PRODUCT AND PROCESS INTEGRATED DESIGN TO ENHANCE SMART MANUFACTURING SYSTEMS

F. Caputo, M. Caterino*, A. De Luca, M. Fera, A. Greco, G. Lamanna, R. Macchiaroli, P. Manco, M. Manzo, D. Perfetto
Department of Engineering
University of Campania "Luigi Vanvitelli"
via Roma 29, 81031 Aversa (CE), Italy
*corresponding author: mario.caterino@unicampania.it

KEYWORDS

Simulation, Product design, Production process design, Digital Manufacturing.

ABSTRACT

During recent years, industrial world faced transformations that led companies to introduce the concepts and the technologies of a new industrial paradigm, named Industry 4.0 (I4.0), in order to improve their products and their production processes. In the context of I4.0, factories are becoming *smart*, more flexible and collaborative, satisfying the current demands of increasingly competitive markets and of products closer to the real needs of customers. Within this framework, the approach to product and process design is changing too, supported by the use of complex numerical analyses for testing and validating the performance of both products and production processes. This is made possible thanks to the Digital Manufacturing (DM) approach, that allows to reduce the design times and to validate the design solution in virtual environments, without setting up detailed and expensive experimental sessions.
This paper aims to propose a possible methodological framework to better carry out the design of new products and production systems, according to the DM principles.

INTRODUCTION

The changes occurred within the I4.0 era became possible thanks to the scientific research that in the last 20 years has been focused on the development of new technologies and oriented to the study of new engineering methods aimed to make the traditional factories become digital and smart. The smart factories are characterised by a unique and interconnected environment in which all components of production systems, such as humans, machines and resources are interconnected and continuously exchange information or data. This new environment makes it possible to reach a high level of operational efficiency and productivity. These objectives are achievable thanks to the introduction of specific technologies in the industrial environment (IoT, VR technologies, Cyber Physical Systems, etc.) that allow the implementation of the concepts of Digital Manufacturing (DM), Human Centred Design (HCD) and evaluating processes and products performance thanks to numerical simulations.
DM has been considered in the past years as a highly promising way for reducing product's time to market (TTM) and cost as well as for addressing the need for customization, increased product quality, and faster response to the market (Chryssolouris et al. 2009). To achieve this goal, many relevant aspects have to be considered:

- a good workplace design allows to obtain the best workers' performances;
- a production process design performed through the scheduling and balancing of activities is important to optimize some measure of effectiveness such as the number of work stations;
- the continuous monitoring of the status of machinery and production systems is important to minimize maintenance times and costs;
- the preliminary product design ensures that the final product meets the requirements before it is put in production and it is feasible with the available production technologies;
- a good policy of quality design and control of the final products allows to have few rejects and to perceive weak signals of damaging for machineries.

Although all these points are interconnected, in most cases they are traditionally treated individually. It is known that through the connection of the production data management systems with the data provided by the simulations of products and processes performance, it is possible to optimize manufacturing processes before production actually starts and to enhance the overall company performance also from continuous improvement point of view when the production processes are just in place. For this reason, the aim of

Communications of the ECMS, Volume 33, Issue 1,
Proceedings, ©ECMS Mauro Iacono, Francesco Palmieri,
Marco Gribaudo, Massimo Ficco (Editors)
ISBN: 978-3-937436-65-4/978-3-937436-66-1(CD) ISSN 2522-2414

this paper is to propose a possible methodological framework able to connect these points in near-real time so that there is a continuous feedback exchange between product designers and production processes respectively. In this way, if there is the need to set out changes in the product, it will be possible to modify also the process accordingly and vice versa, in agreement with and contrary, according to the concepts of *System Integration (SI)*.

About the product design, several numerical methods are nowadays available to investigate the structural performances of a product. These methods are well-established and allow designers to improve and to optimize new design solutions. Moreover, several standards propose the use of numerical tools as support for the product certification, giving rise to the Certification by Analysis (di Napoli et al. 2018, Caputo et al. 2018, Guida et al. 2018, Sepe et al. 2017, Perfetto et al. 2018), by reducing the time to market of the products.

