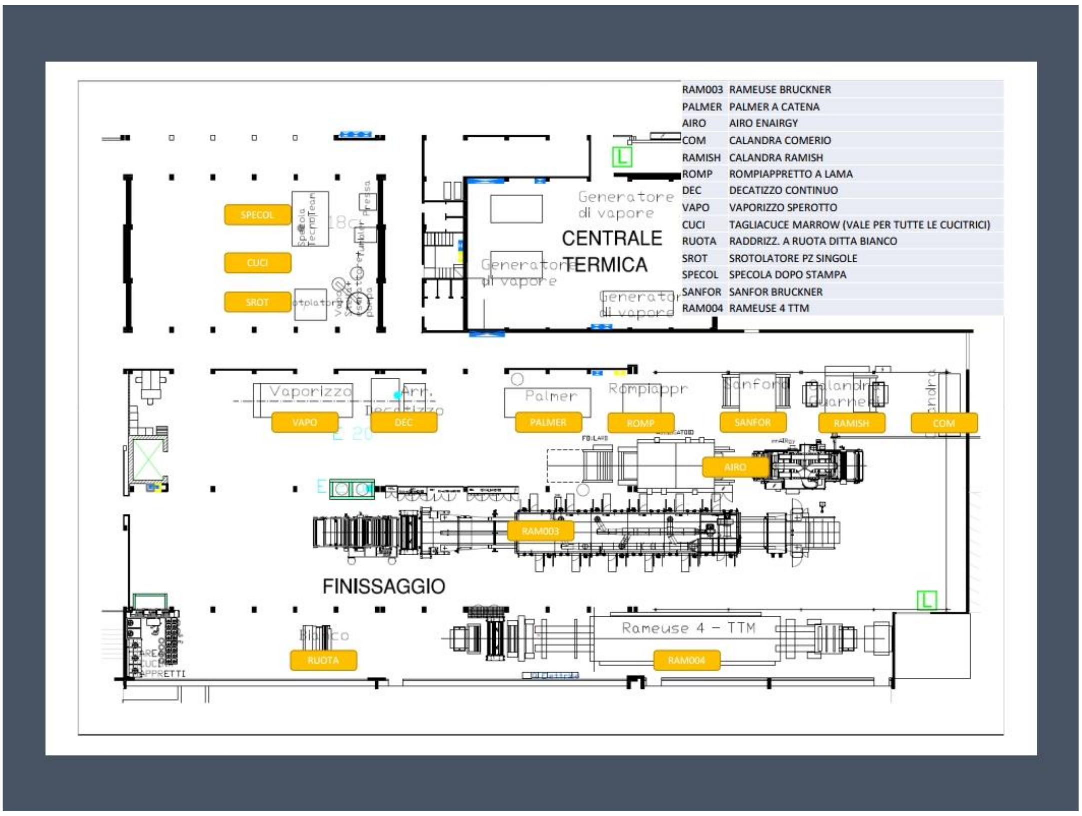
Fig 21: Lee J., Bagheri, et al, 2015

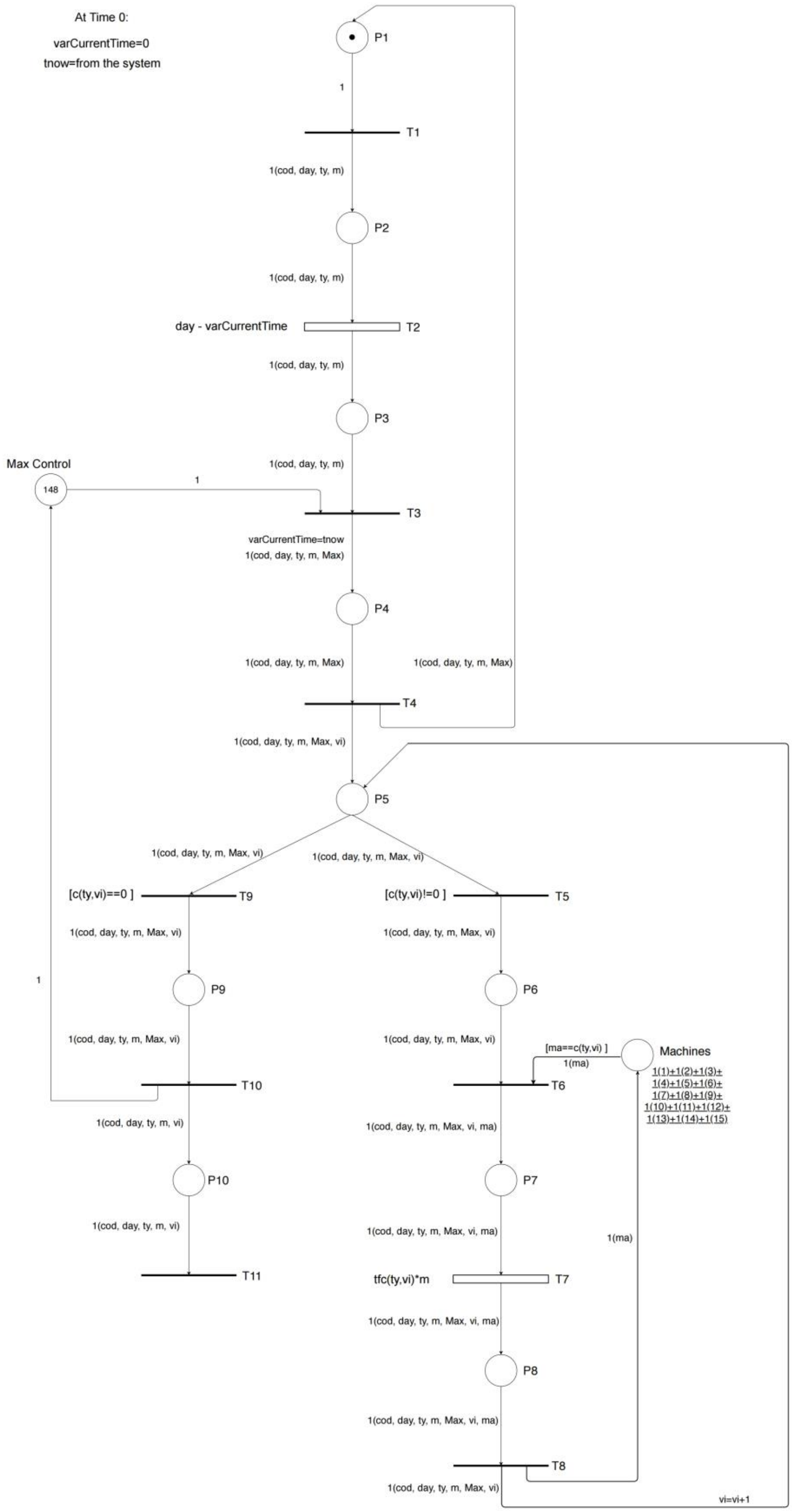
Fig 22: https://www.sciencedirect.com/science/article/pii/S209580991830612X#!

