A Novel Methodology for Assessing and Modeling Manufacturing Processes: A Case Study for the Metallurgical Industry

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Abstract. Historically, researchers and practitioners have often failed to consider all the areas, factors, and implications of a process within an integrated manufacturing model. Thus, the aim of this research was to propose a holistic approach to manufacturing processes to assess their status and performance. Moreover, using the conceptual model, manufacturing systems can be modelled, considering all areas, flows, and factors in the respective areas of production, maintenance, and quality. As a result, the model serves as the basis for the integral management and control of manufacturing systems in digital twin models for the regulation of process stability and quality with maintenance strategies. Thus, a system dynamics simulation model based on the conceptual model is developed for a metallurgical process. The results show how the monitoring of all flows together with the optimal strategies in the quality and maintenance areas enable companies to increase their profitability and customer service level. In conclusion, the conceptual approach and the applied simulation case study allow better decision making, ensuring continuous optimization along the manufacturing asset lifecycle, and providing a unique selling proposition for equipment producers and service engineering suppliers as well as industrial companies.

Keywords: Integrated manufacturing model · Manufacturing process management and control · Quality management · Maintenance management · System dynamics · Simulation · Digital twin · Industry 4.0 · Metallurgical case study

1 Introduction

At present, manufacturing is still a key factor in the global economy [1]. Industrial value chains are evolving rapidly. In this context, companies need to adapt them-selves to allow mass customization and achieve low prices for products with shorter product lifecycles [2, 3]. Furthermore, the level of market uncertainty is higher than ever due to the events resulting from Industry 4.0, the COVID-19 pandemic, and global economic crises. Thus, the adaptability of manufacturing supply chains is a key aspect of companies' success

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[3]. Therefore, organizations need to rethink their production process with the use of digital technologies [4].

Manufacturing companies are currently dealing with the issue of how to process increasing flows of data [5]. In this regard, digital twins (DT) are a tool that have been proven to be effective in supporting the evaluation and control of manufacturing systems [6] and that help to increase flexibility and robustness to unexpected conditions [7] of the manufacturing system. At the same time, if DTs are combined with computing capabilities, new functionalities can be provided to management processes and support systems [8]. Moreover, the use of a DT model allows us to represent the current status of the manufacturing system and to perform real-time optimizations, decision making, and predictive maintenance according to the actual condition of the system. Research on digital twins is still in its initial stage, and there is a need for future research in this area [7] based on real-time synchronized simulations of production system operations [9].

Although several modeling methodologies have been proposed in the last two decades, so far, no methodology that could serve as a framework to model, design, analyze, and optimize manufacturing systems has been proposed [10]. As a result of this, and despite the evolution of industrial processes, existing manufacturing models do not consider all factors that are relevant to the fourth industrial revolution and do not consider the influence of key indicators of manufacturing quality and performance. Thus, current manufacturing modeling methodologies have not achieved the level of Industry 4.0 [11] and it is therefore necessary to model self-organized manufacturing systems [12] that can address all interactions and interrelationships [13]. Therefore, the new elements, relevant factors, and systems of the third and fourth industrial revolution have not yet been fully integrated in a model to provide a framework for the management and control of a manufacturing process in both present-day and future manufacturing systems. In this regard, the fourth industrial revolution promise to transform the manufacturing process and its management. However, many models of the manufacturing process and quality control are based on hardware quantity and quality and do not pay attention to information flows, money flows, and energy flows; these all have a significant influence on key indicators but have not yet been integrated in a manufacturing model. Thus, the aim of this research is to propose a holistic approach for manufacturing processes that can be used to assess the status of a manufacturing system as well as the impact of changes in the target indicators. The result is an integrated manufacturing model aligned with the fourth industrial revolution that considers all relevant areas and factors influencing the manufacturing process and its output indicators, including product quality and the condition of the manufacturing system or machine. This model enables us to predict the outcomes of the process based on input variables. It is used to increase the planning capability and, therefore, the process stability, as well as providing the continuous optimization of the expected variables based on real data.

