A Complete Digital Chain to Enable the Digital Twin of a Shop Floor

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Abstract. Digital twins is a recent paradigm. It creates an entangled link between the physical system and its digital twin. The digital twin has obviously no sense without the existence of the physical system, but the physical system highly depends on the digital twin. This concept opens many new challenges and opportunities.
Authors contributed to the construction of a digital twin architecture to manage a shop floor. The experience concerns a complete shop floor. To reach the status of digital twin, it was expected to reach simulation capacities and a complete digital chain to ensure the real time synchronisation of the real world with the underlying model which is the core component of the digital twin. A bottleneck was to create a coherent information system connecting information coming from various sources (MES, Machine Design, ERP, etc), then to propose first functions to demonstrate the added value of this digital twin; here a production simulation was expected within a visual 3D realistic representation of the shop floor. The simulation uses data directly captured from the shop floor to support better decision making.
This paper presents the developed digital twin and its added value respect to production needs. It focuses on key performance indicators synchronisation as observed in the physical world and the impact on anticipation of the various futures depending on production decisions. It reports a first step of a digital twin deployment.

Keywords: Digital Twin · Production flow · Workfloor · Virtual Reality.

1 Digital twin within product life management

The digital twin wording emerged recently [4, 7] and acts as a new paradigm for industry of the future. It was indeed introduced first in 2012 [4] and finally adopted by Dr. Grieves in 2014 for PLM, after using various names: Ideal Concept For PLM and Mirrored Spaces [8, 6]. Digital Twin concept seems to be adopted by a wide community within academic research and industry. If the digital twin was just a virtual model of the physical world, it would not add value respect to the Digital Mock Up paradigm which appeared in the 1990's [2].

Whenever we mention the development of a digital twin we must consider the type of physical system which is twinned. Apollo XIII spacecraft system is often refereed as a good metaphor to illustrate digital twin concept. Indeed during the Apollo XIII mission an oxygen tank incident [5] stressed the engineers to find solutions to keep the crew alive. By this time, digitisation was still poor and engineers used an earth based physical replica of the aircraft to propose and test problem solving processes. The core idea with the digital twin could be to get a digital model enabling such analysis and decision making about the physical system. Many litterature reviews try to define the digital twin concept [17, 9]. They all agree that the digital twin *is required to reach the interaction and convergence between physical and virtual spaces.* Grieves definition was not detailed and remained application dependent; Uhlenkamp and al. [18] proposes dimensions of digital twin applications.

The digital twin is first viewed as a very realistic system simulation to mirror the product during its usage phase. The concept was generalised to any kind of system matching the cyber-physical system [12] definition and adapted to production systems [11, 17, 13]. The digital twin is not only a model, but it is deeply linked to its physical twin. A major point is the synchronization of the model with the real world. The digital twin must maintain a correct representation of the physical world. A supervision system captures the evolution of the physical system. This supervision is stored and versioned all along the system life cycle. Then the digital twin refers a huge amount of information to support decision making to be applied on the physical system.

The digital twin may concern a standard end user product, a manufacturing machine, or any complex system up to a complete production system. It must refer every important information to make decision all along the life cycle. Efforts from the research community to develop such holistic meta-models [16, 3, 15] did not reach a unique model covering every product life cycle. Then the deployment of the digital twin paradigm will lead to the development of partially incomplete digital twins. Within production systems, the distribution of information would be an argue to use big data technologies but they are complementary to the digital twin and do not replace it [14]. Also, the model must be associated to simulation or any other smart system to make decision automatically or to support end-users to make objective decisions [10].

Many papers (as most paper referenced in this section) deeply define the concept and the potential architectures to support the digital twin deployment. The achievement of these architectures faces many challenges within a real shop floor where information is not always digital and seldom integrated. It must also provide direct added value for operators unless it will be abandoned. The authors participated to the development of a digital twin for a shop floor of a first order stakeholder within automotive industry. A complete digital twin cannot be reached in a single step. This paper presents and justifies the key architecture bricks which were developed.

Section 2 describes the various sources of information as found when the project started (ERP, MES, Machine Design models, maintenance documents, etc.). One key point was to rationalize and integrate these sources of information. Section 3 focuses on the triggers used by production engineers to make decisions; these triggers were used to select the information to be managed within the digital twin and led to a distributed digital twin core model. But to become a digital twin, a model must support making decision on every day life. A production simulator was integrated to fill this dimension. At last, but not least the conclusion of the paper discusses the overall process and issues opened via this digital twin experience.