Concerning the production process, especially in case of manufacturing industries, a good design must take into account all the significant elements from the whole plant layout to workplaces' design, the tools and tasks assignment to each workstation and the evaluation of the feasibility of the proposed solutions. Indeed, the correct choice and sizing of these factors is linked with time and production costs evaluation and optimization for existing and designed industrial plants, as done in (Fera et al., 2017) where a cost model that evaluates process costs of additive manufacturing for relevant technologies is developed. Moreover, as reported in (Giacomin 2014), HCD provides economic benefits when it is used as an approach for designing products, systems and services and it allows to avoid errors and delays in the design and engineering of a production process. For example, in (Caputo et al. 2019), the authors proposed a methodological framework for workplaces' design in automotive industry, based on the use of Digital Twins (DT) of the workplace and on the evaluation of the ergonomic performance by means of numerical simulations, in agreement with the DM approach. In addition, the paper (Grieves and Vickers 2016) described how DT has developed in recent years and how its application is useful to understand systems behaviour. In (Makarova et al. 2015) and (Hovanec et al. 2015), the authors demonstrated that, exploiting the advantages of DM approach by using DTs, the process parameters can be investigated in a virtual environment, offering several advantages in terms of time and costs saving.

Within the I4.0 scenario, also the use of wearable devices for directly measuring data on the factory place, is more and more increasing. From this point of view, interesting studies have been conducted in using wearable motion tracking systems for the evaluation of the working postures. In particular, (Caputo et al. 2018) developed an inertial motion tracking system that uses wearable sensors to acquire data through which it is possible to evaluate the ergonomic indexes and, consequently, to validate the workplaces' design.

Another important issue concerns the evaluation of the work cycle operations' time duration and the balancing of the tasks to assign to each station. Currently, the techniques used to evaluate the time needed to complete the actions in a single cycle before starting the production consists of hypothesizing the sequence of actions and evaluating the time by the Method Time Measurement (MTM) tables. This process is very time consuming because each single complex movement must be broken down into its elementary parts, whose times are reported in the specific MTM tables, and then those times must be added themselves in order to obtain the total time of the entire complex movement. An alternative method (faster than the traditional MTM analysis) is represented by the realisation of a DT that reproduces the working environment and the working tasks (Fig. 1).

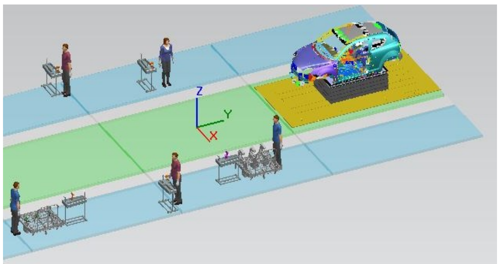


Figure 1: A Digital Twin of an automotive production line.

So, the digital twin of a real work environment allows the simulation of real tasks performed by workers and the evaluation of the cycle time of the operators, but also of other important factors that characterise a production environment, such as the Overall Equipment Effectiveness (OEE). An evaluation of the variability of the human operations' time during an entire work shift becomes feasible.

In addition to the data related to the production systems design, it is universally recognized that machines' health is essential to perform the work processes, since the availability is also part of the previously introduced index OEE. In the industrial context, machine maintenance is a vital function for factories since good maintenance policies allow to minimise production losses due to sudden machine downtime and, consequently, it allows to minimise the related costs, both for repair and sales loss. For this reason, the development of a new maintenance procedures that, using some technologies of the industry 4.0, can act as a decision support for the maintenance managers in factories. Moreover, if a Human-Machine Interaction

(HMI) is present, it is important to evaluate the risks connected to machines to ensure that do not occur dangerous situations that could lead to injuries for workers. In (Fera and Macchiaroli 2010), the authors proposed an assessment method, that by mixing qualitative and quantitative methods, can be easily applied for the risks' evaluation in SMEs. The paper (Caterino et al. 2018), instead, described the development of a safety assessment method using the Petri nets for the representation and simulation of a real machine.

