Synopsis of the MBSE, Lean and Smart Manufacturing in the product and process design for an assessment of the strategy "Industry 4.0"

Eugenio Brusa
Dept. Mechanical and Aerospace Engineering
Politecnico di Torino
Torino, Italy
eugenio.brusa@polito.it

***Abstract*—The industrial product development is currently managed by resorting to the Model Based Systems Engineering (MBSE), aimed to decompose the systems complexity, to the Lean Manufacturing, allowing to achieve the targets of Quality, Cost and Delivery (QCD), and to the enabling technologies of the Smart Manufacturing. Those three approaches are still assumed completely uncoupled, against the evidence of the disruptive power of their mutual and full integration, as is herein discussed. This integration looks the goal to be achieved for a definitive assessment of the so-called strategic initiative "Industry 4.0", as is currently promoted worldwide to improve the industrial productivity.**

Keywords—Industry 4.0, Model Based Systems Engineering, Lean Manufacturing, Smart Manufacturing, Product lifecycle development, System Design.

I. Introduction

The most recent transformation of the worldwide industrial organization aims to improve the system quality, to reduce cost, and to finalize the product delivery to the customer needs [1]. A review of the product and process design activity, respectively, is currently promoted. To achieve those targets, a straight application of the *Systems Engineering* (SE) to the product development [2], of the *Gemba Kaizen* to the process management [3], and of the enabling technologies promoted by the strategic initiative "*Industry 4.0*" to the industry digitalization [4], automation [5] and "autonomation" [6], is proposed. The last two approaches are even known as "*lean*" (LM) [7] and "*smart*" (SM) [8] *manufacturing*, respectively. Many companies currently resort to those approaches, although a complete awareness of their powerfulness seems not yet achieved. Particularly, those approaches are wrongly assumed to be completely uncoupled. The SE is often associated only to the product development, although it is intrinsically linked to the process management. The LM is often perceived as a rationalization of the material processing, by neglecting its connection to the product development. Finally, the disruptive technologies supported by the SM are just considered as a progress of tools, more than a mean to implement the LM and, very seldom, they are considered as a relevant part of the SE implementation. Despite that wrong perception, those three innovation levers are tightly cooperating to face the product complexity, by assuring quality, cost reduction, effective delivery as well as the product reliability, availability, maintainability and safety (RAMS). Moreover, they allow a suitable interaction between customer, designer, manufacturer, maintainer and supplier, as some implementation, like the *Word Class Manufacturing* (WCM), already defines and supports [9]. A comprehensive discussion about the mutual coupling between *Systems Engineering*, even in its implementation as *Model Based* (MBSE), *Lean* (LM) and *Smart Manufacturing* (SM) is herein proposed, by analysing methods, processes, tools applied by each approach. As a result, they look like the edges of an ideal triangle, which defines the perfection of their full integration for a unified approach to design, to produce and to deliver.

II. Characterizing the MBSE, LM and SM

A. *The MBSE and SE*

To synthetize herein briefly, the MBSE primarily looks at the *product* as a *complex system* and helps the designer and the manufacturer to manage the whole *Product Lifecycle Development*. The MBSE allows decomposing the system *complexity*, and assuring a complete *traceability* of the system requirements to functions, of functions to subsystems and components, of subsystems to the built parts, classified by a part number. This action is effectively performed, by resorting to some pillars, like the *method*, the *process*, the *tools* and the *data management* [2].

The *methodology* includes a preliminary selection of a suitable *model of the Product Life Cycle*, as the well-known "V–diagram" depicted in Fig.1, and even other ones [10].

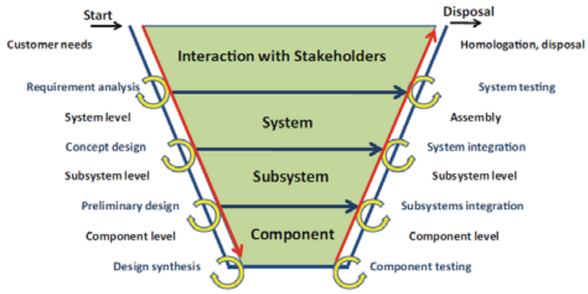

Fig. 1. The 'V–diagram' used as a model for the Product Life Cycle in the MBSE.

This model clearly states the relevant role of the *customer* in defining the system requirements and the importance of the *stakeholders*. The design activity (*Application Lifecycle Management*, ALM) is somehow mirrored, by level, with the corresponding actions of manufacturing (*Product Lifecycle Management*, PLM), and links the system conception to its production, through the "V" look of the diagram. A key issue of this *method* is that it applies some *reusable* and *digital models*. They include a qualitative description of the system behaviour, architecture and operation (*functional modelling*) and a quantitative one (*physical* or better *numerical modelling*), based on a numerical and mathematical structure. The numerical modelling is exploited to describe the system geometry, to predict its performance, to make a *trade-off* of its configurations, typically by resorting to an *heterogeneous simulation*, in which the functional and the physical models are both included. The *verification* of requirements and the product *validation* even resort to those models to check the correspondence between product and model, and between product and customer needs, respectively.

The *process* brings the user to perform the *requirement analysis*, then the *operational, functional, logical and physical analyses*, in sequence, to reach a *design synthesis*. The *tools* exploited include some typical *diagrams*, defined within a standard *language*, as the SysML, but even some *architecture frameworks*, as they are defined, for instance, by several Departments of Defence (DODAF, MODAF, NAF) or some Space Agency (ESAAF). Particularly, some typical system *capabilities*, which are exploited in operation, are identified within the architecture framework, through several *views* of the system, and this helps the designer to define the best solution among those proposed.

Finally, several tool software are *interoperated* through a platform, which defines a *tool chain*, including several data bases, which need an effective *data management* to share the information, through a careful control of *changes* introduced by the operators, classified by a hierarchic level. It is worth noticing that nowadays aside a functional analysis a *dysfunctional* is already accomplished in the preliminary technology trade–off [11]. This includes a preliminary investigation about the system behaviour in presence of classified *failure modes* in its architecture, thus allowing a prediction of the system effectiveness and reliability, before that a final configuration could be defined.