2 Shop floor information sources

2.1 ISA 95 : ERP, MES, SCADA : not yet fully deployed

The digitisation of shop floor was standardized with the ISA-95 pyramid [1]. This pyramid builds foundations by automating physical hardware with actuators connected by sensors. SCADA refers the process control system of a limited machine process. At the top of the pyramid the Enterprise Resource Planning (ERP) manages the information system of the complete shop floor. It is usually prescriptive; it models the shop floor as they are expected by the management engineers. MES is often presented to fill the gap between ERP and SCADA; it usually ensures the storage and management of the sensor values; it allows to get operation feedback.

ISA-95 leads to an information system architecture mainly dedicated to manage the manufacturing operations. The process may be either discrete or continuous. Within discrete processes, operations are sequenced on various workstations, while continuous processes are not split on separated workstations. A continuous production line may be huge but should be managed at the SCADA level. ERP and MES are adapted to manage the physical flows among the workstations.

The level of digitisation of shop floor varies from one company to another and even from a factory to another one inside a same company. Even information properly recorded within the ERP is often printed to get rapid access at operational level. In many companies, updating the information system remains a non priority activity. The priority remains the production; the added value of the information system must be properly balanced with respect to the efforts to maintain it up-to-date. Whatever the justifications, it is easily observed that the usage of all the ISA-95 layers remains very incomplete.

The level of digitised detail depends also of every company. KANBAN system are often paper based while in other companies RFID technologies can automate the management of lots. Quality management expects feedback from every workstations that are still reported by hand following either the production line tag time or the work shift while sensors values are reported at various frequencies.

2.2 Shop floor evolution

At ramp-up, a new factory is mainly organised to support an estimated demand. Its organisation evolves regarding three main activities.

- production order: whenever a production is launched to answer a client command. It is mainly a definition of parameter values of the process. The frequency of creation of new production orders depends on the product, but even for mass production of rapid production process, the production orders are usually decided daily.
- maintenance: it is triggered on anticipated frequency or by random events. The impact of maintenance on the information models may be a simple standby delay information but it may result on modification of a machine and/or the related process parameters but also of the process itself.
- layout reorganisation: it may be due to a performance or quality enhancement (moving machines or integrating new production cells). It may be also driven by a market evolution (observed or anticipated). The frequency of layout re-organisation is seldom less than monthly and can reach several decades for complex equipments (big furnace in a steel production line). In automotive industry the market life cycle of cars is now anticipated from the design stage. Then even stakeholders involved in production of sub-components anticipate the phase-out of references and the layout may be adapted monthly. It was the case in the application where the digital twin was proposed.

The performance of the process depends on layout organisation, on maintenance, on quality processes, and still on the manufacturing process knowledge and know-how. Associated information participate to the digital twin.

2.3 Representations of factory components

The global manufacturing process is organised by the physical and information flows between every work station operation. The work station model depends on the expected simulation or survey. Several sources of information about work stations exists. On one side, every workstation is designed by a machine provider or by the company itself. It relies on physics behaviours that must be technically mastered. On an other side machines are issued from another production process. Models were used for the development of manufacturing machines, but the final production of a machine/work station does not directly depends on its own production model. However production is directly impacted by the machine characteristics. There is thus a direct interest to get access to the design models of the machines (specifications, CAD models, etc). The work station is also modelled by its capacity and performances as reported within a usual ERP. A link between ERP machine structure should be associated with the machine documentation.

When the layout organisation is concerned, all design data is not expected. If the complex geometry impacts the working-station ergonomy and the maintenance process, on the workflow point of view a workstation is mainly a fixed area with material input and output docks. A simplified representation like a footprint is enough for most layout discussions. But some complex layout could be designed and optimised taking advantage of the machine 3D geometry. It is the case if the production lines are stacked up but we must admit that it is not so often. 3D layout is anyhow a real issue for some transfer lines.

It means that it already exists a lot of sources of information about work stations. The impact of every submodel depends on the expected simulations. In addition a model of the factory building is also part of this complete shop floor definition. Most factories do not manage machine models and have basic 2D drawings of buildings. To get access to more complete 3D models, require either a scanning process or a reverse modelling within a CAD modeller. Fortunately for a new machine, a factory should expect its provider to deliver almost a complete CAD model. The 3D model provides a more natural rendering of the factory, which may be an added value to well understand the process for simulations in an immersive modality.

