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Twin tools for intelligent manufacturing: a case study

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Abstract

The article deals with a case of an industrial plant for which a balanced mix of flexibility and production slenderness is sought together with high quality, transparency and production effectiveness.

The study is based on virtual plant assessments (by means of virtual engineering) and considers industrial artefacts (automotive components) aiming at economics of scale figures on short horizons, but undergoing fast updating requests of high flexibility of new hybrid and electric vehicles; the sought solution profits of shop-floor resources modularity and robotic cells use; example simulation issues are given, and the advantages, offered by the use of digital twins, are analyzed.

Keywords: Flexible automation; Modular assembly facilities; Object-oriented modelling; Digital Twin.

1. Introduction

In the automotive industry, electronic components and auxiliary devices face fast evolving requests, with quick response delay, still needing effectiveness achieved by mass-production and high quality reliability. Their manufacturing can conveniently relay on the integration of special purpose sub-items; assembly must be performed taking into account total cost of ownership, maximising productivity and quality with optimal schedules, still allowing adaptation of the plants each time the required production is updated (Schmidt et al., 2017).

New manufacturing systems are functionally aiming to produce highly personalized products at mass production cost exactly when they are needed (Kim et al., 2020). Therefore, modular facilities obtained by combining standardised modules, as for work- and transfer-units, allow that the same functional blocks can be re-used for different productions, only adapting the lay-out and the fixturing implements.

The selection of the new set-ups has to be tested and the performance assessed, each time the new production programme is forecast and computer simulation is basic aid to support the development, after check of the actual productivity figures. Production engineers can rely on many different types of simulations to underpin their decisions that focus on many different aspects of the production environment, bringing together technical, environmental, ergonomic, logistic (Cepolina et al., 2021) and financial perspectives. For instance, a Montecarlo approach has been adopted, together with discrete event simulation, in Giusti et al. (2019) in order to assess the economic performance of different alternative RFID set-ups in a warehouse. Finally, Bruzzone et al. (2020) propose Strategic Engineering as a new discipline that combines simulation, AI (Artificial Intelligence) and data analytics, to support decision making in Industries.

The paper will present a detailed discussion of an industrial example case.

First, the particular item to be manufactured is analysed, in view of its fabrication agenda. The related assembly resources are described, with account of the requested work-cycles. Special care is dedicated to the steering logic of the dispatching policy, with attention on the management of the by-pass units.

Then, the simulation package is considered, to provide clear duplication of the plant behavioural properties for the specialised production. According to Michelini et al. (1997), the facility shall combine multiple-type work-resources (item preparation cells, assembly rigs, testing units, etc.) and complex dispatch services (main and shunt tracks with bypasses, carrying pallets, recovery options, etc.), with mixed-mode work-flows (serial, parallel, random sequence jobs). Simulation of the shop floor logistics (Cepolina et al., 2014), deals with the plant dynamics, according to the production work-cycles (Fredriksson, 2006; Qu et al., 2021). The simulation package profits, therefore, of object-oriented coding (Renteria-Marquez et al., 2020) to help adaptivity and the MODSIM software was retained as valuable option.

Finally, the paper discusses sample simulation trials, comparing several procuration policies and facility governing options, depending on different resources number and shop logistic issues.

After the system configuration and management logics have been chosen, the reference simulator is proposed as a digital twin and is digitally connected in real time to the system resources to follow the plant vicissitudes during its development and offer opportunities for improvement or training during the through-life phase and schedule maintenance thus avoiding risks of malfunctions.

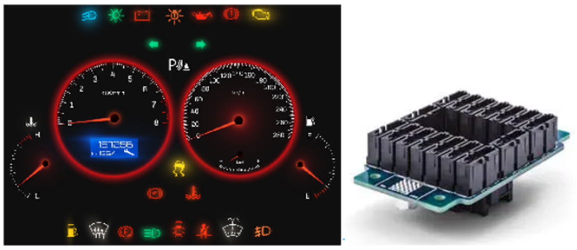


Figure 1. A typical dashboard and ECU (courtesy STW)

2. Assembly tasks and resources

The dashboard belongs to the group called “A” parts, which are safety parts whose production requires a specific schedule. Innovative technologies and the highest quality and safety standards are a constant focus throughout the entire process chain.