The MBSE offers some typical features to help the product developer in reaching the goals above mentioned. As Fig.2 shows, the two common activities of the *trade-off analysis* and of the *requirements verification* and *system validation* (V&V) are deployed by resorting to the three typical analyses of *requirements*, *functions* (and operations) or *dysfunctions*, and *physics* of the system. More recently, the application to the industrial product and no longer only to the software, suggested of decomposing the functional analysis into a preliminary identification of functions and operations and then of the logical activities performed by the system architecture, thus adding the *logical analysis* as an intermediate step of the design activity [2]. The language (as the SysML) provides some diagrams, made standard to be shared between customer, manufacturer and supplier. Three main graphical products as the *functional, logical and product breakdown structures* are created. They allow distinguishing the functions of system, from the logical components, describing their operation, but never the commercial products associated, from the product components, which are then selected, among those actually available on the market. The design synthesis brings to a definition of the whole product integration, tailored to homologation, when is foreseen, or to product liability and RAMS.

It is worth noticing that nowadays the MBSE approach includes a combined *functional* and *non-functional* or *dysfunctional analysis* to anticipate the prediction of system reliability, since the preliminary design activity [11]. This action is made easy by a straight correspondence between the main steps of the product development and those required by the RAMS analysis, as is described in Fig.3.

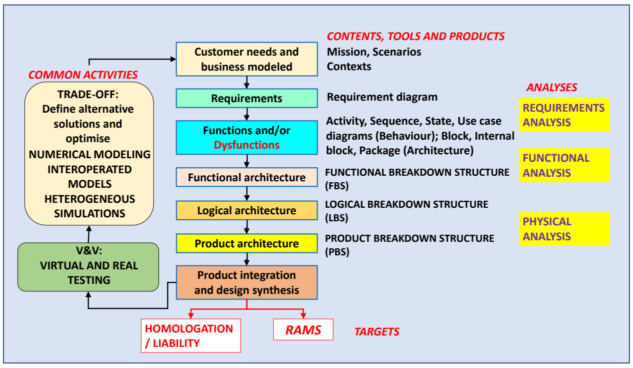

Fig. 2. A synopsis of the main features of the MBSE approach applied to product development.

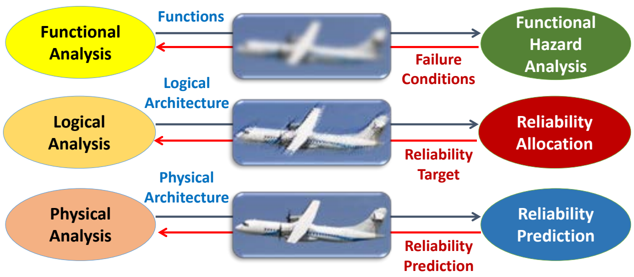

Fig. 3. Comparison between activities and results of the functional and dysfunctional analyses.

The analogy between functional and dysfunctional behaviors is defined. As the functional analysis focuses on the functions, the *functional hazard analysis* identifies the system *failures*. Similarly, a logical component performs a logical operation, while in the other analysis it is required to assure a *target of reliability*, which becomes a real *reliability performance* in the final product, as a commercial component is identified to physically provide that logical operation.

When the MBSE approach is implemented, a digital model of the whole product is preliminarily synthesized and used to predict the product performance in operation. Particularly, the FBS, as is depicted in Fig.4, representing the example of a flywheel on magnetic suspension, is used to generate an IBD, for instance, which allows the trade-off analysis [12]. The latter is sometimes converted into a LBS, or directly into a numerical model, having the same layout, but including, in addition and within the blocks, some mathematical equations, describing quantitatively the system performance. Numerical simulation is used to define the label data of the commercial components most suitable to be selected for composing the PBS.

The software tools used to build up the digital model need to be interoperated, i.e. connections must allow a straight transition of information between the tools [13]. This is sometimes a bottleneck for the development of this approach although several solutions are currently available. They are based either on a *tool chain* provided by a unique vendor, who assures the products interoperability by design, or on some connectors, compliant with some standards like the OSLC [14].

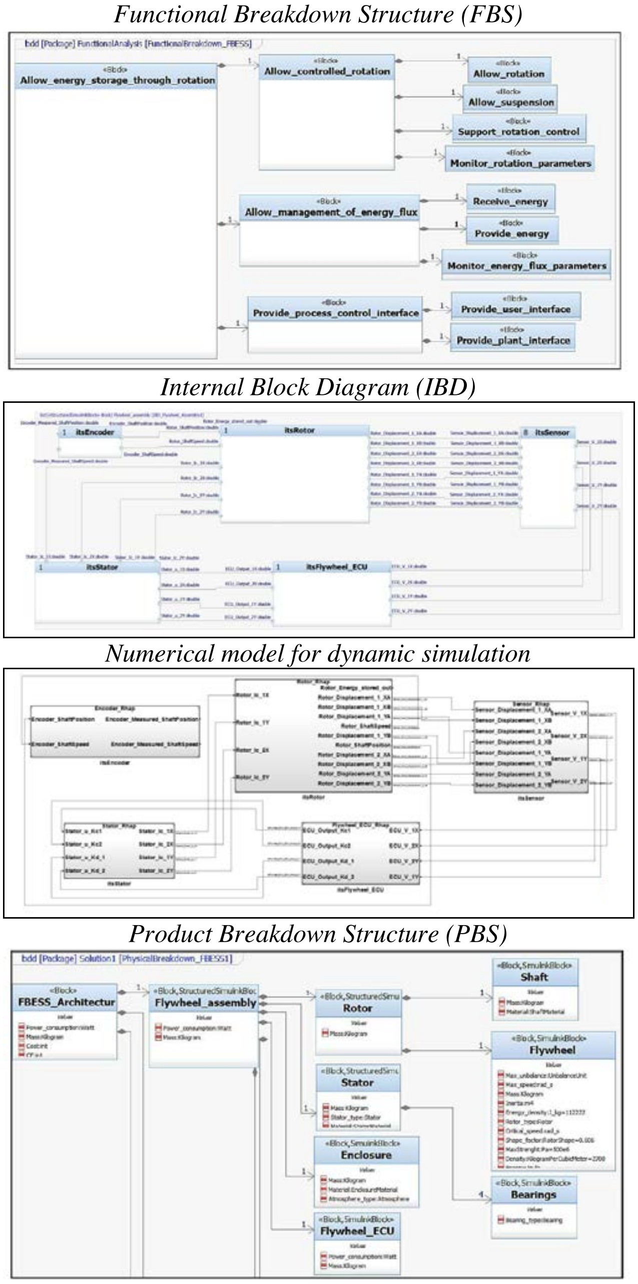

Fig. 4. Example of the evolution of the MBSE digital model of a flywheel on magnetic suspesion.