3 Supervision key performance indicators

3.1 A factory use case

The sources of information for a complete factory are widely spread and far from standardisation. But all these models should support making efficient decisions. Decisions take place about production orders, maintenance and layout organisation. This article focuses on production orders. The study is carried out at a first tier automotive supplier. The company produces sub-components in factories. Each factory has about 1000 staff members mainly dedicated to production. Production is organised on 8 hours work shift. A factory is hierarchically decomposed into production lines dedicated to a process type. A line is a set working cells which are composed of several workstations.

3.2 Production order decisions

In the factory the production orders were decided daily. During a collaborative meeting, every factory line manager is expected to report the current state of his line. Then based on customer commands, and with a more or less formal knowledge of future demand evolution, they can discuss production orders priorities.

The main shared object is a 2D map of the factory layout which is used for sharing the locations of the main current issues. The main triggers for making decisions are the expectation to increase the production performance. They expect to maximise and make uniform the sales revenue associated to every square meter. The machine involvement must be optimised: non productive machine must be minimised taking into account both maintenance periods and ramp-up processes. Launching a new reference into production is not instantaneous and expects a calibration process. Longer production runs for a given reference avoids to stop and re-launch the production line for another reference: it is thus more efficient than a serie of short production runs.

Some objective key performance indicators (KPI) become the main argues for decisions making. KPIS are well known from most production system and may be adapted to any management vision. Here the following KPIs were expected: 1.OEE (Overall Equipment Effectiveness which measures the equipment usage rate), SPA (Sales per unit area which measures the ratio of net sale involving a surface leading), WIP (the work in process which measures output and scrap rate), Total count (of produced item), Bad count (of scrapped items), EFF (efficiency).

These KPIs reflect the global state of the overall factory and indeed integrate various measures. From the standard definition of these KPIs and an analysis of the factory sensors we built the graph of Figure 1 which defines the dependencies between available measures and the OEE KPI (a complete graph was produced for all the expected KPIs. They are classified as raw parameter (P), raw measures (M) or aggregated values (A). A measure is directly and automatically captured from sensors while raw parameters are data that are set by hand because no direct sensor can capture them. One can note that in our case the number of automated measure remains low.

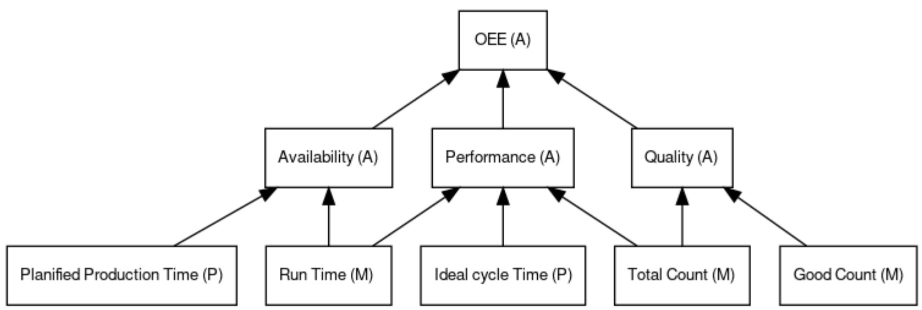

Fig. 1. Links between available measures and the OEE KPI

The supervision from the factory MES is supposed to deliver versioned values of raw parameters. It is also in charge to compute aggregated parameters.

3.3 Shop floor structure

The layout organisation has also an impact on the transfer time. To compute transfer times a structural model of the factory is thus expected. In our use case, the factory engineering office has the CAD models of every machine but do not use them. A CAD modeller is also used to maintain the layout definition. But the distance between workstations cannot be directly extracted from this model which was created mainly to get 2D drawings of the layout.

Thus a specific information model is expected. The factory hierarchy can be easily maintained in either a database or a simple excel sheet. A specific process was created to export a 3D wavefront model of every machine plus basic geometric information such as the 2D footprint and the relative position of the machine within its father inside the hierarchy decomposition. Geometric information is exported from a CAD modeller and we create:

- one or several obj file (wavefront format) to define various represention of every item at various levels of simplification.
- a structure file (a csv table sheet within our implementation) which decomposes the hierarchy and links to the representation files.