In this paper we refer to one of the main components of the dashboard: the Electronic Control Unit ECU. Over time, the term ECU evolved into an electronic system that could control powertrain, transmission, body, brakes, seats, communication board. For instance, a body control module is responsible for power distribution to enable to control the body functions such as automotive lighting, door, windows, security access etc. In the following we refer to this kind of ECU: its manufacturing process simulation and the digital twin pilot.

A typical dashboard and ECU device are shown in Figure 1, typical ECU contains combined instruments, the cable wire harness, several switches and trim strips. It is obtained combining a set of circuits carried by isolating boards (the wafer) between a top, with series of fuses and remote-switches, and a bottom, with patterned connections and power feeding port. The work-cycle aims at automatic assembly and profits of dispatching lines, special purpose resources, collaborative robotic cells, manual stations (Rahoum and Jamouli, 2019). Basically, one distinguishes: circuit pre-set, pins alignment and electric check, terminals ploughing, continuity/isolation check, bolt, wafer, electromagnetic switches insertion, cable fastening, functional test and packaging.

The basic layout splits in:

- the preparatory section, side-connected to the main line, made up by automatic cells;
- the integration section, based on the assembly and two test stations, where the assembly and joining with related components are performed and the functions are checked;
- the shop logistic service, obtained with modular parts, to establish main and shunt tracks with bypasses to enable flexible dispatching of the work-in-progress.
- the auxiliary units (input/output stations, feeding devices, etc.) and the series of the carrying pallets.

The facility flexibility reports to on-process managing the shop logistics, updated, as case arises, by the overseeing controller, which monitors the work in progress and makes possible to re-process defective items and to achieve desired standard quality levels.

The functional modules are combined along a transfer line, serviced by the pallets, the units are operating at each assembly stand. They receive (after singling and orienting) the parts to be joined by suitable local feeders; each cell is provided with a local storage that provides autonomy to the cell. Figure 2 shows the adopted concept.

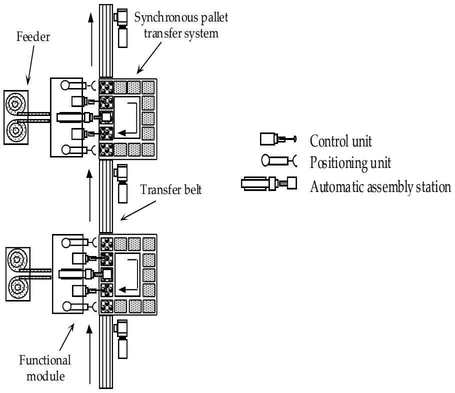


Figure 2. Working cell concept

The facility and related governing logic are described by a functional model and a simulation code is established, based on the MODSIM software, according to mnemonic icons such as in Figure 3. The resort to object- oriented programming is useful to make easy the addition of new (physical or logic) resources, the change of the product-or-process properties and the likes.

Object coding separately deals with each resource, functional details shall cover:

- each automatic cell is stated precisely with tasks and pertinent interfaces (feeding devices, robots, buffers, processing units, etc.);
- the next ploughs stringing together stations are detailed with account of the included special purpose devices;
- the bottom shell completion and joining stations are similarly described, followed by the first testing station to check the insulation levels;
- the test stations are, then, considered with the related check and identification units for approval, re-working or rejection assessments;
- the facility dispatching system, with pallets and pertinent management facilities, is acknowledged, as for inherent operation abilities;
- the shop logistic machinery, with main and shunt tracks, bypasses, buffering belts, input/output stations and related overseeing instrumentation, is modelled.

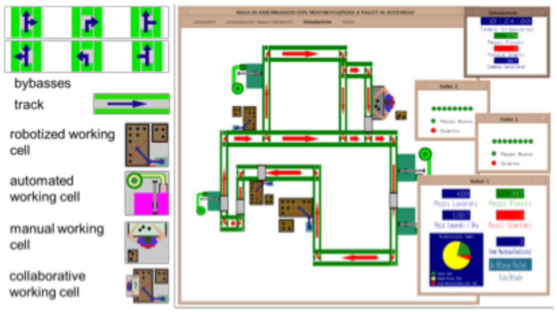


Figure 3. Example display of a model's layout

The study goes on by coding the objects reporting to logic and govern resources. Pallet dispatching resorts to distributed intelligence, with local sensors and updated labels, so that actual path and chosen task are timely adapted, with account of on-line occurrences.

