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Laszlo Monostori
Vidosav D. Majstorovic
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Proceedings of the 4th International Conference on the Industry 4.0 Model for Advanced Manufacturing

AMP 2019

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Editors

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Preface

The 4th International Conference on the Industry 4.0 Model for Advanced Manufacturing, Industry 4.0 and Internet of Things for Manufacturing—AMP 2019, will be held at the Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia, from June 5 to 7, 2018. It is organized by the Faculty of Mechanical Engineering, University of Belgrade, and Belgrade Chamber of Commerce and Industry. This year's conference attracted more than 250 participants, including academics, practitioners, and scientists from 22 countries, who contributed 32 keynotes on plenary and workshop sessions.

The previous conferences on the Industry 4.0 model for advanced manufacturing —AMP were:

1. First International Conference USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, May 31 – June 2, 2016, Serbia (AMP Conference 2016), with main topic: Advanced Manufacturing Program—Industry 4.0 model for Serbia (AMP Conference 2017).
2. Second International Conference USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, June 7–9, 2017, Serbia—Smart And Intelligent Products (AMP Conference 2017).
3. Third International Conference USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, June 5–7, 2018, Serbia—Industry 4.0 for SMEs (AMP Conference 2018).

The main objective of these conferences is to bring together leading world experts to discuss the challenges and opportunities of the new Industry 4.0 model of manufacturing. Our hope is that such an event will assist in the development and growth of new innovative manufacturing industries in Serbia, producing smart products with intelligent characteristics, and relying on modern, new manufacturing processes and systems.

The conference is hosted by the Faculty of Mechanical Engineering of the University of Belgrade. Belgrade is the capital city of Serbia, located at the scenic confluence of two major European rivers, with a uniquely remarkable and turbulent history, and a vibrant cultural and entertainment scene. University of Belgrade has a long tradition of academic excellence, where great minds from Nikola Tesla and Mihajlo (Michael) Pupin to Milutin Milankovic held lectures or were faculty. Its engineering still remains exceptionally respected in Europe, with its alumni scattered in top universities around the globe. Faculty of Mechanical Engineering in Belgrade is the largest such school in southeastern Europe and one of the largest in Europe.

Main topics of interest for this conference include:

- Industry 4.0 model framework
- Design of smart and Intelligent products
- Innovative design and development of intelligent products
- Internet of Things for manufacturing
- Big data challenges, data integrity, accuracy, and authenticity
- Cloud computing, cloud-based products, cloud manufacturing
- Cyber-physical manufacturing
- Manufacturing automation in the Industry 4.0 model
- Manufacturing systems and enterprise models for Industry 4.0
- Advanced manufacturing
- Engineering education for Industry 4.0
- What we can to do?
- Road map for AM based on I4.0 model in Serbia.

We acknowledge the outstanding contributions of the following colleagues and friends for the conference establishment and development as follows:

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Prof. Dr. S. V. Sreenivasan, UT Austin, USA; Prof. Dr. M. Zimmermann, Technische Universität München, Germany; Prof. Dr. J. Vancza, TU Budapest, Hungary; Prof. Dr. L. Wang, KTH Stockholm, Sweden.

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Dr. Slavenko Stojadinovic, Chair, Assistant Professor, FME—University of Belgrade, Serbia; Nemanja Gligorijević, FME, Belgrade; Nemanja Lukovic FME, Belgrade.

AMP 2019 Conference can be regarded as a leading global conference in the area of modern manufacturing to several of its special dimensions: (i) It presented a spectrum of scientific and practical advancements in the field of advanced manufacturing (cyber-physical manufacturing, Industry 4.0), and (ii) it offered practical applications and solutions for various problems in the world of modern manufacturing.

The conference planning, preparation, and realization required engagement of a number of persons and organizations. We express our gratitude to all of them, especially to:

Founder, Chair, Co-Chair, and Conference International Program Committee members,

All authors, especially the authors that prepared keynote papers, thus contributing to the high scientific and professional level of the conference,

All members of the International Program Committee for the review of the papers and chairing the Conference Sessions,

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Ministry of Education, Science and Technological Development of the Republic of Serbia for the support in the conference, and

Chamber of Commerce and Industry Serbia, Belgrade; and Conference Co-Organizer.

We wish to express my special gratitude to all colleagues at the Faculty of Mechanical Engineering, University of Belgrade, for their invested efforts that enabled preparation and realization of the AMP Conference in the possible best manner, especially to Nemanja Lukovic for the arrangement of proceedings.

March 2019

Laszlo Monostori
Conference Chair

Vidosav D. Majstorovic
S. Jack Hu
Dragan Djurdjanovic
Conference Co-chairs

Contents

Nano - Precision Systems for Overlay in Advanced Lithography Processes

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Abstract. Improvement in lithographic overlay has been a key enabler of Moore's law. Overlay control has improved from above 300 nm (3σ) in early lithographic systems, to close to 2 nm (3σ) in state-of-the-art photolithography systems as well as in the emerging area of nanoimprint lithography systems. In this article, we survey the innovations which led to these incredibly precise overlay capabilities in modern patterning systems.

Keywords: Nano production · Lithography · Processes

1 Introduction

Transistor scaling, predicted by Moore's law [1], has been enabled by sustained innovation in semiconductor lithography. In this article, we will survey this progress through the lens of lithographic overlay. While resolution has been the primary metric of progress in lithography, layer-to-layer overlay[1] has been equally critical in enabling lithographic scaling. This is a consequence of the fact that semiconductor devices, composed of transistors and many layers of metals and dielectrics, can only be fabricated in a layer-by-layer manner. These layers need to be integrated precisely on top of each other to realize a functioning device[2]. The precision of layer-to-layer overlay required is a function of the size of features being overlaid - generally close to 30% of the lithographic half-pitch, and as low as 7% of the half-pitch (in 22 nm imaging node with double-patterning [4], for instance)[3]. This level of precision is unprecedented in high-throughput industrial systems and has been the product of years of advancement and incorporation of new technologies into overlay control.