2 Theoretical Fundamentals

A manufacturing system is an integration of resources that can carry out one or more production activities [1]; all manufacturing systems have in common the fact that they process material to give it a new functionality [17]. The sustainable market success of products requires an increase in quality level and the definition of quality can be extended to include production factors. Moreover, while current systems are optimized toward a set of target parameters, self-optimizing systems need to be optimized in terms of product quality; expert knowledge is required to achieve this goal [17].

For the conceptual and simulations models, systems theory, and modeling as the representation of a real-world scenario as well as system dynamics simulation are used. The use of simulation for manufacturing system design and analysis is recognized by scientists and industrial managers [18].

3 Conceptual Model Development

The aim of this study is to provide a conceptual model that enables the assessment of manufacturing operations with transparency regarding the areas, flows, and factors involved as well as the predictive, preventive, and corrective measures to deal with potential failure modes of the system. Moreover, the conceptual model seeks to serve as a basis for digital twin models and systems for assessing, managing, monitoring, and for improving decision making in manufacturing systems.

3.1 Delimitation of the Model and Methodological Approach

The conceptual model pursues the goal to provide a "total" conceptual model and "total" simulation to provide a global evaluation and support tool for managers and planning employees addressing the challenges of managing and controlling manufacturing processes with all potential elements of the fourth industrial revolution. The steps performed to develop the model for a generic manufacturing system are as follows:

1. Identification of areas and flows.
2. Breakdown and classification of areas into input, process, output, or other elements.
3. Definition of the factors in each area or flow.
4. Development of the conceptual framework for a generic manufacturing process.
5. Generation of a casual loop diagram (CLD) to represent the interrelationships among relevant factors.
6. Methodology for the application of the conceptual model to assess specific manufacturing processes: manufacturing process case study.

3.2 Identification of Areas and Flows that Have an Influence on the Manufacturing Process

A manufacturing process depends on several flows [15]; without these flows, opera-tions are not possible or will be limited. Furthermore, these flows that enable manufacturing operations to be carried out were developed over the course of different industrial revolutions. Each flow has a set of indicators that determine the effective-ness and efficiency of the flow. Furthermore, if the flow is not working or has operating limitations, the manufacturing process indicators will be influenced and, therefore, its stability and ability to produce products at the required quality level will also be affected. Based on the literature, the following flows are considered in this research: money flow, information flow, material flow, capital equipment flow, energy flow, human resource flow, order flow, maintenance management and control, manufacturing process, and quality management and control.

3.3 Classification of Manufacturing Process Areas

Figure 1 describes the manufacturing process input–output diagram, in which various different areas can be identified:

- Inputs: these include information, material, money, and energy flows.
- Process: factors such as human resources functions, information flows from IT systems, and maintenance functions are relevant during this process.
- Regulation mechanisms: this refers to the functional elements that will ensure the optimization of the process in the future while securing its stability. This includes the maintenance, quality management, and control functions; process design and optimization; and other order flow decisions that influence the current and future system states.
- Finally, the output areas are obtained - i.e., information, material, money, and energy flows. Furthermore, an important output is the quality control of the output according to quality requirements as well as the six goals of logistics [19].

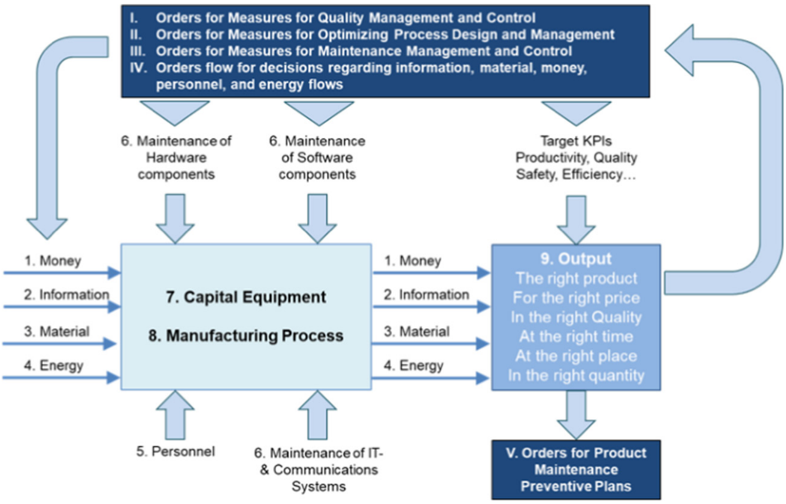

Fig. 1. Diagram of the manufacturing process: areas & flows including decisions/orders (own elaboration).