So, it is clear that the integration of the product and process design are not only welcome, but it is a need of the I4.0 paradigm implementation. Aim of this paper is to propose a possible methodological framework for an integrated design of products and production processes based on the use of numerical simulation, according to the DM approach.

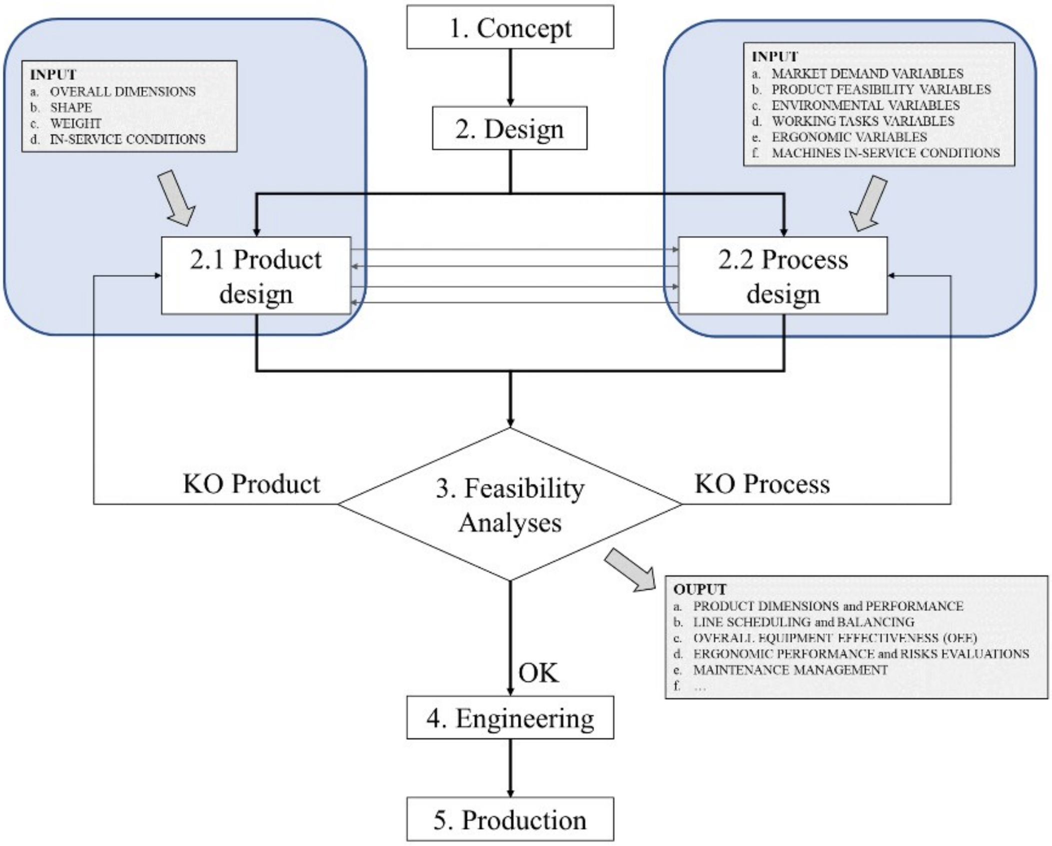


Figure 2: Methodological framework.

METHODOLOGICAL FRAMEWORK

Fig. 2 shows a methodological framework for the design of a manufacturing system in which the design of products and production processes are strictly connected.

The framework considers all the main phases related to the product development process, typical for a manufacturing industry: concept, design, engineering and production.

The paper is focused on providing an iterative procedure for the design phases, according to DM approach.