Fig 24: MartinKunathaHerwigWinklera, 2017, Integrating the Digital Twin of the manufacturing system into a decision support system for improving the order management process.

Fig 25: https://ec.europa.eu/futurium/en/system/files/ged/a2-schweichhart-reference_architectural_model_industrie_4.0_rami_4.0.pdf

Fig 26: https://ec.europa.eu/futurium/en/system/files/ged/a2-schweichhart-reference_architectural_model_industrie_4.0_rami_4.0.pdf


RAM003 RAMEUSE BRUCKNER
PALMER PALMER A CATENA
AIRO AIRO ENAIRGY
COM CALANDRA COMERIO
RAMISH CALANDRA RAMISH
ROMP ROMPIAPPRETTO A LAMA
DEC DECATIZZO CONTINUO
VAPO VAPORIZZO SPEROTTO
CUCI TAGLIACUCE MARROW (VALE PER TUTTE LE CUCITRICI)
RUOTA RADDRIZZ. A RUOTA DITTA BIANCO
SROT SROTOLATORE PZ SINGOLE
SPECOL SPECOLA DOPO STAMPA
SANFOR SANFOR BRUCKNER
RAM004 RAMEUSE 4 TTM
CENTRALE TERMICA
Generatore di vapore
FINISSAGGIO
Rameuse 4 - TTM
Vaporizzo
Palmer
SPECOL
CUCI
SROT
VAPO
DEC
PALMER
ROMP
SANFOR
RAMISH
COM
AIRO
RAM003
RUOTA
RAM004


At Time 0:
varCurrentTime=0
tnow=from the system
P1
1
T1
1(cod, day, ty, m)
P2
1(cod, day, ty, m)
day - varCurrentTime
T2
1(cod, day, ty, m)
P3
Max Control
148
1
1(cod, day, ty, m)
T3
varCurrentTime=tnow
1(cod, day, ty, m, Max)
P4
1(cod, day, ty, m, Max)
1(cod, day, ty, m, Max)
T4
1(cod, day, ty, m, Max, vi)
P5
1(cod, day, ty, m, Max, vi)
1(cod, day, ty, m, Max, vi)
[c(ty,vi)==0]
T9
[c(ty,vi)!=0]
T5
1(cod, day, ty, m, Max, vi)
1(cod, day, ty, m, Max, vi)
1
P9
P6
1(cod, day, ty, m, Max, vi)
1(cod, day, ty, m, Max, vi)
[ma==c(ty,vi)]
1(ma)
Machines
1(1)+1(2)+1(3)+
1(4)+1(5)+1(6)+
1(7)+1(8)+1(9)+
1(10)+1(11)+1(12)+
1(13)+1(14)+1(15)
T10
T6
1(cod, day, ty, m, vi)
1(cod, day, ty, m, Max, vi, ma)
P10
P7
1(cod, day, ty, m, vi)
1(cod, day, ty, m, Max, vi, ma)
1(ma)
T11
tfc(ty,vi)*m
T7
1(cod, day, ty, m, Max, vi, ma)
P8
1(cod, day, ty, m, Max, vi, ma)
T8
1(cod, day, ty, m, Max, vi)
vi=vi+1