In this article, we will focus primarily on developments from 1980 onwards. Additionally, we will focus on commercial high-throughput patterning technologies - photolithography and next-generation lithography - primarily, nano-imprint lithography.

[1] A detailed coverage of overlay theory can be found in Levinson's monograph on lithography [2].

[2] Lithographic overlay is critical in maintaining device yield. See Chapter 6 of Levinson's monograph [2]. For an exemplar chart of overlay-limited yield, see Fig. 3 in reference [3].

[3] This corresponds to an overlay precision of better than 2 nm (3σ) over the area of a 26 mm-by-33 mm lithographic die.

The original version of this chapter was revised: The incorrect legends of the figures 2, 3, 4, 5, 6 and 7 have been corrected. The correction to this chapter is available at https://doi.org/10.1007/978-3-030-18180-2_18

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For the purpose of this survey, we will divide the evolution of overlay control into three broad eras (Fig. 1):

1. Photolithography systems utilizing direct-referencing overlay metrology - Pre-1990
2. Photolithography systems utilizing indirect-referencing overlay metrology - 1990s and onwards
3. Overlay control in next-generation lithography - 2010 and onwards

2 Photolithography Systems Utilizing Direct - Referencing Overlay Metrology - Pre - 1990

Early photolithography tools were of the contact printing type. These used high-NA microscope optics for observing alignment marks placed on both the wafer and the photomask. Alignment was off-axis (from the exposure optics) and was performed manually. Both wafer and mask had to be brought in focus separately, prior to the actual patterning, to determine their positions in relation to the microscope optics. Stage drift post-alignment, and optical axis misalignment were common error sources in these systems. The best overlay achievable was generally in the 300 nm (3σ) range [5]. Alignment metrology at oblique angles, using scattered light, was explored to perform alignment during exposure, thereby avoiding errors due to stage drift [6]. This allowed alignment detectivity close to 10 nm, however the system was extremely sensitive to process variations.

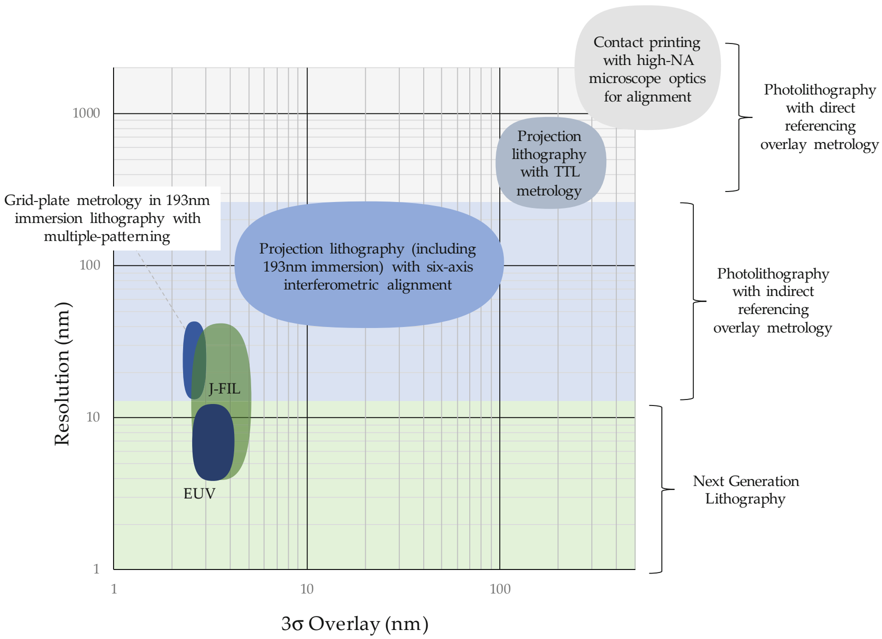


Fig. 1. Evolution of overlay control correlated with resolution. Here, NA stands for numerical aperture, TTL stands for through-the-lens, J-FIL stands for Jet-and-Flash Imprint Lithography and EUV stands for Extreme Ultraviolet Lithography

Projection-based photolithography systems supplanted contact printers commercially in the 80s. With sub-micron design rules, this was the time around which overlay became relevant in place of simple alignment[4]. Early systems used automated off-axis overlay methods, similar to the ones used in contact printing, along with compensation methods for stage drift [7]. Overlay systems soon switched over to on-axis, through-the-lens (TTL) alignment detection [8–13]. As the name suggests, the alignment beam (s) were routed through the same lens stack that was used for pattern exposure (Fig. 2). This permitted alignment during exposure, eliminating detrimental effects due to stage drift, substrate thermal distortions, etc.

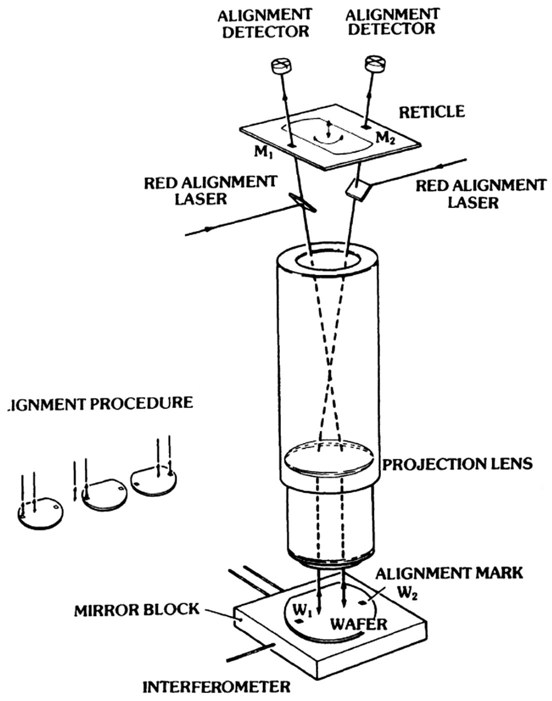


Fig. 2. Exemplar through-the-lens overlay system described in van den Brink et al. (reprinted with permission from [9])

These systems also frequently used phase gratings, which were insensitive to process variations, instead of box-and-cross-type marks. In combination with interferometric stages, TTL alignment allowed these systems to achieve better than 0.15 um (3σ) overlay, under a large variety of process conditions.