B. The Gemba Kaizen and the Lean Manufacturing

Many approaches currently applied to the *process* management, more than to the product development, as the SE does, including the *Total Quality Control* (TQC), or *Management* (TQM), the *Just In Time* (JIT), the *Total Predictive Maintenance* (TPM), the *WCM* already cited, basically resort to the Japanese philosophy of the *Gemba Kaizen* [3]. It promotes a continuous improvement (*kaizen*) of the process and of the frame within which is actually performed (*gemba*), through some small and effective changes, overcoming specific problems or inefficiencies (*muda*), identified step by step, by the people involved in the production activity. This leads to a *simplification* of the process itself, to improve the *customer satisfaction*, and to *rationalize* the whole production line (*lean production*). The five principles of the *Lean Thinking and Manufacturing* [15], are applied, since, the main issues of this approach are the *value*, the *value flow*, the *process flow*, the *pull production* and the *perfection of results*. Particularly, a specific goal in the material transformation process is making the *theoretical time* to produce a given element (averaged on the production baseline), known as the "*takt time*", as much as possible close to *the real time* to produce it, or the "*cycle time*", to increase productivity and effectiveness [3,15].

The three pillars of the LM are the so–called *house-keeping* (HK), the *identification* and *elimination of inefficiencies* or *muda* (ME), and the assessment of suitable *standards* to be repeatedly applied, by the operator, to the process (STD).

As for the SE, a *method* can be identified in the practice of *Gemba Kaizen*. The process management is meant to perform simultaneously two actions, as the *maintenance* of the existing practices and their continuous *improvement*. The first rule applied is "*Plan–Do–Check–Act*" (PDCA), then a coherent standardization follows, and applies the rule *Standardize–Do–Check–Act* (SDCA). The goals driving those activities concern the priority of *quality* over all; the use of *data*, collected and retrieved by the process, to evaluate its effectiveness, but even to create a base for a statistical analysis; the target of *customer needs and satisfaction* as a unique and real target of the whole process.

Several *tools* are exploited. A *policy* is first stated, to define the object of improvement (*policy deployment*), then people are involved through the *Quality Circles*, being groups of operators asked to express their useful suggestions about any process inefficiency (*QC*). Particularly, they must monitor the effectiveness of operations, to reduce the fatigue of operators, by increasing the ergonomics, safety, productivity, quality, and security, and decreasing the production time and cost.

The operators express their *suggestions*, through different means, but all concern the quality improvement, the cost reduction and the delivery enhancement (QCD). Upon the suggestions received, the management defines some *standards*, and then the operators, who drive their continuous refinement, test them and allow a definitive assessment.

When the *Gemba Kaizen* is applied, several *paths* are followed, constituting a sort of checklist of activities. They are organized like into a matrix form. The rows of that ideal matrix are the three activities of HK, ME, and STD previously described. They define the items of the process management, somehow like the use cases of the SE. The matrix columns are the three main goals defined by the QCD system. They define also the metrics to be applied, to evaluate the effectiveness of the running process. Particularly, when the manufacturer *plains* the activity, he defines the *Quality Function Deployment* (QFD, related to ISO 9000 series and 14000 and others), the *Cost* metrics (about product quality, productivity, stocks, production line flexibility, machinery stops, use of space, lead-time), and *Delivery targets* (efficiency, promptness, completeness, time, related to the implementation of the JIT).

The *maintenance* is performed by implementing the *housekeeping*, and five activities are performed. They compose the so–called set of "5 S" (*seizi* = clean out the production line; *seiton* = configure properly what you kept in line; *seiso* = clean the machinery and check; *seiketsu* = applied the three above steps to the operators; *shitsuke* = assure the self-discipline of the operators, write the standards and make some practices). According to that scheme, the rules of housekeeping are defined, and the related standards are written.

The *standardization* is even deployed by considering the targets of quality, by resorting to a list of five issues, known as the "5 M" items (men, machinery, materials, methods, metrics).

The *improvement* is based on the *elimination of inefficiencies* or *muda,* and is performed by identifying the root cause by answering to a sequence of the so–called five "why?" or "5 W". A classification of *muda* into *mura* (changes, variations, irregularities) and *muri* (excesses), respectively, helps in sorting the problems to be solved. They consider seven typical categories (7 *muda*), as the excess of production, the excess of stocks, inefficiencies related to product defects, operator motion, process performance, late incoming of goods in production, and transportation systems.

The architecture of the *Gemba* is even well defined. The *Gemba House*, like in a framework, describes it completely [3]. The *production line layout* is configured upon the principles of the *Total Productive Maintenance* (TPM) and the *Total Flow Management* (retrieving the information back from the customer, as an input to retail units, distribution, manufacturing, and supplier), respectively. Very often, a structure organized by *cells* is proposed, to define different steps of the manufacturing activity [15] (Fig.5).

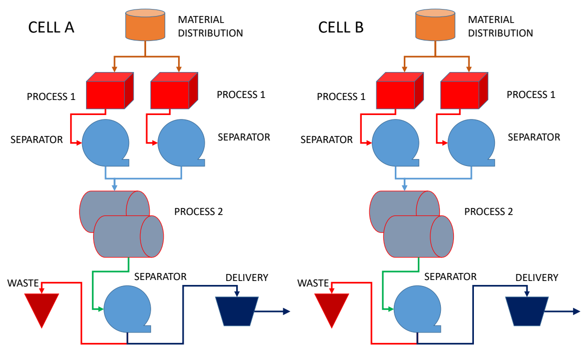

Fig. 5. Example of generic structure by cells of the industrial process as proposed by the Lean Thinking [15].

The *Gemba* includes also a *hierarchy* of managers and operators, all playing a specific and delimited role (to be interpreted as cells of people). The model of *Learning Enterprise*, where everybody sees, observes and suggests, is implemented, through an *operational chain* starting from the CEO (Chief Executive Officer) and going to the workshop operator, through the chiefs of unit, department, and section. Therefore, the LM exploits a real *Training Within Industry* (TWI) [15].

The performance of process is easily evaluated, by filling, along the production line, the so–called *Value Stream Map* (VSM), in several *data boxes*, where all the indexes describing the effectiveness of the running process are certified.