The csv file refers every equipment of the factory, linked to its father (the working cell, the production line, sector up to the facto) and associates every equipment to some basic characteristics : CAD model, OBJ files, 2D footprint, etc. A unique id for every equipment is defined here and every other information source (ERP, MES, etc) uses refers to this id. The digital twin becomes a distributed model. Specific processes were implemented to keep this model coherent and synchronised with the real world.

4 Production simulation

4.1 An enhanced supervision

The previous model creates a supervision model. It changes the initial state of the art of the company by providing objective KPIs to make decisions. The system was used to create both traditional 2D dashboards but also to experience a full 3D representation of the company with KPIs. Figure 2 shows the 3D system where two complete production lines were modelled. A direct connection to the supervision system in relation with the shop floor structure(csv file) enables to visualise the KPIs and to investigate their evolution along the time. The left picture of Figure 2 is a picture of the real shop floor while the right snapshot shows the digital twin extended with a direct representation of KPIs (here OEE) on the top of machines. A calendar widget at the bottom of the virtual model allows to navigate along the versioned values of the model.

This digital twin creates a collaborative framework as soon as this vision is shared by several engineers. They have a direct access to objective feedback about the current state of the factory which is in most real situations a real added value since usually the exchange of knowledge about the factory state remains informal through direct discussion. The 3D model makes a realistic framework which makes the framework easy to learn.

The framework enables making decision for production orders, or in few cases layout re-organisation by visualising the main troubles but it does not change drastically the production management. It is expected to go further by providing direct support to make decision through simulation. A simulator was thus integrated to the current system.

4.2 Production simulator

The simulator is a discrete event based simulator. There exist many industrial well known commercial solution for this type of simulations. Every machine consumes inputs and creates output at every simulation step. The process duration, the type of inputs and outputs depend on machine models that must be defined

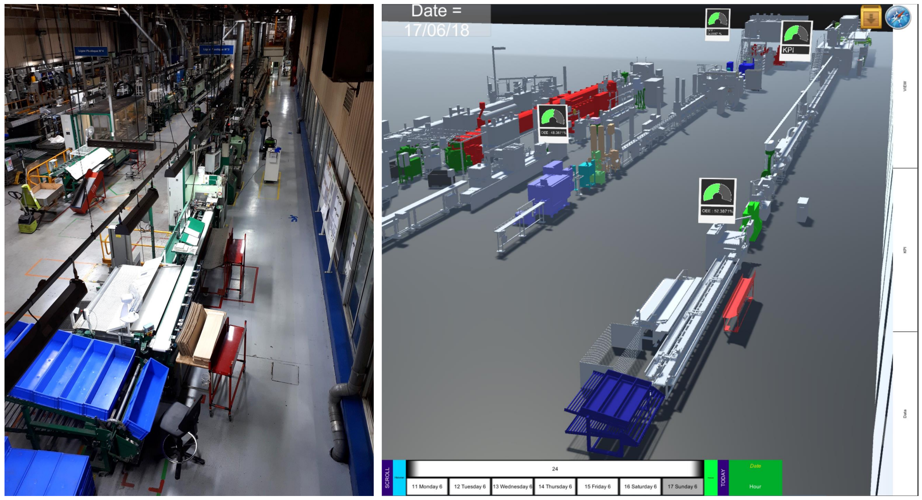

Fig. 2. 3D representation of the factory connected to KPI supervision

a priori. Evoluate solutions undertake randomized models based on statistical behavior of machines. Then the simulation result depends on some randomized values. Starting with a given state two simulation occurences will lead to two different results. For our study a home made simulator was developped. The originality here is that the simulator has a direct access to versioned supervised data. Then the machine input models are continuously updated through the real feedback of the real world.

Figure 3 describes the overall architecture of the digital twin including the simulator:

- The factory digital model merges the 3D geometric model (obj files) exported from the CAD models given by machine providers plus the hierarchical structure which is a simple excel sheet saved as a csv file. All this data can be updated at any time but the real refresh frame-rate is about the month. It is then stored within a shared repository and the information is accessed by network authorisation to the corresponding drive.
- Factory MES is in charge of populating a supervision model. It is also in charge to compute the overall KPIs and to provide them on request through SQL application protocol interface. From the versioned supervision data either the MES or the simulator is able to update statistical models of every machines.
- A specific module must be in charge to export information from ERP system in order for the simulator to get access to the expected phyical flow to make any reference product. Such a physical flow is usually made for a given reference and should not evolve frequently. The simulator must also access to production orders which evolve on an every day basis.