4 Alignment refers to superposition of a few (strategically-placed) marks on the mask and substrate, whereas overlay refers to superposition of the entire patterned area on the substrate and the mask. Good alignment does not necessarily ensure good overlay, however good overlay necessarily implies good alignment.

While through-the-lens (TTL) systems were widely used in the 80s and 90s, they were eventually phased out. Projection optics for excimer lasers were designed to operate optimally with sub-pm wavelength spreads. This meant that TTL alignment systems, which shared this same optics, either had to operate at the exposure (actinic) wavelengths - which was non-ideal since resist layers are highly absorptive at the exposure wavelength [14] or operate at a different wavelength and have additional optics to correct for the inevitable chromatic aberrations. This made the design of both the alignment and exposure optics quite challenging. Eventually, this and other concerns ended up outweighing the benefits of TTL.

3 Photolithography Systems Utilizing Indirect-Referencing Overlay Metrology - 1990s and Onwards

All systems described until now used direct-referencing of mask and wafer to determine overlay. While these systems have obvious advantages in terms of accuracy of overlay measurement, they generally result in reduced throughput (in addition to the other concerns described previously) –

> “(1) Throughput is reduced because the required data acquisition of the wafer to reticle image marker measurement at every field cost extra time.
> (2) Marker placement connected to each field costs wafer surface in case of large markers, or accuracy in case of small markers.” [15]

Indirect-referencing systems were able to supplant direct-referencing systems, with the implementation of six-axis interferometric metrology (see Fig. 3) [15].

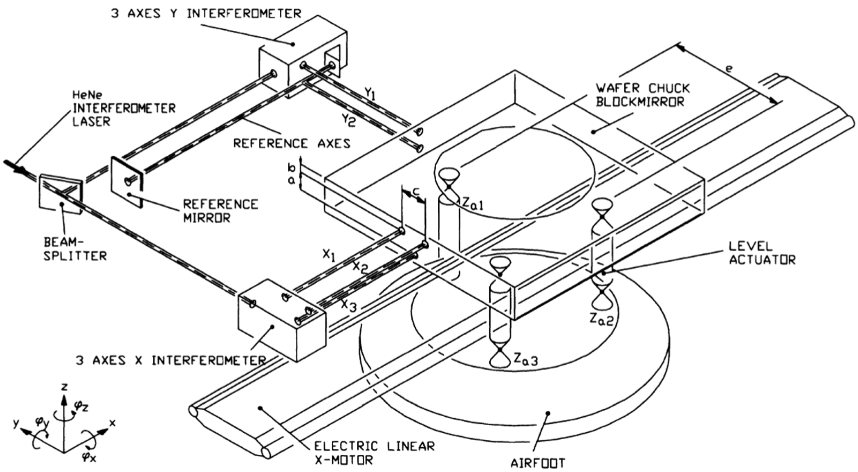


Fig. 3. Exemplar six-axis interferometric system described in van den Brink et al. (reprinted with permission from [15])

Since interferometers can only measure the position of mirrors mounted on the wafer chuck, and not the position of the wafer itself, prior versions which used reduced number of interferometer arms, either had to use stages that were extremely accurate in the theta axes, or were prone to abbe errors [16]. However, with six-axis interferometric metrology, along with thermally stable wafer chucks and mirrors made of ultra-low expansion materials, it became possible to outperform direct-referencing systems.

As lithography progressed from exposure at 365 nm, to 248 nm, to 193 nm, to 193 nm immersion, and then to immersion-lithography-with-multiple-patterning, the basic framework of 6-axis interferometric metrology remained largely unchanged[5]. The next evolutionary jump occurred with the development of grid-plate based stage metrology - to support the extremely tight overlay budgets required for litho-based multiple-pattering [4, 19][6]. Classical interferometers, with their long beam-arms, are susceptible to measurement errors due to refractive index variations in the air. Since, advanced photolithography systems have several sub-systems that do not function well in vacuum (advanced air-bearing stages, water immersion, convective temperature control systems, etc.), there is no easy way to get rid of air in the process chamber[7]. The interferometer measurement problem is further aggravated by the fact that the air is constantly being churned by the wafer stage, which moves at high speeds to maintain high throughput. Conventional interferometer metrology, in the presence of turbulent air, was found to be limited to $\sim$1 nm measurement errors. This was a problem, since the net overlay budget was $\sim$2.5 nm. Grid-plate metrology were adopted to solve this

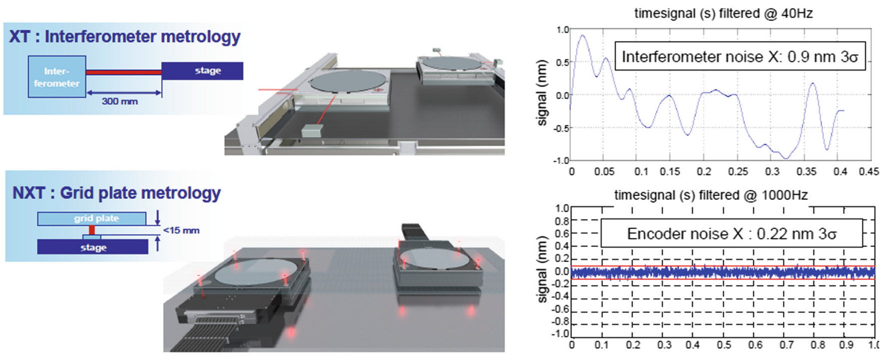


Fig. 4. Comparison between conventional interferometer metrology and grid-plate metrology (reprinted with permission from [4])

[5] Of course, each transition presented its own specific challenges, and auxiliary systems had to be added to supplement the basic 6-axis framework. In immersion lithography for instance, overlay error due to evaporative cooling of the immersion fluid was a significant challenge. Advanced design of the immersion nozzle [17], and active thermal control of the substrate [18], were used to improve overlay in immersion systems.