C. *The Industry of the Future and the Smart Manufacturing*

Proposing in few sentences a complete description of the strategic initiative "Industry 4.0", resorting to the *Smart Manufacturing* aimed to enhance the industrial productivity, is rather difficult. Nevertheless, it is known that the *Fourth Industrial revolution* [4], coming after the introduction of machines, production lines, robotics and automation in the factories, is based on the *smart cyber-physical systems* and the *Big Data technologies*, which deeply exploit the internet (now *Internet of Things*, IoT), the *cloud*, and remote sensing and monitoring systems. Those *enabling technologies* are bringing the *Industry* to *the future*.

They support the creation of suitable *infra-* and *intra-structures* to implement the SE and the LM. Smart and intelligent systems are widely interconnected, to perform a true *collaborative* and somehow *autonomous work*, to be *adaptable* to the working environment changes, to allow a continuous and effective *monitoring, prognosis, diagnosis* and *control* of systems in operation.

To investigate the interaction between SM, MBSE and LM, a short synthesis of the enabling technologies characterizing the fourth revolution is proposed in Fig.6, according to [16].

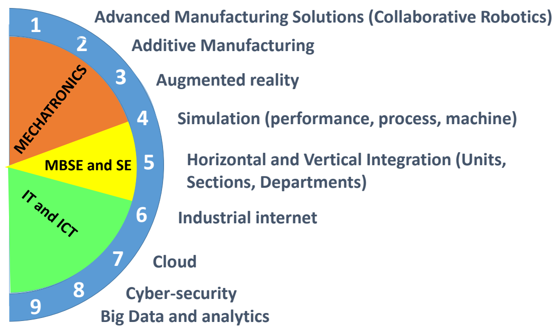

Fig. 6. Selection of enabling technologies introduced and enhanced by the Industry of the Future [16].

One of the main goals of those technologies is allowing a *cyclic use of products*, i.e. monitoring and maintenance of the manufactured systems should increase the possibility of re-use or longer use. A crucial issue is the integration of manufacturing units spread on the different locations (horizontal), with customers and suppliers, as well as that between the design, the management and the workshop, inside the same factory (vertical).

All the enabling technologies introduced support an effective enhancement of the manufacturing *performance, quality* and *safety*, because they are based on the extensive use of both the *mechatronics* and the *digitalized information*. The system *smartness* is often related to different levels of artificial intelligence, corresponding to some functions of *sensing*, *controlling* and *actuating*, under a defined strategy [17]. The advanced manufacturing solutions basically include the *automated systems* and the *collaborative* *robotics*, expression of mechatronics, and the *additive manufacturing technologies*, fully based on the industrial digitalization of product [18].

The *collaborative robotics* helps humans in making faster, controlled and more precise the manufacturing action, improving the performance, decreasing the pain of operators and assuring high levels of quality and safety. The design of collaborative robotic devices surely faces some issues related to complexity and to the actual needs to be satisfied, as in the exoskeletons. The intensive use of *automation* in manufacturing and material processes increases the complexity related to *multi-physics* involved in the coupled phenomena exploited [19]. Moreover, sensors in automated systems allow simultaneously the application of control actions, but even to extract a continuous information from the operated system, which can be monitored, and analyzed for an effective *prognosis* of failure and damage conditions, as well as for a *diagnosis*, after that failures occurred. This monitoring action can be connected by *the industrial internet* and shared with the operators interfaced with the operating system, or even remotely analyzed, by working units, even far from the location of the monitored system. This use involves the transmission of *data*, through the *internet* (IoT), the *cloud* and under a severe requirement of *cyber security*.

The *additive manufacturing* introduces another kind of smartness, related to the digital content of information directly sent by the designer to the production line, extensively adaptable to many needs of shaping and optimizing the product. It allows manufacturing systems and components previously never built up, because of some surface inaccessible to the tooling machines. The strength of additive manufacturing is the lying of production data directly within the *digital product mock-up*, made through the SE as a result of the *trade-off* accomplished between technologies.

Two examples might simplify the above mentioned concepts. The so-called *smart bearing*, for instance, is embedded into the machinery as a component of the whole assembly, but is even equipped with some miniaturized sensors, which allow monitoring the inner environment of bearing, to prevent failures and damage, but even the outer and surrounding environment of the hosting frame, as it measures the loading, thermal, vibration and acoustic conditions [20,21].

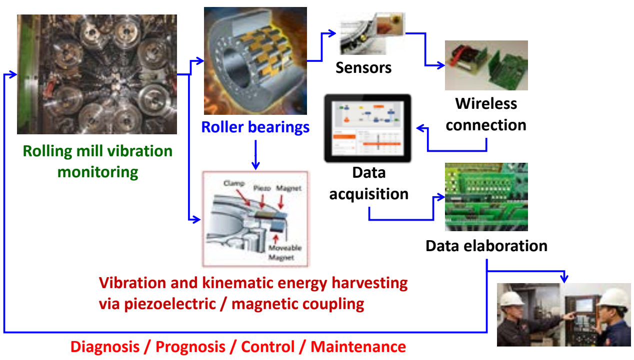

Fig. 7. Concept of smart bearing for large equipment monitoring with embedded sensors and autonomous energy supply.

It might be used as a *sentry node of a network* to warn the operators about any abnormal behavior of either the bearing components or the hosting system. If it is used remotely, it allows applying *the IoT technology*, to monitor the life of components and warn the manufacturer about any need of maintenance. In case of the active magnetic bearing, the system simultaneously performs the monitoring action and the active vibration control. To install the smart bearing it is required a deep description of its calibration and properties, which is digitally provided, since its production, through the *ISO Data Matrix* method [22]. Therefore, the smart bearing looks simultaneously as a smart device in operation and a smart product in terms of the information contained in its assembly and shared with the manufacturer, in service.

The *augmented reality* is another effective mean to implement the smart manufacturing, as in case of the *smart helmet* for operators involved in steelmaking or similar industrial plants. Basically, this tool provides two services. The information coming from some sensors embedded and from the network are plotted through a head-up display, and read in real time by the user. These data might prevent the exposure of the worker to some risk or any severe operating condition. Some recent evolutions of this device include a *smart glass*, allowing to look at the working environment through a glass shield, whose transparency and color can be regulated by resorting to either thermochromic or electrochromic material [23], which might be automatically activated by a light sensor to protect the user against the risk of blinding glare [24]. When the operator is required to perform a quality assurance activity in production line, by monitoring the product, the same device is equipped with some augmented vision system for damage detection [25], which supports the vision activity. It allows detecting failures, damages and marks as in gears, rolling elements of bearing, or on the surface of the steel strip.