3.4 Factors and Parameters in Each Area of the Manufacturing Process

After identifying the manufacturing process areas, the identification of parameters and factors that have an impact on the manufacturing process within each of the areas is carried out. For the nine areas, a representative selection of factors related to them is given. Therefore, a representative selection of manufacturing process factors and parameters shown in Fig. 2 that are related to the above-mentioned areas and flows is as follows:

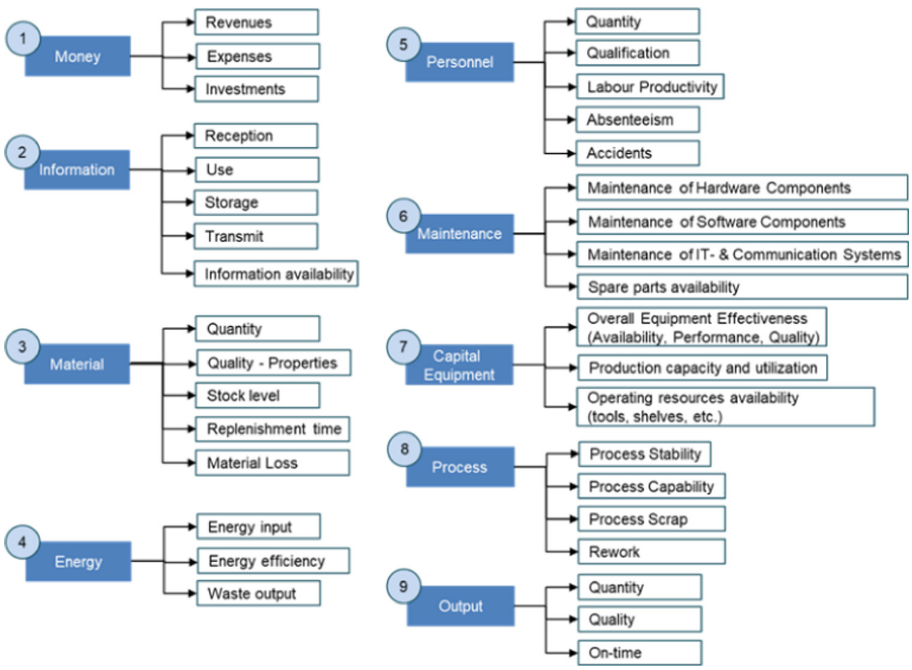

Fig. 2. Manufacturing process factors and parameters (own elaboration).

3.5 Development of the Conceptual Framework for a Generic Manufacturing Process

The model aims to offer a framework that would allow existing manufacturing organizations to manage and control their processes, a concept relating to the servitization potential based on remote monitoring, and a conceptual model that would allow the integration of the real and physical worlds with regulation and self-optimization mechanisms. The model considers all of the flows and areas covered in the previous subchapters. The framework shown in Fig. 3 describes the order in which the different manufacturing process areas are considered in the model. First, the generic process is explained. This consists of five steps: first, whether the company has the necessary means to cover the expenses of the manufacturing operations is deter-mined; second, the preparation and distribution of the planning information needed to specify the required details to plan, monitor, and control the required operations are carried out; third, the required production factors—i.e., material, energy, and hu-man resources—are prepared for the process; fourth, the process is performed, where process stability is key to obtaining the final output product in the fifth step. After describing the generic five steps of the con-ceptual framework, the differences be-tween the flow of a manufacturing process carried out before the third and fourth industrial revolutions and the flow of current industrial processes can be compared. Due to the fact that many differences exist as a result of the industrial revolutions and the development of production systems, this study focuses on the manufacturing process. Six main differences are syndicated in Fig. 3:

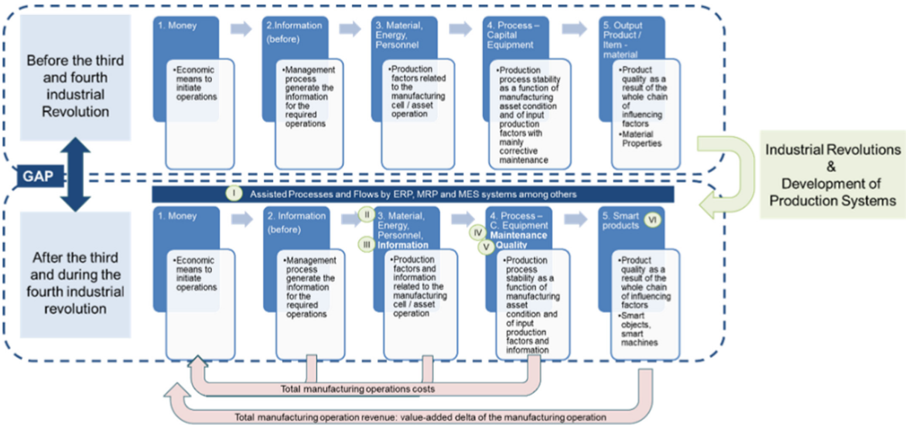

Fig. 3. Conceptual framework for a generic manufacturing process over the industrial revolutions (own elaboration).

From the perspective of the control engineer, the smart factory can be viewed as a closed-loop system [12]. The traditional production line aims to produce a single type of product in an input–output process without a controller or the need for self-regulation. The first-order cybernetic principle introduces an independent controller to the manufacturing process, but there is barely any communication between machines and there is no capability for self-optimization. On the other hand, a manufacturing system within a smart factory aims to produce several products [12] within a self-optimizing production system.

3.6 Interrelationships and Casual Loop Diagrams (CLDs)

Between the areas and factors of any manufacturing process are mutual or direction-al impacts. Table 1 depicts the interrelationships among areas. In this table, the columns are influenced by the lines; that is, the lined areas influence the columns according to the legend below the table.

Table 1. Interrelationships among areas.

No.	Areas	Money	Information	Material	Energy	Personnel	Maintenance	Process	Equipment	Output
1	Money		X							
2	Information	[X]		X	X	X	X	X	X	X
3	Material		(X)					X		X
4	Energy		(X)					X		
5	Personnel	(X)					X	X		
6	Maintenance		(X)					X		
7	Process			(X)	(X)	(X)	(X)		(X)	X
8	Capital Equipment	(X)	(X)				(X)	X		

[X]: Before manufacturing activities related to the asset.
X: Related to manufacturing activities before/during manufacturing operation.
(X): Feedback of the system related to manufacturing activity.

The interrelationships between factors are depicted in Fig. 4:

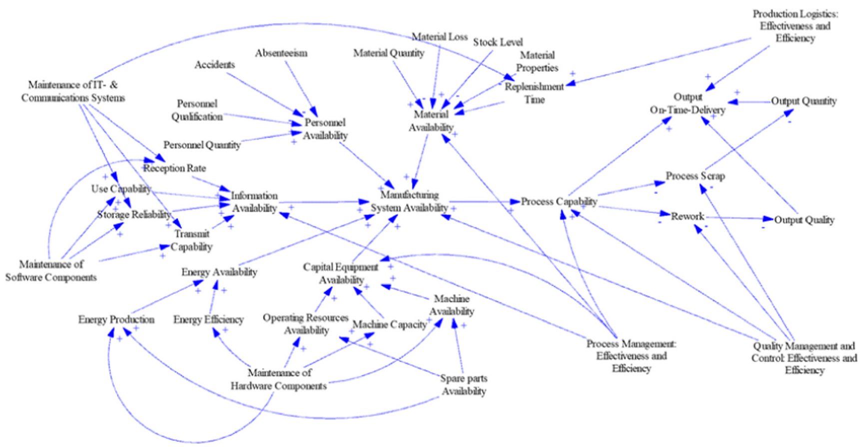

Fig. 4. Casual-loop diagram (CLD) for the manufacturing process factors (own elaboration)