Simulation assessment might follow different approaches, here example running conditions are addressed, specifying typical and/or worst case issues of plant operation schedules and production plans.

This approach is followed hereafter, including within the plant model a set of objects, to join material resources and attached operation methods, and other objects, to code the decision logic. The pallet work-cycles are explanatory example. The possibility of programming the production cycles to be followed by the pallets has been introduced. If there are stations running in parallel or carrying out operations that do not have to be carried out in a predefined order, it is possible to group them together. There are two types of groups:

- The first, called XOR, is used to contain the stations operating in parallel. It is enough for one of them to be machined for the group to be considered executed. They can be machining of the same or different types.
- The second, called AOR, is used when there is a group of operations that must all be carried out, but without a predetermined order.

The individual job characterizes by the operation-type and schedule-identifier, and by the station kind and progressive location. The dispatching is, then, ruled with account of updated information, enabling the bypasses to the shunt track for recovery actions and using the track buffering ability, whenever necessary.

3. Behavior assessments and assembly performance

Object coding, as previously mentioned, is powerful means to provide a detailed definition of the material or logic resources properties and functions (Cepolina, 2016). The fabrication agenda presents as a two-dimensional array to identify items inventory and operation sequence. The work-stations are specified by a status (ready, busy, out-of-order, etc.), job identifier (type, time intervals, etc.), service code (input and output queues, part feeding, monitoring functions, etc.) and, in general, the data defining the functional units, robots, fixtures, etc. which condition the considered resources. Figure 4 shows an example of production plant. The bypasses deserve special interest; they are used:

- to enable optimal pairs of work-in-progress and consistent work-stations,
- to switch the pallets, with random sequence cycles, toward the nearest free station,
- to move toward the shunt track the pallets with items to be re-worked,
- to re-route pallets with repaired items, according to the prescribed work-cycle,
- to update the dispatching policy in case of work-station failures,
- to manage the track buffering ability minimising the items completion time, or any other function allowing to use the device (with one input and two outputs) for re-orienting a pallet or for modifying its path due to a given goal.

The pallets carry the items with pertinent (updated) information from one station, and help specify attributes and logic relations among the plant many elements. The next station address is used as pointer to update the dispatching policy; when a bypass is met, carried items and branching options data are compared and choice is set depending on the above listed goals. The shop logistic, thereafter, refers to a series of fields, with behaviour-conditioning information, such as:

- *inventory*, to specify the pallet order number;
- *identifier*, to establish a link (for the user) with the physical element;
- *cost*, to rank the resource by respect to a price scale;
- *location*, two (planar) coordinates specify the initial position of any element of the shop;
- *size*, identifying pallets selected out of commercial catalogues or personalised at user's will;
- *status*, namely: ready, busy, out-of-order;
- *attitude*, to provide a pallet guide along tracks;
- *skip*, to acknowledge stations to be avoided;
- *monitor*, to specify the window type where current data are displayed;

further information is given to fix the number of carried items, the work-cycle status, the job sequence, etc.

The pallet-attached methods are powerful means to modify facility evolution; for example:

- set/reset is used to specify a given attribute;
- target update accomplishes the switch to the next work-station;
- download transfers the list of fulfilled tasks and erases the pallet data-log;
- start enables the control sequence to move the pallet on the track, with account of the existing external constraints;

Besides, a work-cycle recorder helps collect simulation results into a structured data-base, with links to the pallet (and carried items), to the fulfilled tasks, to the partial and final time intervals, to the work-in-progress or to any other quantity that should be monitored.

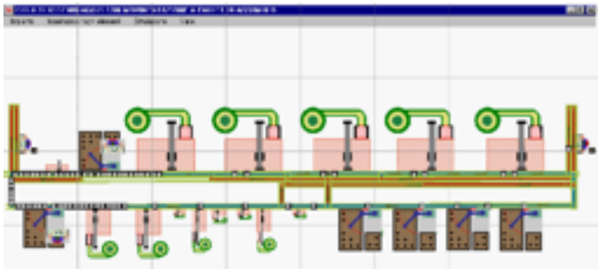


Figure 4. Model of a candidate production plant

The simulation code profits of additional options, e.g.:

- the access to catalogues (with items supplied by the manufacturers of modular resources);
- series of checks (on geometrical coherence, on positioning consistency, etc.);
- statistical processing blocks (to work out productivity figures, availability data, etc.).