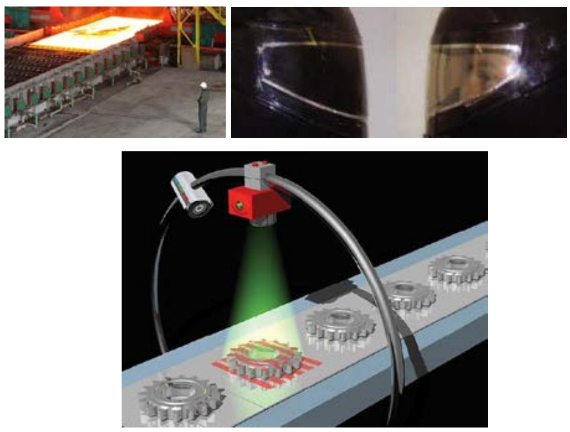

Fig. 8. Concept of smart helmet with protection shield based on the electrochromic smart materials [24] and augmented vision system for damage detection.

All those systems exploit a variety of coupled phenomena and include a number of components that their complexity easily rises up and requires some systematic approach to design the device, as the MBSE, and to perform the detection of waste, according to the LM approach.

		MBSE Model Based Systems Engineering			Gemba Kaizen	Lean Manufacturing		
1	4	PRODUCT Development		TARGET	PROCESS management		1	5
5	6	*Traceability*		MAIN FEATURES	*Visual management*		5	7
7	8	*Reusability*			*Continuous improvement*		3	9
3	4	*Decompose complexity*			*Apply the Learning Enterprise approach*		5	6
1	5	*Improve quality*		GOALS	*Improve quality*		1	5
4	5	*Reduce cost*			*Reduce cost*		1	3
3	4	*Avoid human mistakes in product design*			*Avoid human mistakes in processing*		3	6
4	9	*Avoid re-engineering*			*Improve delivery process*		9	2
4	7	*Digital models*		NEEDS	*Flexible production line (Gemba)*		1	2
6	5	*Interoperable tools*			*Self-disciplinated operators*		5	7
6	7	*Reliable tool chain*			*Reliable machinery*		1	9
8	5	*Secure Data Base*			*Data retrieving*		9	7
5	8	*Customer*		ACTORS	*Customer*		5	7
5	6	*Stakeholders*			*Stakeholders*		5	6
5	8	*Operators*			*Operators*		5	8
				METHODOLOGY				
		Product Life Cycle		*Object*	Gemba (Process cycle)			
		Model of product lifecycle (V, spiral ...)		*Base*	Model of process: Total Flow Management			
4	6	*Application Lifecycle Management (ALM)*			*Process maintenance*		5	6
5	6	*Product Lifecycle Management (PLM)*			*Process improvement*		9	3
				Methods vs targets				
		Selection of technologies						
4	6	*Modeling*	Reliability, Availability, ...		*Housekeeping*	Quality	9	3
			...Maintainability, Safety (RAMS)					
1	9	*Trade-off*	Sustainability		*Elimination of Muda*	Cost	3	9
1	5	*Deployment*	Service		*Standardization*	Delivery	5	9
4	7	*Heterogeneuous simulation*						
4	3	*Verification*						
3	9	*Validation*						
5	7	*Requirement Analysis (System goals, ...*		*Process*	*Identification and charcterization of Gemba*		5	
		...requirements)			*Housekeeping: apply "5S"*		5	6
4	6	*Operational analysis (System context, ...*			*Planning of process ...*		4	9
		... mission, scenarios, stakeholders)			*...(Plan-Do-Check-Act PDCA)*			
4	5	*Functional and dysfunctional analysis...*			*Standardization: apply "5M"*		4	5
		... (Functional Breakdown System)						
4	5	*Logical analysis ...*			*Standardization of process...*		5	9
		...(Product Breakdown System)			*... (Standardize-Do-Check-Act SDCA)*			
4	5	*Physical analysis (Product Integration)*			*Elimination of inefficiencies: apply*		3	5
					"5 W" (Muda identification)			
4	6	*Design synthesis*			*Classification of muda - mura - muri...*		3	4
					...and problem solving			
				Tools				
4	5	*Diagrams*			*Driving lists*		5	6
		Requirements diagrams			5S (Housekeeping); 5M (Quality and standards);...			
					...5W (Root cause); 7 Muda			
		Context diagrams			VSM - Value Stream Map (of Data)			
		Behaviour diagrams (Use case, States,...						
		... Sequence, Activity)						
		Structure diagrams (Block Definition,...			*Diagrams*		5	6
		...Internal Block Definition, Package)						
		Parametric diagrams			Example: Fish Diagram			
4	5	*Architecture frameworks (views)*			*Procedural frameworks*		4	6
		(MODAF, AF-EAF, AFIoT, AAF, DoDAF, ...			TQC - TQM - JIT - TPM - QFD			
		...ESAAF, MODAF, NAF, TOGAF, UAF)			The Gemba House			
4		*Language*			*Operators team*		5	6
		UML - SysML - IML - AML - LML			Quality Circles (QC) who express visual suggestions			
				Information				
		Requirements, Functions, Components, Parts			Standards			
		Numerical contents			Value Stream Map			
		Key Performance Indicators (KPI)			Key Performance Indicators (KPI)			
1		Product baseline		*Platform*	Process driveline		1	
6	7	Tool chain of interoperable software			Operator hierarchic chain		5	
6	7	Data bases			Data bases		6	7

INDUSTRY 4.0 - ENABLING TECHNOLOGIES				
1	1	Advanced Manufacturing Solutions and Collaborative Robotics	5	Horizontal / Vertical Integration
2	2	Additive Manufacturing	6	Industrial Internet
3	3	Augmented Reality	7	Cloud - IoT
4	4	Simulation and system integration by modelling	8	Cyber-security
			9	Big Data and Analytics

Fig. 9. The proposed synopsis of the MBSE, Lean and Smart Manufacturing.

III. TOWARDS A UNIFIED APPROACH

A. *A synoptic interpretation*

If one compares the two approaches of the MBSE and the LM actually realizes that a punctual correspondence exists. That comparison is tentatively proposed in Fig.9. Particularly, following some typical references as [3,7,10,15], the main contents of the MBSE (left column) are compared to those of the LM (right column). Each element of comparison is described in the middle column. Moreover, after collecting the replies to a preliminary questionnaire of 26 companies, the major influence of the disruptive technologies proposed by the SM were associated to each item, by selecting the two most commonly identified. The legend of numbers and colours is proposed at the bottom of Fig.9.