[6] For instance, litho-based double-patterning at 38 nm half-pitch and beyond, required overlay accuracy of $\sim$7% of the half-pitch.

[7] Some of these issues have eventually been addressed in the development of the EUV lithography system which operates in vacuum.

problem. By utilizing significantly shorter beam-paths in the vertical direction, grid-plate metrology essentially eliminated the issues associated with air turbulence. Details regarding the design of these can be found in Castenmiller et al. [4].

4 Overlay Control in Next - Generation Lithography - 2010 and Onwards

Photolithography, with numerous clever tricks, has been able to support scaling at the level of Moore' law for the last five decades. However, it has become increasingly difficult to support scaling beyond 22 nm half-pitch. Multiple patterning, although widely used, is expensive, requires complex processing steps [20], and is not well suited for non-periodic patterns. Next-generation lithography technologies are being explored to supplant conventional photolithography and continue transistor scaling. Some of these, such as Extreme Ultraviolet Lithography, are direct extensions of conventional photolithography, whereas others, such as directed self-assembly and nano-imprint lithography [22] use novel mechanisms for pattern creation. No one technique has yet emerged as successor to 193 nm immersion lithography, and challenges remain with all three of the primary contenders - EUV [21, 22], DSA [23] and NIL [22]. In this section, we will look at these emerging technologies through the lens of overlay.

1. **Overlay Control in Extreme Ultraviolet Lithography (EUV)**
   Unlike litho-based multiple-patterning, overlay no longer defines the CD of the most critical layers in EUV. Therefore, the overlay spec is relaxed compared to multiple-patterning [4], and existing overlay techniques can be used. For instance, the overlay required at $\sim$20 nm half-pitch using EUV is $\sim$4 nm (3σ), compared to $\sim$2 nm (3σ) using double-patterning. The primary challenge with maintaining overlay in EUV is compensating for the heating of the reticle, optics and substrate (essentially everything) in the EUV beam path. For instance, EUV masks are generally made to be reflective to reduce light absorption and must be planarized to a high degree to prevent image distortions [24].
2. **Overlay Control in Directed Self-Assembly (DSA)**
   DSA is primarily envisaged as a pattern multiplication technique at advanced device layers. As a bottom-up approach to patterning, DSA, in and of itself, doesn't really permit much in the way of overlay control. Overlay in DSA is primarily driven by the overlay of the directing top-down patterns.
3. **Overlay Control in Nano Imprint Lithography (NIL)**
   Nanoimprint lithography [25] is essentially a micro-molding technique for the resist. It involves a template which has patterns physically etched into it. This template presses down onto a liquid resist, which takes the shape of the patterns in the template. The resist is then cured, using UV light or heat. The template is subsequently removed, and the resist pattern can be transferred into the wafer using conventional etch processes. Early NIL systems used a combination of heat and pressure to cure a thermoplastic material, which precluded nano-precision alignment in these systems. Jet-and-Flash Lithography (J-FIL), which is a form of NIL,

uses room temperature curing of programmably-dispensed low-viscosity resists [26] (Fig. 5). It is inherently suited to the problem of nano-precision overlay, and in recent times, has been able to achieve excellent overlay performance. In the subsequent paragraphs, we will discuss these developments in some detail.

Fig. 5. Outline of the steps in Jet-and-Flash Imprint Lithography [22]

Overlay systems for J-FIL have been designed with two key characteristics of the process in mind -

1. Unlike projection lithography, there are no intermediate lenses in J-FIL to morph the template patterns. To correct overlay errors in J-FIL, the template and substrate themselves have to be morphed. This forms the basis for the magnification and scale control system [27] (Fig. 6), and of thermal actuation-based [28–30] overlay correction in J-FIL.
2. Since the template makes physical contact with the imprint resist during pattern transfer, at the nanoscale both template and wafer can move in relation to their respective chucks. Thus, only direct-referencing based overlay metrology can be used in J-FIL. Current J-FIL systems use an interferometric spatial-phase imaging system [22] (Fig. 7).

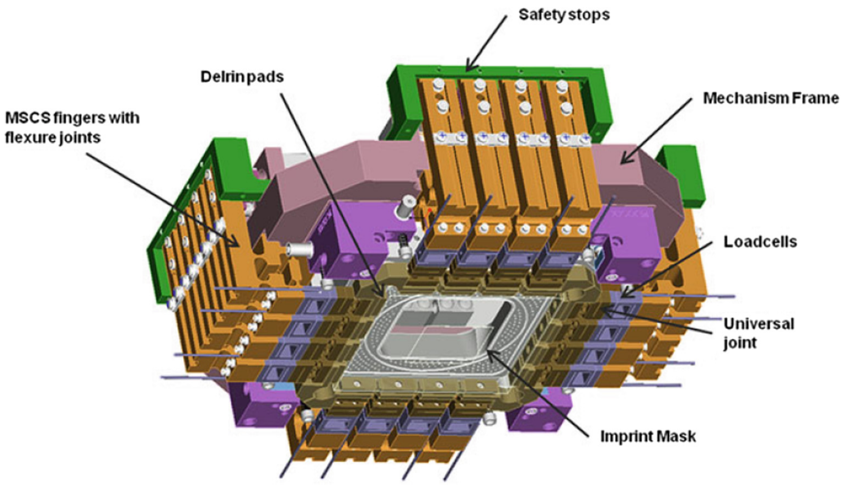


Fig. 6. Isometric view of the magnification and scale control system. The imprint mask is shown in the middle, with 16 surrounding fingers which deform the mask in a controlled manner. (reprinted with permission from [27])