The procedure is composed of five steps:

1. *Concept*: this phase includes the producing ideas, taking into account the pros and the cons of implementing this idea, that can regard a new product or a new production system. At the end of the step a preliminary design is provided;
2. *Design*: this phase focuses in detail on the implementation of the ideas defined by the previous step. The design regards both the products and the related production processes. Within this procedure, the step 2.1 and 2.2 are strictly connected, with continuous feedback exchanges between designers, in order to

minimise the design times and to provide optimised design solutions;

3. *Feasibility analysis*: thanks to the information exchanges during the previous step 2, this phase is focused on the feasibility analyses in order to verify if the design solutions for products and processes are actually feasible. This step can be carried out thanks to detailed numerical simulations, reducing the time for the start of the following phase;
4. *Engineering*: this phase is related to eventually improve the design solutions, in case of bugs, to implement the best technical solutions to minimise the time necessary for the assembly in the future production and to facilitate the maintenance;
5. *Production*: defined the production system, this phase concerns the production of the components and their assembly, during which the designed product takes shapes, ready to be launched on the market.

In the following section, a detailed description of the steps 2 and 3 of the proposed framework is reported.

DESIGN AND FEASIBILITY ANALYSES

Step 2.1 is focused on the design of products.

Thanks to the possibility to investigate the structural behaviour of new products under the loads expected to occur during their life, it is possible to optimize and to improve them with reference to the structural response. As a result, numerical simulations can be performed to assess in a virtual environment new structural solution, leading to a reduction of costs related to prototyping, experimental testing and certification. However, according to the current design practice, several problems can be faced during the production phase, due to the lack of detailed communication between product and process designers. The proposed approach permits overcoming these problems, by verifying, starting from the product design phase, if the product can be made taking into account the technological and production systems constraints. In addition, this approach allows using Virtual and Augmented Reality (V/AR) devices to consider, during the design phase, also the customer's feedback, since the customer can experience in a virtual environment the interaction with the product, for which the design phase is still in progress (Fig. 3).

Figure 3: V/AR for visualise the designed products.

Step 2.2 concerns the design of the production process. This phase considers a series of input variables upon which the realisation of the production system is based. These variables are related to the product characteristics, first of all its dimensions and those related to the components. It is worth noting that since the product and process design overlapped, the product characteristics will change during the development and for each iteration both design solutions will be optimised. Other variables are related to the product demand in the market that determine the production volume and mix, the environmental variables that regard the analysis of the eventual existing plant, the resources and tool definition and the line setup.

The working task variables are related to the human resources, the working times, the variability of the tasks. Fundamental variables to be taken into account are the ergonomic ones, aimed to realise a safe working environment, reducing the injury risks and the machines in-service conditions that will define their maintenance processes.

At the end of step 2.2 of the framework illustrated in Fig. 4, the designers should be able to define the line layout, to define the Standard Operating Procedures (SOP), to estimate the working times and to provide the design solutions for the whole production system.

The testing of the products and production processes design solutions and, hence, the feasibility analyses at step 3, are carried out by means of numerical simulation (Fig. 4), according to the DM approach. The simulation allows to have feedback about the design solutions, identifying the incorrect choices during the design, avoiding they will negatively affect the real production. Even if the simulation tools require initial costs for the company, the simulative approach is convenient to point out, through interactions, the best solutions for both products and processes, thanks to the integration of their design phases.

For a typical manufacturing system, both time-based and event-based simulations can be considered. The former, in which the system state change over time, can be use for an immediate feedback for the working tasks feasibility, for validating the SOP, the product assembly feasibility, the ergonomic evaluations. The latter, in which the system state changes when a certain event occurs, can be useful for simulating the whole production process, statistically analysing the measured data for validating the whole production system, preventing eventual critical tasks.