As is evidenced by Fig.9, the MBSE applies to the industrial product a methodology that is similarly applied to the process by the LM. An almost perfect dualism is perceived. In some cases a superposition of contents occurs. For instance, the goals are the same, they focus on quality, cost, mistake, and inefficiencies. In the LM the role of humans is very evident and the operators are elements of the process, like in the MBSE, although they are less expressively evidenced. The actors are even the same, and customer plays a crucial role. The data are extremely important in both the drivelines

B. *Dualisms and analogies*

Analysing deeply the synopsis, one can find some dualisms and analogies. A first evident dualism involves the *requirements* of the product development and the *standards* of process deployment. They are both used as a reference for the verification and validation, they come out from an iterative process of assessment and refinement, which motivate resorting to all of tools foreseen in the two contexts. The requirement *traceability* is a key issue of the SE methodology, as in the LM the *Visual Management* is, i.e. for a continuous improvement the information, the problems and the corrective actions applied must be clearly accessible by all of the operators. For both the *digitalization* is a crucial target of innovation, as is promoted by the SM, but even the effective integration among units (horizontal and vertical).

In both the contexts, decomposing the *complexity* is a priority, in the MBSE simplifying the system architecture is mandatory as well as making lean the process is the goal of the LM. The goals even include a difference like the reduction of cases of *re-engineering* in the product design, and the improvement of *delivery*, in the process design. They are both focused on the overall process implemented and they promote a *unique execution*, to keep the costs as low as possible. The implementation of the two methodologies of the MBSE and of *Gemba Kaizen* look needing a straight use of augmented reality, simulation and modelling, as well as an efficient communication and sharing of information, through the internet.

The *needs* express a complementarity of exigencies, i.e. the MBSE expressively requires suitable tools for modelling, interoperated and reliable, based on secure data; the LM points out the need for machinery and operators, reliable and very well interfaced, by some suitable *Man to Machine systems* (M2M), and more in general by *Human Machine Interfaces* (HMI). Actually, both the drivelines exploit all of those elements. Moreover, the attention to *stakeholders* is high in both the contexts.

As the *method* is implemented, it can be realized that despite the difference of nomenclature and of the context (product vs process) a certain dualism is present. The *ALM* activity is mirrored in the "V-diagram" by the *PLM*, as in the LM *maintenance* is alternately performed with *improvement*. The targets are analogous; since the aim of product development is the *RAMS* as in the process, the *quality* must be assured. The *sustainability* pursued in the product development corresponds to the *efficiency* in process, and both require keeping *cost* low. The output of MBSE is the *service* as a phase of the *delivery*, being the target of the LM.

The different steps of *process*, in both the contexts, express a dualism. In the product development, the *analyses* are performed in sequence, and in the manufacturing, actions are executed in sequence, by resorting to a number of conventional driving lists ("5 S", "5 M", "5 W", 7 *muda*), as well as in the MBSE, the applied language provides several suitable diagrams. Even in the LM, some diagrams are plotted and exposed in the production line, to involve the operators in the continuous improvement, as the *Ishikawa diagram* or "*Fish" Diagram*, where the targets of QCD are related to the 5M at different levels, and to the environment. The smallest arms in this diagram are the so–called *key points* for the punctual intervention of change (Fig.10). For all those activities, the use of tools to implement a *heterogeneous simulation* is mandatory, as well as the support of an effective *cloud* and of the *internet*, to allow a complete *interoperability*. The data sharing and management is crucial, thus requiring a perfect horizontal and vertical integration, and to resort to some software deploying the *Manufacturing Execution System* (MES).

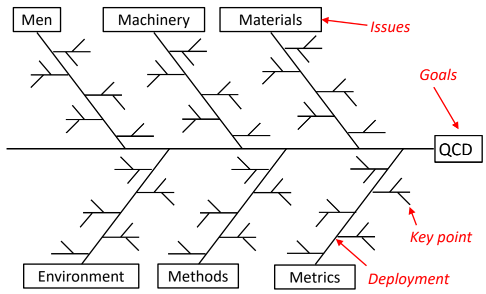

Fig. 10. The Ishikawa or "Fish" Diagram, used in the Lean Manufacturing.

It is worth noticing that in both the contexts, the frameworks play a significant role. The MBSE resorts to the *architecture frameworks* to deploy the system, in terms of capabilities and views, as the LM actually implements several *procedural frameworks* (the *Gemba House* or the TQC, JIT, QFD) to manage process, materials and time.

By converse, it is relevant that the MBSE totally trusts in the *language* used to create the *digital models*, while the LM directly organizes the *operators,* both in hierarchy and in groups, or *Quality Circles*, to retrieve the information and to support the improvement. Similarly, if one looks at the platform applied, the *tool chain* is dominant in the MBSE while the *LM* focuses on the *operator chain*.

Concerning the *information*, a superposition between the two approaches occurs. The elicitation of traceable requirements, linked to the customer needs, corresponds to the assessment of the process standards, based on customer needs (where customer might be even the following manufacturing unit), but refined step by step through the concurrent contribution of all the operators or the stakeholders. The *Value Stream Map* is somehow overlapped to the quantitative contents of data shared in the product development.

The use of *Key Performance Indicators* (KPI) is definitely recommended by both the SE and the LM approaches. They define the metrics used to evaluate the product and the process, respectively, and provide a list of suitable items about which the analysis can be effectively performed. In the LM some KPI are frequently used as the *Overall Equipment Efficiency* (OEE), or the *Single Minute Exchange of Die* (SMED).

At higher level, it might be noticed that as in the SE the *Product Lifecycle Management* is the highest level of the organization driving the building up of a tool chain to control the changes, in the *Gemba Kaizen*, the *Total Flow Management* drives the strategy of production. It might be oriented to a "one piece flow", with a synchronization based on the "Just in Time", to perform a "pull production" more than to a "push production", since it is excited by the customer demand.

The impact on those analogies of the SM looks large, according to the feedbacks collected. If one looks at the proposed association between the enabling technologies and the items identified for both the methodologies (Fig.9), immediately can realize that a good coverage is assured.