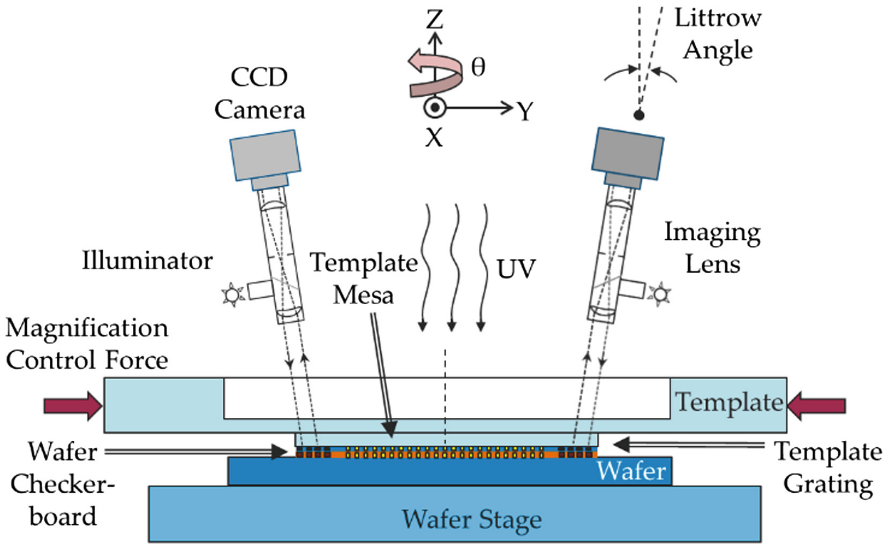
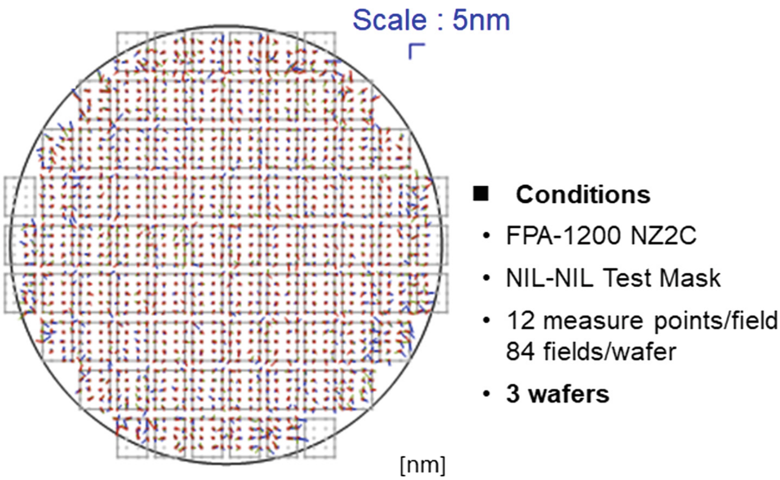


Fig. 7. Schematic showing the Interferometric Moiré Alignment Technology (I-MAT)



SMO	X	Y
Ave.+3σ	2.2	2.4

Fig. 8. Single machine overlay (SMO) based on an FPA-1200 NZ2C imprint system. SMO of better than 2.5 nm (mean +3σ) was achieved in both x and y directions [31]

In the process sequence shown in Fig. 4, overlay correction is performed from Step 2 through Step 4. As the template is brought close to the substrate, coarse alignment is first done. Once the template has been brought in contact with the liquid resist, in-liquid alignment using the magnification and control system is performed.

The most recent results have demonstrated that, using the methods described above, overlay performance of better than 2.5 nm (mean + 3σ) can be achieved in both x and y directions, see Fig. 8 [31].

5 Conclusion

Improvement in lithographic overlay has gone hand-in-hand with patterning resolution to enable Moore's law scaling over the last 50 years. In this article, the evolution of overlay control in semiconductor lithography has been discussed. Beginning with simple manual alignment systems for contact printing, overlay control in photolithography has evolved into intricate grid-plate metrology systems. Next-generation lithography technologies like J-FIL have brought their own novel constraints into the picture and have led to the development of novel systems like the magnification and scale control system. As feature sizes shrink further and lithography becomes more sophisticated, improvements in overlay control will not only remain an integral part of semiconductor lithography, but will likely be even more important in advanced nanofabrication for semiconductor fabrication.

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Interoperability in Coordinate Metrology

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Abstract. Coordinate metrology is an essential part of a product life-cycle management, since it guarantees the quality of component used in industrial processes. Nevertheless, nowadays industry environment is complex and full of players, which are correlated or even dependent one to another. Manufacturers use hardware and software to support their industrial process; these assets are provided by different companies, specialized in each specific segment, so there is the need to manage the communication between them. Usually, Coordinate Measurement Machines (CMM), together with their related metrology software and CAD/CAM/CAE/CAIP (Computer-Aided Design, Computer-Aided Manufacturing, Computer-Aided Engineering, Computer-Aided Inspection Planning) software, are developed by different companies. Moreover, the urge to integrate data into a Product Life-cycle Management (PLM) system is increasing; it allows to have a comprehensive control on the product, improve performances and develop strategies. Starting from these necessities, interoperability becomes a topic of interest and important point of arrival in manufacturing; specifically, the focus of this paper is on interoperability Issues in coordinate metrology.

1 Introduction

The dimensional and geometrical measurement process is not just analyzing the dimensions and tolerances of manufactured components. The product design specification must be considered in planning the measurement process; the measurement process must be carried out to obtain appropriate measurement data; the measurement data must be analyzed, and the related results reported in order to accept or reject the component and provide feedback to the manufacturing process behind. In mechanical industry, dimensional metrology data are closely tied to a company's product quality and to its performance assessment efforts; this information has to be easily shared with production scheduling, design, purchasing, and the other manufacturing company functions. Many software applications, including those incorporated in machine tools, support these processes, but the entire measuring system is most effective if software applications are seamlessly integrated together with the information interfaces. Indeed, in an ideal situation, a manufacturer should be able to acquire and store any type of measurement information in the same format, regardless of the type of equipment used to acquire it.

Dimensional metrology interoperability is defined as "*the ability of two system components to communicate correctly and completely with each other with minimal*

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cost to either component user or component vendor, where the two components can come from any vendor worldwide" [26, 27]. Component-to-component interoperability using open standards reduces training costs, allows best-in-class component choices and provides a more innovative and competitive technology provider environment. The main challenge to achieve dimensional metrology interoperability is the specification of a minimum set of information exchange standards to cover the information exchanges required that will also enable integration for the full range of software applications available.