The study is, thereafter, carried on considering the time behaviour of the resources for actual production plans and fabrication agendas, under different external disturbances, which give account of possible failures or mismatches. A probabilistic approach has been adopted to describe real system uncertainty. In case there was not enough information about the system to build the corresponding probabilistic models, a fuzzy approach could have been adopted, as proposed in Azadeh et al. (2012) for an actual large complex multi product assembly shop.

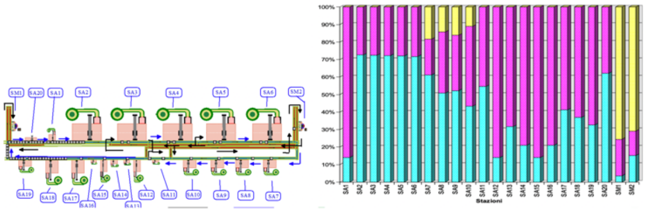
As explanatory example, the cases of 70, 85 and 100 pallets have been considered, even if a finer tuning of the optimum number might be later carried on. Table 1 shows the results of Lay1 plant simulation.

Table 1. Production figures (Lay1 simulated layout).

	Units	Target	70 pallets	85 pallets	100 pallets
Assembled parts	parts	1064	1093	1008	1047
Throughput	parts/h	133	137	126	131
Production time	s/part	27	26	29	27
Parts/pallet	parts/pallet	-	16	12	10

These results make evident that a high number of pallets simply yields to traffic jam cases, while production figures are near their expected values for 70 pallets in the loop.

Figure 5 presents the diagram of resources utilisation, showing working time (light blue), idle time (violet) and stop time (yellow) for each station in two layout cases Lay2 and Lay3. Lay2 presents 20 automatic stations (SA1->SA20) and 2 manual stations (SM1 and SM2) whilst Lay 3 presents 15 automatic stations, 1 collaborative robotics station (SA15) and 6 robotized working cells (R1→R6) and 2 manual stations (SM1 and SM2). The effects of interval coupling and bottleneck built-up are easily recognised; many significant information can be read from the diagrams about the most critical stations for proper plant running.



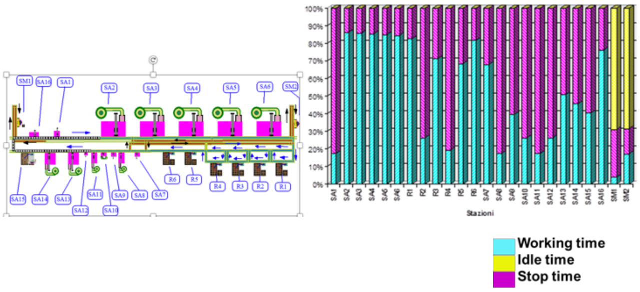


Figure 5. Time charts of stations status for two different plant layouts in case of 70 pallets (Lay2 on the top and Lay3 on the bottom)

Virtual reality testing offers wide amount of information on the plant productivity, current throughput, expected due dates, etc. to compare alternative manufacturing schedules, recovery capabilities, resources layouts and governing options.

In fact, flexibility has complex effects on the plant characteristics, with coupled fall-outs on productivity, which can only be assessed by referring to production schedules facing actual running constraints. Checks on real facility are, of course, out of reach options and virtual experimentation are common way to help production engineers for current applications.

Special relevance of the investigation is connected with modularity of the assembly facility. The resources layout can easily be modified and adapted each time product types or fabrication agendas change. Indeed, flexibility is exploited at two levels:

- as off-process opportunity, to adapt the plant versatility with due account of the selected production programmes;
- as on-line capability, to select the proper logistics in function of process monitoring outcomes.