Moreover, the contribution of *advanced mechatronics*, in terms of *advanced solutions for manufacturing and robotics* and *augmented reality* is relevant and affects both the product development and the process deployment. By converse, the *Additive Manufacturing,* nowadays so strategic, provides a good contribution in some issues, while the perception of a huge impact on the overall system looks lower.

The *simulation* still represents an important element, particularly in the meaning of extended *heterogeneous simulation*, including functional and numerical modelling. The *horizontal and vertical integration* seems more a target than an input for the application of such unified approach, although a preliminary organization of the working units and of the operators to be effectively integrated is needed, to apply the disruptive technologies above described.

All the issues related to the network, the *data* collection, elaboration, transmission and management are crucial, for many activities here mentioned. Particularly, the technology and the infrastructures related to the *industrial internet* and to the *cloud* is perceived as a key element of powerfulness of the whole rationale. The impact of the *Big Data and analytics* is impressive, although the *cybersecurity* might be, simultaneously, the element either of strength or of weakness of this system.

C. Towards the integration

As it was demonstrated, a relevant issue of the convergence among MBSE, LM and SM is the *customization of product*. More and more the customers require a personalized version of product, or better a complete satisfaction of needs. This can be assured, thanks to flexible and lean production lines, as well as by means of smart systems and equipment, easily adaptable. The smartness often increases the system complexity, thus motivating the application of the MBSE to decompose and handle it.

What kind of benefits a final integration of the MBSE, LM and SM might provide? To this question, some answers are proposed.

A. The *integration between MBSE and LM* shall refine and complete the assessment of the *Product lifecycle model* assumed by the SE. Particularly, it is well known that a link between the ALM and the PLM or PDM (*Product Deployment Management*) is established by the SE tools, and is currently exploited to clearly define the requirements related to manufacturing. Nevertheless, the SE very seldom defines in details the activities foreseen by the ascending arm of the "V-diagram", visible on the right, in Fig.1. A clear decomposition of the actions after sale, as the delivery, the service, the maintenance are seldom defined, as in some specialized contribution as in [26], where the introduction of a second path looking itself as a "V" is exploited to add the personnel training, the maintenance, the monitoring and the decommission, as useful actions to describe completely the delivery.

B. The *Gemba* looks like a system and, in principle, no limitation inhibits to apply some of the tools of the SE to the process, once that the production line is identified as the system to be analysed. Particularly, the diagrams exploited by the SysML to decompose the system complexity might be freely used to analyse the process. Some specialized diagrams, as the State Machine, can be even simulated to check the performance of the system [2].

C. The *integration between LM and SM* looks natural, if one assumes that the SM is conceived to enhance the productivity. Many enabling technologies are required to make faster, more effective and more precise the action of improvement. Nevertheless, all the technologies supporting the monitoring, prognosis and diagnosis activities will provide a key contribution. Particularly, if the remote control currently applied to systems in operation, like motor vehicles, trains, aircrafts and spacecrafts, will be even applied to the elements of manufacturing systems, for instance to the bearings, to retrieve data for an effective maintenance [20], or to the testing facilities, assuring the system quality, the benefit will increase significantly.

It is known that mechanical components requiring a continuous maintenance, being designed for a finite life and somehow consumable, need a clear traceability of their intrinsic and operational data since the *testing* performed before the delivery. Therefore, a real horizontal integration with customer will be complete, when the test, the service and the maintenance will be suitably monitored and coupled. This action resorts to the SM smart systems and data management ass a key element of the infrastructure to actuate the remote testing and operation monitoring.

D. The *integration between MBSE and SM* is defined in two levels. If one looks at some smart systems like robots, mechatronic and autonomous systems, the system integration is suitably driven by the MBSE, through all its tools. Nevertheless, if the activity of remote monitoring is designed, the MBSE is helpful to define all the system parameters, considering the mission, operation and requirements, related to service. Quite often, it happens that despite the application of remote monitoring systems connected through the cloud, the designer is poorly aware about the real specifications required by the application, since a too short investigation about the requirements and the functions to be exploited is preliminarily performed.

E. To clarify the mutual integration of the MBSE, LM, and SM, the example of the *smart bearing* looks suitable. It is first a *product* to be developed and equipped with a set of sensors, then it becomes a node of the monitoring network and can perform the *in-monitoring* of its own defects and failures, as well as the *out-monitoring*, i.e. it is a sentry of the process performance for the machinery, where is embedded. Moreover, the bearing as a system to be tested needs a test bench for a complete homologation. The results of this activity are enclosed into the firm of the bearing, nowadays traced, by the labels applied, easily detected and read in operation, according to the ISO Data Matrix [22]. The contents of the data collected and marked on the bearing as well as their direct transmission to the central data base for monitoring purpose can be done by a smart test bench itself, when equipped with the needed devices.

This example clarifies the mutual interaction occurring between the MBSE, the LM, and the SM. Actually, when the product bearing is developed, the required testing and monitoring activities are designed together the system, through the PLM, within the MBSE approach. In service, it plays the role of system exploited to support the process, as a mechanical component, but even to monitor its performance, as a node of the IoT, thus contributing to the data retrieving useful to implement the LM. As a smart system, it resorts to the disruptive technologies of the SM, including the mechatronics, the IT, especially in terms of cloud, network, data management and storage.

IV. CONCLUSION

A full integration among the MBSE, the LM, and the SM is the natural path for the final assessment of the "Industry of the Future" strategy. They certainly help in assessing the required standards, to assure the security and safety levels in products and processes, compatible with the desired sustainability.

The means to perform that integration are currently available, or at least are in rapid development. Despite the different origins, all those levers for innovation focus on the same goals. They are motivated by the need of satisfying the customer, by assuring quality, keeping cost as low as possible, improving service and delivery. To assure a complete integration, some actions are required.

A full awareness of people about the powerful contribution of the MBSE-LM-SM system must be reached. This activity is currently promoted by the educational programmes to the digital factory, worldwide proposed, and especially by some dedicated competence centres.

To refine the tools of that synoptic system, the disciplines of mechatronics [27], smart materials [28], and micro and nanotechnologies [29] need to be deepened and enriched, by some new and original contributions. The machine learning and the artificial intelligence require to be equally developed and embedded, in the smart systems.

For the product development, the main stream of innovation concerns the application of the digital twin and functional modelling in addition to numerical modelling, for a comprehensive virtual engineering, prototyping and testing [30]. Nevertheless, the effectiveness of those tools depend on a complete development of the interoperability protocols, of the IoT infrastructures, of the cloud and related services, needing to be more and more service oriented [31].