1.1 Elements of a Dimensional Metrology System

For a better understanding of the interoperability issue in dimensional metrology, it is important to comprehend the main elements of a typical dimensional metrology system. The process can be divided into four major interacting elements: product definition, measurement process planning, measurement process execution, and analysis and reporting of quality data.

Product definition is the process in which a part is designed using CAD software based on customer requirements. In this step, all relevant information must be indicated to permit the generation of a downstream measurement process; such information must include part geometry, features, tolerances, and part characteristics such as surface finish, reflectance, and material properties. Subsequently, the measurement process planning activity produces the inspection plan to measure the part so that its functionality is ensured. Then, the measurement process execution is carried out; this step can be complicated, since it must support not only the huge number of different types of measurement equipments, but also an almost limitless number of ways in which the inspection of a part component can be conducted. Corrective actions may be required on the measurement process plan upstream in order to make the plan executable on the chosen measurement equipment; for example, there may be the need for a translation of the measurement process plan into some format compatible with the available equipment. Following this phase, there is the analysis and reporting activity. Its most important functions are receiving input from measurement process execution and product definition activities, to analyze the data in terms of product requirements, to perform a statistical analysis of the results, present them in a report, and archive it.

Each of these four activities can be broken down into sub-activities; some of them involve only software modules, and some involve both software modules and dimensional measuring equipment hardware. The information communicated between these software modules is where the interoperability is achieved or not. It is a matter of the assumed syntax and semantics of the information passed from one sub-activity to another. In today manufacturing systems, a comprehensive software is the combination of several modules. The production definition software includes a CAD software module, allowing definition of part geometry and associated GPS/GD&T; the measurement process definition software includes solid modeling, inspection planning, and inspection programming modules; the measurement process execution software includes math computing, inspection instruction execution and probe instruction execution modules; the report and analysis software includes solid modeling, math computing, and reporting and analysis modules. For interoperable dimensional metrology, clear and unambiguous metrology information is needed to flow across each of these interfaces. This is best achieved through the definition and worldwide implementation of information interface standards.

1.2 Interoperability Issues

Interoperability issues exist within each of the four pillars of a dimensional metrology system and are going to be discussed. In the product definition section, the part must be decomposed into geometric features to support automatic dimensional metrology plan generation. Then, dimensions and tolerances must be assigned to a geometric feature or set of features; datum features must be defined adequately for both manufacturing and inspection. Product Manufacturing Information (PMI) must be included in the model. All this information must be defined completely and accurately in a CAD data model.

The existing issues in the product definition activity are summarized as follows:

1. CAD data including GPS/GD&T information does not flow seamlessly to downstream processes when components are not from the same vendor.
2. GPS/GD&T data not semantically associated with individual feature in the CAD model makes impossible to automate inspection process plan generation.
3. There are divergences in the interpretation of ISO GPS and ASME GD&T standards.
4. There is no CAD product implementation of PMI information using non-proprietary standards.

However, ISO develops exchange standards, and among them ISO 10303, informally known as STEP, "Standard for the Exchange of Product model data". Its AP242 [19] merges two most widely used STEP standards: AP203 [17] ("Configuration Controlled 3D Design") and AP214 [16] ("Core data for automotive mechanical design processes"). It allows interoperability of PMI in both graphic and semantic representation. PMI graphic representation captures the information displayed by breaking down the annotations and symbols into basic geometry; this approach is the only one independent from representation, and it is not machine-interpretable. PMI semantic representation describes the exchange of reusable, associative PMI in a STEP file. This information is by itself not visible in the 3D model, but a CAD system importing this file can use the representation data to re-create the visible PMI. The representation approach also aims at passing PMI data on to downstream applications, such as CAM. Representation, simply stated, is machine-readable/interpretable.

The generation of measurement process plans is closely related to machining planning. Process planning for both machining and inspection can be generally divided into macro planning and micro planning. In the macro planning, decision about what to measure and when to measure are taken based on the choices of machine tools and assigned manufacturing tolerances; in the micro process planning, detailed machine tools commands, inspection commands, motion commands, reporting and analysis commands are generated and passed onto a vast diversity of measurement equipment. Most of the measurement process plan generation is expected to provide device-dependent support for the myriad of inspection devices available for process execution. It is impossible for medium and large manufacturing companies to employ only one type of inspection device. The top interoperability issues in the industry are the following:

1. The lack of comprehensive non-shape information available from the product definition activity.
2. The lack of a standard data model able to represent semantic GPS/GD&T and PMI with CAD geometry model.
3. The lack of an extensible interface standard that can catch and exchange measurement process planning knowledge and the associated norms.

DMIS (Dimensional Measuring Interface Standard) [18] is the only standard that defines measurement instruction data within the measurement process definition activity. It is a language for controlling measuring equipment that includes an input and an output language. Part of the DMIS input language defines feature, tolerances, sensors, etc.; the output language serves both as a log of action commands and settings and a report of results, with actual and nominal point data, features, and tolerances. However, it does not define complete measuring equipment resources, which are necessary for the effectiveness of DMIS. CMM machine type and configurations are defined in ISO 10360-1 [12]. A standard data model in compliance with these standards needs to be developed and validated so that industry can develop implementations in software modules.

Once a measurement plan is generated, it must be properly run through the measurement execution process. The most important functions of this step include acceptance of input from the measurement process plan and usage of the input to provide clear instructions to a great number and type of measurement equipment. However, interoperability here is hindered once again by the lack of standardization; the need for interoperable software products that execute the manufacturing and measurement process in a highly automated and equipment-independent way is crucial to the enterprise survival. Especially in large corporations, a single-vendor solution is impractical when not impossible; even at the job-shop level, it can restrict the ability to choose best-in-class equipment for a particular application or it may require redundant training on a new software. Nevertheless, standardization for the detailed equipment commands is still missing. There are two publicly available specifications: DMIS Part 2 and I++DME [9] Interface Specification. The former has not known implementations, the latter is not yet ubiquitous for either CMM software or CMM systems.