4. Digital twin pilot

Having chosen the plant in terms of layout as well as the type and characteristics of the individual resources, the simulator can be used as a monitor of current activities and the status of the plant. For this purpose, a correspondence must be established and a connection made between each of the virtual resources with the real twin (Luttersa and Damgravea, 2019): individual resources are connected and provided with sensors to exploit the data-gathering requirements for the digital reference system (Lee et al. 2015). Redelinghuys et al. (2020) present an architecture for enabling the exchange of data and information between the simulator and the physical twin.

These concepts synthesise sensoring/measurement (in situ and ex situ) with the modelling and simulation of existing and evolving resources/processes at operational, tactical, and strategic levels. The digital twin evolves with the development cycle through the entire value chain, providing structure while giving meaningful access to tools, methods, and captured data.

Production engineers aim to establish production environments that are equipped to engender physical products in an effective and efficient manner. Besides traditional key performance indicators product throughput, product quality and investments, further environment related key performance indicators such as energy sustainability of resources minimizing both total cost and environment impact have to be considered.

While the simulator represents the plant that works in ideal reference conditions, the digital twin follows the real trend of production and any misalignment of the two requires reflections on the causes and the definition of corrective actions to improve the plant and schedule pro-active maintenance or even resource replacement. In this context, Giannetti and Essien (2021) and Wang et al. (2021) propose predictive models for digital twins in order to address the dynamic and often stochastic nature of time series signals.

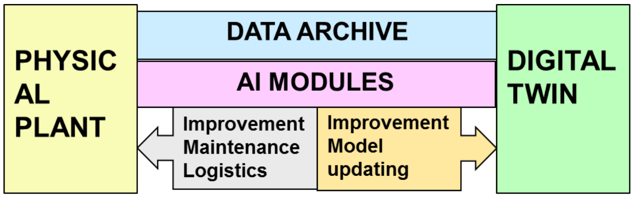


Figure 6. Digital twin concept

The information on the misalignment can be evaluated on different levels and, in our case, we preferred to refer to key performance indicators that the industry has considered strategic for production.

However, a wide range of methods of corrective interventions can be seen that are based on theoretical knowledge of the model and on the knowledge of the actual operation of the plant working in real conditions.

The digital twin concept is synthetically shown in Figure 6.

In the case in question, in the early use of the pilot, the discrepancies between the twin plants were mainly linked to the operation of the collaborative robotics cells since the work rates depend heavily on the persons in charge and on the logistics as sometimes there have been doubts about the choice of the path for supplying pallets to alternative stations equipped with the appropriate tools for subsequent processing and the related rules were not included in the model.

Corrective actions were made on the digital twin to make it more consistent with the real plant and to have more significant information on the state of the system.

The discrepancies observed in the comparison between the physical plant and the digital twin are used directly to improve the production process, to outline the production plans, to update the models and reference methods of the digital twin as well as for the training of operators.

5. Comments and conclusions

Virtual reality assessments provide wide extent validation of competing lay-outs and/or process controls and management, with only limited investments, making possible quick setting and resetting of the facility, whenever useful. The paper discusses a sample case for explanatory purposes, directly referring to an industrial application. Shop logistics is specially investigated, with focus on the bypass's management logic and the total number of pallets, which might any time be forwarded on the tracks. The part feeding policy is, as well, considered with concern to robotic equipment, possibly, modified to improve the facility performance.

The issues previously recalled are clearly stated with simple simulation tests that simply show the effectiveness of plant layout and shop logistics and allows to avoid periodical out-of-order stops. The conjecture, once the effects are recognised, can lead to adapt the (modular) assembly fixture or to modify the production plans so that the actual assembly operations could continuously run with proper productivity. Modelling and simulation-based approach does not provide exact or optimal solutions to problems but it allows users analysing the behaviour of complex systems, performing what-if analysis and choosing correctly among different possible scenarios/solutions (Bruzzone and Longo, 2013).

The example issues confirm empirical guesses, with the advantage to attest the plant performance by quantitative figures (for any given particular situation). Moreover, hints are made available, to corroborate typical assembly policies and few remarks are provided to stress on the advantages of modular assembly facilities for the specific manufacturing problem.

The use of the developed simulator, customized to the physical production plant, was implemented in terms of digital twin of the real plant. The early tests, conducted at the pilot level, provided significant information and indicated interesting themes for future developments.

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