4 Manufacturing Process Case Study

4.1 Design of the Case Study for a Metallurgical Process

The simulation was performed with 250 time periods, each representing one production day. Secondly, the manufacturing system structure was set to apply the conceptual model and to simulate it under certain conditions. The structure consists of a steel-making manufacturer producing shot-peened round bars. The system consists of warehouses of raw materials and finished products in addition to their production facilities. Finally, end-customers are at the end receiving the products shown in Fig. 5:

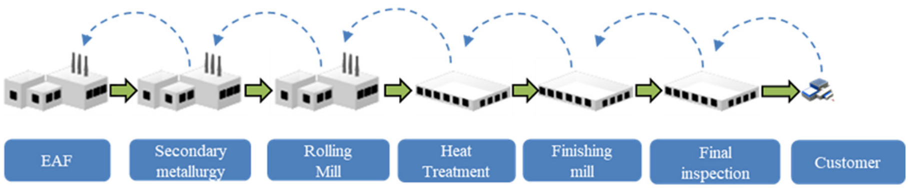

Fig. 5. Manufacturing system of the metallurgical case study (own elaboration).

4.2 Key Performance Indicators (KPIs) for the Case Study

The KPIs for the simulation case study are:

- $\sum$ Demand (tons)
- Ø Money availability (%)
- Ø Information availability (%)
- Ø Material availability (%)
- Ø Energy availability (%)
- Ø Personnel availability (%)
- Ø Capital Equipment availability (%)
- Ø OEE (%)
- Ø Availability rate (%)
- Ø Performance rate (%)
- Ø Quality rate (%)
- Labor productivity (tons/empl.*day)
- Process capability (Cpk)
- Ø WIP stock (Mio. tons)
- On-time delivery (%)

4.3 Simulation Logic for Assessing the Manufacturing Process

To assess a manufacturing system, first, it is necessary to determine the state of the manufacturing process, i.e., its areas, factors, and parameters, based on real data if possible. Secondly, an organization should understand how the manufacturing system evolves over time. In this regard, Fig. 6 provides how the system develops from a certain system state n to a system state n + 1. As a result, the manufacturing system state, and the output indicators of period n + 1 are determined by the system state at time n and the decisions or order flow related to the levels, self-optimization, or/and goal adjustments determining the output indicators.

After determining how the system evolves over time, the third step is to identify the priorities of the system in which an improvement toward the goals can be achieved to focus on activities with higher impact on the overall manufacturing system. Because of the third step, the conceptual model provides the following statement: "For a manufacturing process to take place, it is needed to secure the money flow; it is fundamental to prepare and provide the necessary information about the management and technical conditions of the process, including the technical parameters, the energy needed, and the

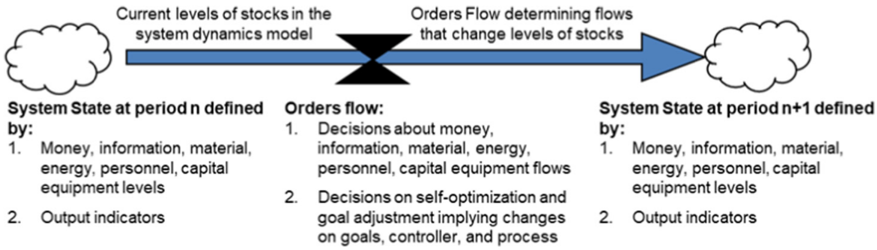

Fig. 6. Manufacturing system state in different periods: decisions from stock and flows (own elaboration)

material input required. Moreover, it is key to describe and coordinate the availability of the required human resources in quantity and qualification as well as to describe and provide the necessary capital equipment, such as machine and tools". The previous conditions first determine whether the resource area is needed; if yes, then it is determined if it is available as required, and if no, then the process regarding this resource is prepared. By conducting this for all resources, it can be determined whether the manufacturing process can initiate and perform its activity with all of the resources needed. Thus, the following formula lead to the manufacturing system availability:

$$\text{System Availability} = \text{Money Availability} \times \text{Information Availability} \times \text{Material Availability} \times \text{Energy Availability} \times \text{Personnel Availability} \times \text{Capital Equipment availability} \times 100\%, \quad (1)$$