Lastly, measurement data analysis and reporting systems are responsible for gathering results, analyzing workpiece inspection data, realizing statistical reports and proposing process improvements. The main interoperability issues are due to the lack of definition of how measurement results and statistics can be used to improve the manufacturing process, the lack of a uniform model for traceability, and the lack of a standard format for measurement data and single part report. DML was developed to store and standardize measurement result data and had moderate usage mainly in North America; however, several problems have been found by industrial users and further development and consolidation is needed. A format for CMM measurement result is defined within DMIS, and has benefited from some usage, wherever DMIS is used. STEP AP219 [14] was defined to cover all important metrology information, including measurement results; it has too limited definitions, though. A harmonization among the three mentioned standards is essential for a standardized measurement data format.

Figure 1 shows the current state of interoperability in dimensional metrology, with its flows and obstacles. There is in particular one interoperability issue which has an adverse effect on every aspect of the dimensional metrology process: GPS/GD&T and PMI information are still not properly associated to CAD data. When components come from different vendors, it represents an obstacle to the seamless flow of GPS/GD&T and PMI information to the downstream processes. To overcome the problem, vendors, end users, and standardization organizations must work together to fix political and cultural issues first. End users have the power to play a leading role in the matter by demanding standards-based hardware and software. On the other side, standardization organizations need to gather sufficient information from major dimensional metrology vendors to establish their business and organizational objectives. In the end, vendors need to realize the possibility of economic incentive to offer standard-based products; the more progressive vendors try to get in on the ground floor of new developments in these areas so that they are ahead of their competitor.

The benefits of standardization can be summarized as follows:

- Elimination of time, costs, and resources involved in data integration tasks.
- Redirection of savings to value-added activities, enhancements, etc. Also, solution providers and metrology manufacturers can redirect more energy to new developments.
- Communication between metrology solution and other solutions, making both more useful.
- More focus on core business on the manufacturers' side.
- Independence from proprietary schemas that require separate technical support.

Although benefits are clear, companies also need the political will to work with others and consider the larger picture. There is no direct participation by vendors, who wait to see if a given standard will reach critical mass and establish some level of adoption. Standards exist, but value is provided by its usage. Figure 3 represents a future vision of dimensional metrology systems.

2 Product Life-Cycle Management

Product Life-cycle Management (PLM) is an information management system that can integrate data, processes, business systems and people in an extended enterprise. A PLM software allows to manage information throughout the entire life-cycle of a product efficiently and cost-effectively from conception, design and manufacture through service and disposal. Thus, the PLM is a management model based on informatics solutions that support the collaborative creation, form the management, to the diffusion and the usage of the overall knowledge associated to a product, with the objective of better managing product-related data and information that, without a PLM solution, cannot be efficiently exploited during the entire product life-cycle because they are not easily recoverable or are lost in the overall process. A PLM is considered an enabling technology for Industry 4.0 and the Smart Factory, because of the more

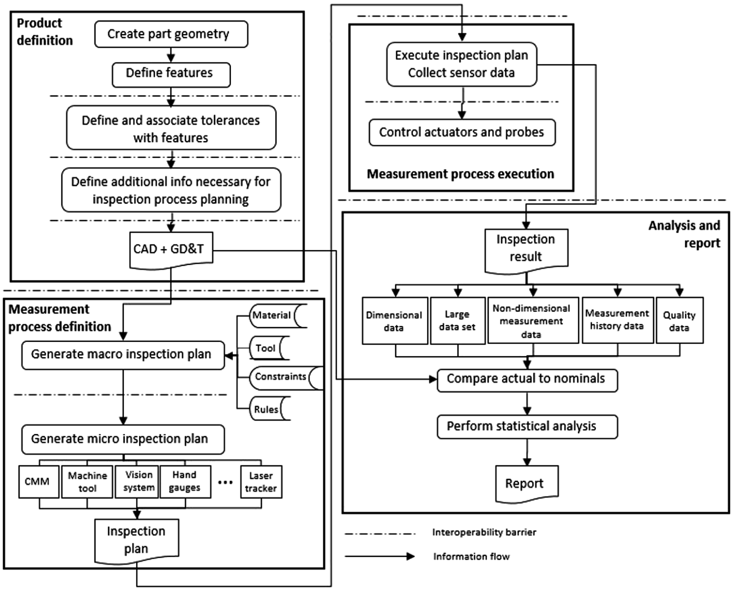

Fig. 1. Current state of interoperability in coordinate metrology

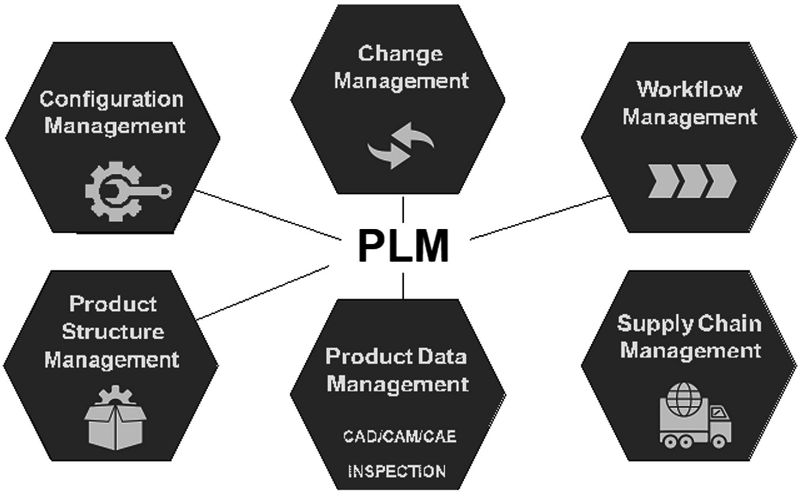

Fig. 2. PLM breakdown into its modules

transparent collaboration allowed and the unique access to data and documents for all company departments.