- The rendering digital twin system is expected for simulation conditions definition. Indeed engineers expect to simulate various production scenarii depending on:
  1. production orders priority: it is the main job to make decision about the command sequence organisation.
  2. resource assignment. Engineer can decide to assign more or less staff on a given machine or line
  3. layout reorganisation. Even if these decisions are seldom on a daily basis the layout reorganisation is expected
  4. external market information: raw material delivery assumptions, raw material cost evolution, etc.

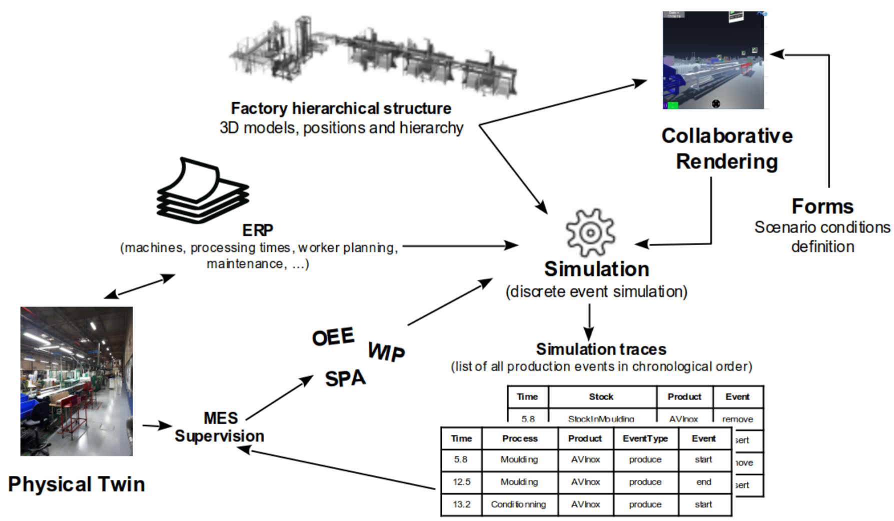

Fig. 3. Simulation information flow

The simulator could used any existing factory simulation software. Here it was encoded based on the open-source DESMO-J library [1]. The behaviour of a given production line is simulated within a few seconds to anticipate several production weeks. From the MES supervision, the simulation is based production order scenarii entered by engineers and on behaviour models directly constructed from the physical world observation. The simulation integrates randomised events following the recent statistical behavior of every machine.

With random event, two consecutive simulations on a same scenario lead to different results. The simulator launches a set of randomized simulations and creates every production events in a simulated period of production. An average answer (in term of KPIs) is created from the set of simulations which is saved

[1] http://desmoj.sourceforge.net/home.html

in the MES supervision database with a specific status since this data is not historical data but anticipation data for a given scenario. Since it is managed inside the MES, this anticipated scenario is easily displayed on the collaborative rendering digital twin module as a standard supervision. Then Engineers use these results to make comparisons between scenarii and at last to decide which scenario will be executed.

5 Conclusion: digital twin opportunities and limitations

With the achivement of simulation we reach a first level of the digital twin paradigm. It remains a quite simple simulator but internal behaviors are deduced from the real world. The simulator has access to versioned values of parameters. It can build random models which cover the current risks of real factory because it is not just a model but a more direct physical world measure. It acts as a first step to support Digital Twin deployment.

But new steps with new functions must extend the digital twin usage. As mentionned by Uhlenkamp [18] the digital twin *concept meets the needs and the expectations of people performing different product related tasks.*

Anyhow some questions arise with such a development. The weight to populate the information model then to keep it synchronised with the real world becomes a real challenge which must be discussed regarding the final added value of the complete system. For example the interest of a 3D model must be discussed since most layout are 2D and the decisions do not need 3D simulation and perception. But indeed such a 3D digital twin opens new steps for maintenance or operator training operations where 3D model will be expected. The return on investment will thus depend on the initial simulation added value but also on all the new processes that will be achievable thanks to the digital twin investment.

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