4.4 Simulation Models

The three scenarios can be differentiated by the following characteristics:

1. Manufacturing process system modeling:

   a. Input–output process without controller or regulation.
   b. First-order cybernetics.
   c. Second-order cybernetics.

2. Maintenance policy:

   a. Corrective.
   b. Preventive.
   c. Predictive.

3. Quality control:

   a. Without adjustments.
   b. With adjustments.
   c. Predictive adjustments based on self-regulation.

4. Areas in focus:

   a. Only material flow area is in focus.
   b. All areas are in focus.

Based on the previous four characteristics, the simulation models can be described as shown in Fig. 7:

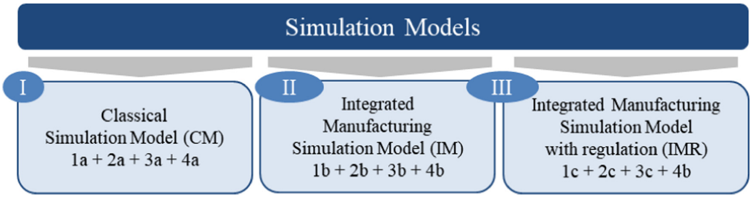

Fig. 7. Simulation models (own elaboration)

4.5 Simulation Results

After a validation with extreme-tests evaluation, scenarios for the simulation case study are generated based on different patterns and values of customer demand over 1 year with 250 periods of working days. Different scenarios with various demand patterns as well as disruptions for the flows were simulated. As a result, all of them show the same trend between the three models. Therefore, the results are shown exemplarily for one scenario for the three simulation models. As shown in Table 2, the third model presents better results than those of the second model, and the second model presents better results for all relevant indicators than those of the classical simulation model. The results show how the IM increases the OTD of the CM by 50% through the improvement of the availability and performance rates by almost 20% and the quality rate by more than 10%, leading to an OEE value that is almost double the OEE of the CM. While the IM enables the manufacturing system to reach acceptable indicator levels, the IMR helps the system to achieve excellence by attaining a 98% quality rate through the use of a more stable process. Moreover, the OEE of the IMR is more than 20% higher than the IM, leading to an OTD of more than 95%.

Table 2. Simulation results.

No.	Key indicator	1. Classical Simulation Model (CM)	2. Integrated Manufacturing Simulation Model (IM)	3. Integrated Manufacturing Simulation Model with Regulation (IMR)
1	∑ Demand (tons)	608,660	608,660	608,660
2	Ø Money availability (%)	100	100	100
3	Ø Information availability (%)	91.0	93.8	95.8
3	Ø Material availability (%)	93.1	96.0	100
4	Ø Energy availability (%)	91.0	93.8	95.8
6	Ø Personnel availability (%)	93.1	98.0	98.0
7	Ø Capital Equipment availability (%)	65.0	84.0	89.0
8	Ø OEE (%)	28.7	53.1	74.1
9	Ø Availability rate (%)	46.6	63.4	80.0
10	Ø Performance rate (%)	74.6	92.3	94.3
11	Ø Quality rate (%)	82.1	92.9	98.0
12	Labor productivity (tons/empl.*day)	0.91	1.86	1.96
13	Process capability (Cpk)	0.83	1.33	2.00
14	Ø WIP stock (Mio. tons)	23.7	37.8	37.9
15	On-time delivery (%)	32.1	84.3	95.4

5 Discussion

Based on the conceptual model developed, an organization must make decisions regarding its manufacturing system while bearing in mind four areas: focus, which takes into account resource areas; scope, which takes into account factors and inter-relationships; organizational structure, which considers how to include the control, assessment, and improvement of the manufacturing process in its functional structure; and development strategy, which considers Industry 4.0 in sequence or in parallel with quality, maintenance, and production logistics improvements.