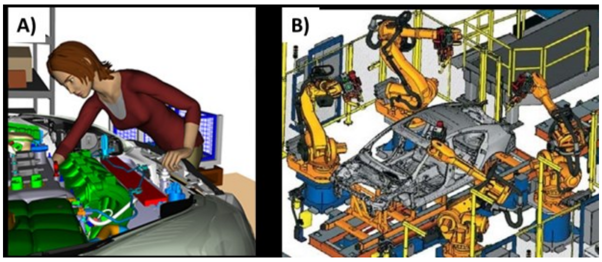


Figure 4: Siemens® Tecnomatix Process Simulate environment: A) human assembly task simulation; B) welding task simulation.

After the validation of the design solutions in virtual environment, for the definitive validation it is necessary only a rapid experimental test, set up in a laboratory. In this way it is possible to save a high amount of time and costs, significantly anticipating the start of production.

CONCLUSIONS

The main aim of this paper has been to propose a possible approach for the design of smart manufacturing systems integrating the design of products and production processes in a unique information exchange network. The proposed framework is based on the Digital Manufacturing approach that incorporates technologies for the virtual representation of the factories, the resources, the products, the equipment that, by means of numerical simulations, allows to find the best design solutions and to validate the design of products and production systems in a virtual environment, reducing the time and costs for the set-up of experimental sessions.

In this way it will be possible to close the gap between the product and the production process designers, optimising the information exchange, the design itself and laying the bases for the realisation of the so-called Digital Factory.

REFERENCES

F. di Napoli, A. De Luca, F. Caputo, F. Marulo, M. Guida, B. Vitolo. 2018. “Mixed FE–MB methodology for the evaluation of passive safety performances of aeronautical seats”. *International Journal of Crashworthiness, 1-12 https://doi.org/10.1080/13588265.2018.1441616.*

F. Caputo, A. De Luca, A. Greco, S. Maietta, A. Marro, A. Apicella. 2018. “Investigation on the static and dynamic structural behaviours of a regional aircraft main landing gear by a new numerical methodology”. *Frattura e Integrita Strutturale 12 (43), 191-204.*

M. Guida, A. Manzoni, · A. Zuppardi, · F. Caputo, F. Marulo, A. De Luca. 2018. “Development of a multibody system for crashworthiness certification of aircraft seat”. *Multibody Syst Dyn Multibody System Dynamics 44 (2), 191-221, https://doi.org/10.1007/s11044-018-9612-0.*

R. Sepe, R. Citarella, A. De Luca, E. Armentani. 2017. “Numerical and Experimental Investigation on the Structural Behaviour of a Horizontal Stabilizer under Critical Aerodynamic Loading Conditions”. *Advances in Materials Science and Engineering 2017, ID 1092701.*

D. Perfetto, A. De Luca, G. Lamanna, A. Chiariello, F. Di Caprio, L. Di Palma, F. Caputo. 2018. “Drop test simulation and validation of a full composite fuselage section of a regional aircraft”. *Procedia Structural Integrity 12.*

G. Chryssolouris, D. Mavrikios, N. Papakostas, D. Mourtzis, G. Michalos and K. Georgoulias. 2009. “Digital manufacturing: History, perspectives and outlook”. *Journal of Engineering Manufacture 223(5)*.

J. Giacomin. 2014. “What is Human Centered Design?”. An *International Journal for All Aspects of Design 17 (4), 606-623*.

F. Caputo, A. Greco, M. Fera and R. Macchiaroli. 2019. “Digital twins to enhance the integration of ergonomics in the workplace design”. *International Journal of Industrial Ergonomics 71, 20-31*.

F. Caputo, A. Greco, E. D’Amato, I. Notaro and S. Spada. 2018. “Human posture Tracking System for Industrial Process Design and Assessment”. *Advances in Intelligent System and Computing 722, 450-455*.

M. Grieves and J. Vickers. 2016. “Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems”. *Transdisciplinary Perspectives on Complex Systems, 85-113*.