Other technologies are strictly involved, as the ICT, with particular care of the network band and configuration, as the 5G. In addition, even the HMI systems could improve the impact of the proposed approach. A crucial issue concerns the inclusion into the global deployment environment previously described of optimized business models, supply chains, logistics to configure a balanced ecosystem in the factory.

REFERENCES

[1] J.P. Womack, D.T. Jones, and D. Roos, The Machine That Changed the World: The Story of Lean Production - Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry. Free Press, 1990.

[2] E. Brusa, A. Calà, and D. Ferretto, Systems Engineering and Its Application to Industrial Product Development. Cham, Switzerland: Springer, 2018.

[3] M. Imai, Gemba Kaizen: A commonsense approach to a continuous improvement strategy. The Kaizen Insiitute, 2012.

[4] K. Schwab, The Fourth Industrial Revolution. Cologny, Switzerland: World Economic Forum, 2016.

[5] Industrie 4.0 integrative production, Aachener perspektiven. RTW Aachen and Fraunhofer, 2014.

[6] I. Garbie, Sustainability in Manufacturing Enterprises: Concepts, Analyses and Assessments for Industry 4.0 (Green Energy and Technology). Springer, 2016.

[7] J.P. Womack, D.T. Jones, Lean Thinking: Banish Waste and Create Wealth in Your Corporation, Revised and Updated. Free Press, 2003.

[8] H. Kühnle, G. Bitsch, Foundations and Principles of Distributed Manufacturing: Elements of Manufacturing Networks, Cyber-Physical Production Systems and Smart Automation. Springer, 2015.

[9] R.J. Schonberger, World Class Manufacturing: the Next Decade Building Power, Strength, and Value. Free Press, 2013.

[10] D. Walden, G. Roedler, K. Forsberg, D. Hamelin, and T. Shortell, Systems Engineering Handbook of INCOSE. 4th Ed., John Wiley and Sons, 2015.

[11] A. Tundis, M. Muhlhauser, A. Garro, E. Brusa, and D. Ferretto, "Dependability assessment of a deicing system through the RAMSAS method", Proc. 2017 IEEE ISSE, 3rd Int. Symp. on Systems Engineering. Wien, Austria: October 11-13, 2017.

[12] E.Brusa, D. Ferretto, "Impact of the Model Based Systems Engineering on the design of a mechatronic flywheel–based energy storage system", Proc. IEEE 2nd ISSE 2016, Int. Symposium on Systems Engineering, Edinburgh, October 4–5, 2016 pp.171–178.

[13] E.Brusa, D. Ferretto, A. Calà, "Integration of heterogeneous functional-vs-physical simulation within the industrial system design activity", IEEE 1st ISSE Int. Symposium on Systems Engineering, Rome, September 29–30, 2015, pp.303-310.

[14] I. Vagliano, D. Ferretto, E. Brusa and M. Morisio, "OLSC based tool integration in the aerospace domain: an industrial case", Proc.IEEE COMPSAC 2017, Turin (Italy), 4-8 July, 2017.

[15] P.L. King, Lean for the process industries. Taylor and Francis, 2009.

[16] Piano nazionale Industria 4.0, Investimenti, produttività e innovazione. Min. Svil. Econ., Repubblica Italiana, 2017.

[17] E. Brusa, A. Calà, "Identifying the Smartness of a Mechatronic Coiler through the 'Systems Engineering'", Proc. INCOSE Conf. on Systems Engineering (CIISE 2014), Rome, Italy, November 24-25, 2014, pp.116–125.

[18] E. Brusa, R. Sesana and E. Ossola "Numerical modeling and testing of mechanical behavior of AM Titanium alloy bracket for aerospace application", Procedia Structural Integrity, 5, 2017, pp.753-760.

[19] E. Brusa, M. Mohammadzadeh Sari, "Modeling of the electromechanical coupling between crack propagation and piezoelectric behavior in active layers of smart device", Mechanics of Advanced Materials and Structures, 25(2), 2018.

[20] E. Brusa, "Development of a sentry smart bearing as a node for connectivity and monitoring of steelmaking system", Proc. 2017 IEEE ISSE, 3rd Int. Symp. on Systems Engineering. Wien, Austria: October 11-13, 2017.

[21] E. Brusa, "Design of a kinematic vibration energy harvester for a smart bearing with piezoelectric/magnetic coupling", Mechanics of Advanced Materials and Structures, on line since November 5th 2018, https://doi.org./10.1080/15376494.2018.1508795.

[22] ISO/IEC 16022:2006 – Information technology, Automatic identification and data capture techniques, Data Matrix bar code symbology specification. ISO, 2006.

[23] C. M. Lampert, "Chromogenic smart materials," Naval Research Logistics Quarterly, 7, 2004.

[24] A. Azens, E. Avendaño, J. Backholm, L. Berggren, G. Gustavsson, R. Karmhag, G. Niklasson, A. Roos, and C. Granqvist, "Flexible foils with electrochromic coatings: science, technology and applications," Materials Science and Engineering: B, 119, 2005.

[25] V.E. Marin, "A novel sensory System for the 3D Surface Profiling of Small Complex Objects", PhD thesis, University of Toronto, 2016, pp.72-73.

[26] A. Garro, "System dependability analysis: main issues and possible solutions", Proc. CIISE 2014. Rome, Italy: 24-25 Novembre, 2014.

[27] E. Brusa (ed.), Mechatronics: Principles, Technologies and Application. New York, USA: Nova Publishers, 2015.

[28] A. Araujo, C. Mota Soares (ed.), Smart Structures and Materials. Springer, 2017.

[29] E. Brusa, "Design for reliability of micromechatronic structural systems" in B. Ekwall, M. Cronquist (Eds.), MEMS: Technology, Fabrication Processes and Applications; pp.67-126. Nova Science Publishers, 2010.

[30] E. Barkmeyer, E.K. Wallace, "Reference Architecture for Smart Manufacturing - Part 1: Functional Models", NIST Adv. Man. Series 300-1. National Institute of Standards and Technology, U.S. Department of Commerce, USA, 2016.

[31] M.M. Mabkhot, A.M. Al-Ahmari, B. Salah and H. Alkhalefah, "Requirements of the Smart Factory System: A Survey and Perspective", Machines 6 (23), 2018.