Finally, the methodological steps to assess and improve manufacturing systems are shown in Fig. 8:

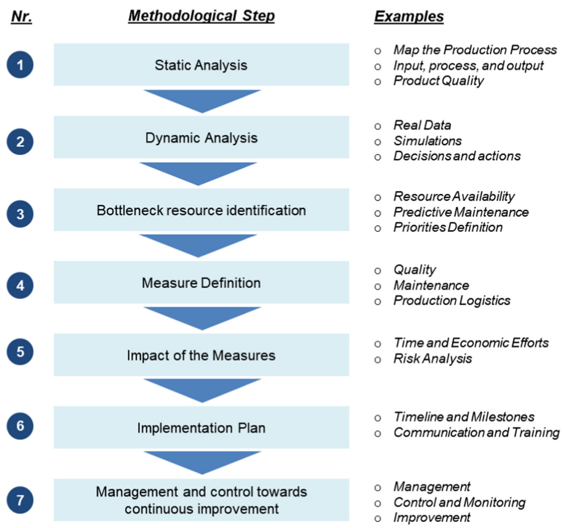

Fig. 8. Methodology to assess and improve manufacturing systems (own elaboration)

This methodology can be applied with sensors and a digital twin model of all are-as, factors, parameters, and interrelationships, enabling a simulation to improve the overall system performance and the managerial decision making. Moreover, this methodology enables condition monitoring to be carried out at the levels of the network, plant, production line, manufacturing cell, and machine. Thus, global transparency can be achieved, enabling the quick identification of the system state, bottlenecks, and risks, as well as potential measures for improvement. On this basis, new business models based on services can be generated to design, manage, control, and improve the manufacturing process and its related areas, flows, and factors.

6 Conclusions and Future Outlook

This paper provides a conceptual model that includes guidelines and steps to follow in order to successfully apply the approach in real manufacturing systems. Moreover, the current challenges faced by manufacturing systems were described and the areas, factors, parameters, and their interrelationships were defined for a generic manufacturing system. In addition, the relevant differences between the industrial revolutions were identified in an attempt to develop strategies for improving manufacturing-related issues. Based on this, a new concept using industrial dynamics was developed and steps used for assessing a manufacturing system were described. Therefore, the application of a conceptual model to digital twin models could become a key strategy in managerial decision making.

Furthermore, to prove the utility of this new concept, a simulation example for a metallurgical manufacturing system was created by applying system dynamics. The benefits of the change from an input–output process to a self-optimizing production system are a global optimization, an increase of the manufacturing system availability, product quality, system performance, and delivery reliability.

The limitations of this research work are that the assessment methodology was not developed for the operative level or for specific cases. Additionally, the individual interactions that take place among staff, machines, robots, and other elements were not considered and the complexity of the metallurgical manufacturer was only partially taken into account in the simulation model. Further limitations include the lack of detail included in the mathematical interrelationships between the manufacturing process parameters and quality characteristics.

As a result, the potential future research is to transfer this research method to real production systems and applying it as a digital twin tool considering organization units within the model and improving it based on implementation feedbacks.

The integrated manufacturing process model represents a novel approach to serve as a guide model for the fourth industrial revolution. Furthermore, the model describes how manufacturing processes can be assessed, managed, and controlled in an integral way allowing one to develop maintenance and quality plans, which enable the prediction of critical factors in the process. Finally, the study provides the conceptual model and the simulation tool that can support the activities of equipment producers, service engineering suppliers as well as for production and assembly companies allowing better decision making and continuous optimization along the manufacturing asset lifecycle. As a result, the proposed methodology represents a useful tool for organizations and managers in order to increase their efficiency, competitiveness and, therefore, viability over time allowing also to develop their traditional business models.

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