F. Caputo, A. Greco, M. Fera, G. Caiazzo and S. Spada. 2019. “Simulation techniques for ergonomic performance evaluation of manual workplaces during preliminary design phase”. *Advances in Intelligent Systems and Computing 822, 170-180*.

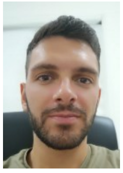
M. Fera and R. Macchiaroli. 2010. “Appraisal of a new risk assessment model for SME”: *Safety Science 48 (10), 1361-1368*.

M. Fera, F. Fruggiero, G. Costabile, A. Lambiase, D.T. Pham. “A new mixed production cost allocation model for additive manufacturing (MiProCAMAM)”. *International Journal of Advanced Manufacturing Technology 92 (9-12), 4275-4291.*

M. Caterino, M. Fera, R. Macchiaroli and A. Lambiase. 2018. “Appraisal of a New Safety Assessment Method using the Petri Nets for the Machines safety”. *IFAC-PapersOnLine 51 (11), 933-938.*

AUTHORS' BIOGRAPHIES

FRANCESCO CAPUTO was born in Napoli, Italy, in 1971. He received his Ph.D. in 1999 and currently he is an Associate Professor at the University of Campania Luigi Vanvitelli. His main teaching and researches involve Machine Design.

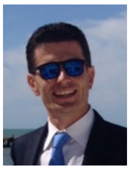


MARIO CATERINO was born in Caserta, Italy, in 1990. He received his master's degree in 2017 and currently he is a 2nd year Ph.D Student at the Dept. of Engineering of the University of Campania "Luigi Vanvitelli". He is deeply involved in research topics in Operations Management.

ALESSANDRO DE LUCA was born in Napoli, Italy, in 1988. He received his Ph.D. in 2016 and currently he is a Post Doc researcher at the Dept. of Engineering of the University of Campania Luigi Vanvitelli. He is deeply involved in research topics in Machine Design.

MARCELLO FERA was born in Napoli, in 1979. He received his PhD in 2008 at the same University in Mechanical Systems Engineering and he is currently Assistant Professor of Industrial Systems Engineering at University of Campania "Luigi Vanvitelli". He is author of more than 40 publications in the operations management field.

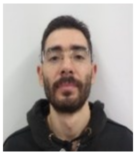
ALESSANDRO GRECO was born in Sapri, Italy, in 1987. He received his Ph.D. in 2019 and currently he is a researcher at the Dept. of Engineering of the University of Campania Luigi Vanvitelli. He is deeply involved in research topics in machine design.



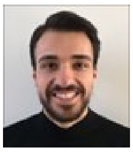
GIUSEPPE LAMANNA was born in Caserta, Italy, in 1978. He received his Ph.D. in 2005 and currently he is an Associate Professor at the University of Campania Luigi Vanvitelli. His main teaching and researches involve Machine Design.

ROBERTO MACCHIAROLI was born in 1964 in Bari, Italy. He received his PhD in Electronics Engineering in 1994 and he is currently full Professor of Industrial Systems Engineering at University of Campania "Luigi Vanvitelli". He is author of more than 50 publications in operations management field.

PASQUALE MANCO was born in Naples, Italy, in 1992. He received his master's degree in 2018 and currently he is a 1st year Ph.D. Student at the Dept. of Engineering of the University of Campania "Luigi Vanvitelli". He is deeply involved in research topics in Operations Management.



MARIO MANZO was born in Caserta, Italy, in 1987. He received his master's degree in 2015 and currently he is a 1st year Ph.D. Student at the Dept. of Engineering of the University of Campania "Luigi Vanvitelli". He is deeply involved in research topics in Machine Design.



DONATO PERFETTO was born in Naples, Italy, in 1993. He received his master's degree in 2017 and currently he is a 2nd year Ph.D. Student at the Dept. of Engineering of the University of Campania "Luigi Vanvitelli". He is deeply involved in research topics in Machine Design.