A PLM is composed by different modules which contribute and collaborate to the product development. Usually they can be categorized as in Fig. 2. The implementation

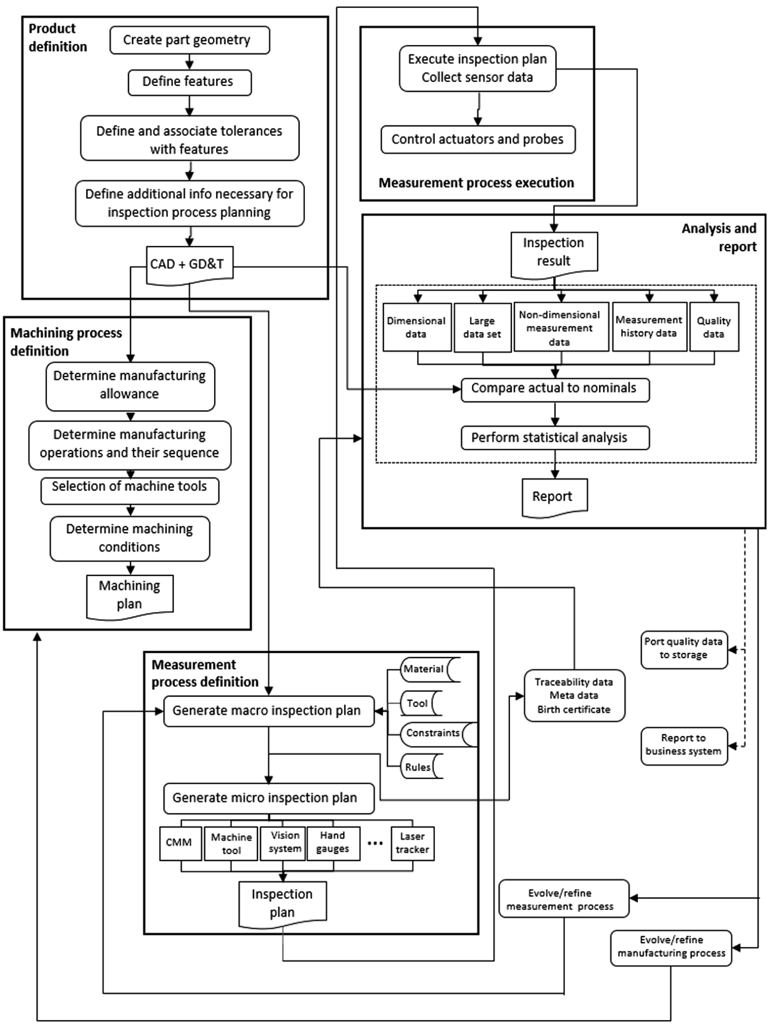

Fig. 3. Future vision of dimensional metrology systems

of one or more modules in a PLM system depends on the integration degree that the company wants the productive process has.

2.1 Product Data Management in Dimensional Metrology

The main idea behind PDM (Product Data Management) is to link all product-related information to the product itself. Nevertheless, in many companies, not all documents are integrated in the product data management, remaining therefore independent and disconnected without converging with the others. In the area of dimensional metrology, the PDM information is of most interest. It is within this pillar of the PLM system that product nominal and tolerance information is kept. The company product knowledge is contained mainly in its CAD models and relative documents and data. Inside drawings all specifications of a product are included. Some of them, if not respected, have a great impact on the final product quality and functionality. Due to their critical nature, they are the ones to focus on during design and manufacturing. Just one unique label should be assigned to each of these characteristics, so to be traced and marked during the production process.

Closing the gap between product definition and actual manufacturing activities within the enterprise is one of the key priorities in digital manufacturing. As a result, all specifications and related variation information flow must propagate from design to production and be implemented using closed-loop and bidirectional relationships. Historically, production data have not been collected and fed back to up-stream phases. Measurement and metrology information and knowledge (e.g. dimension and error data, process capability data, process FMEA knowledge) need to be integrated with product and process design, particularly in assembly design.

This idea of integration is what stands at the basis of the PLM software, even if in a broader perspective: the concept is that if all product related data are stored in a unique PLM data base where all information are always updated and coherent internally and among different functions, the company should gain in efficiency and productivity while breaking intra-function barriers (as the one between engineering and production), and avoiding functional information misalignment and data repetitions. Information is no longer synchronized, but basically all units work on the same data, whose modifications are immediately visible to every other part of the company.

The creation of a PLM comprehensive data model to represent product life-cycle information is complex due to the heterogeneity of entities integrated inside the PLM: people, data, process, knowledge and systems together.

2.2 Product and Manufacturing Information

The PDM module includes different sub-modules among which CAD (Computer-aided Design) and inspection are the core of dimensional metrology.

A CAD file is the 3D model of the part to be produced. It substitutes the 2D drawings, even though, in the recent past, the latter were often still included in the documentation because needed for data set utilization. 2D drawings had been used as a mean of defining a finished product through a standard symbolism that could be therefore universally interpreted. In the past, the manufacturing process needed both 2D information, contained in the 2D drawings, and the 3D form. Therefore, 2D drawings were the downstream communication channel for production requirements. In such an environment of 3D part decoupled by its related information, in 2D drawings, required information were multiple and duplication and interpretations errors, together with revision inconsistencies, could lead to costly mistakes that quickly translated into lower productivity and quality. Moreover, this working approach slowed the product developing cycle: a simple change in the product definition not only required updated 3D digital data, but also necessitated numerous engineering changes to all 2D documentation associated with the product. This way the lead time for implementing a product change grew with the extent of its associated data.

When the concept of Product and Manufacturing Information came up, the need of 2D drawings was removed. Product and Manufacturing Information (PMI), is any attribute embedded in 3D CAD files and Collaborative Product Development systems, necessary for manufacturing product components and assemblies. PMI annotations are created on the 3D CAD model, associated to geometric features (edges and faces). This information can be used by a number of downstream processes, extending the digital thread past production all the way through inspection; as outlined by ASME Digital Product Definition Data Practices, the manufacturing industry as a whole is moving towards a standardized approach to automating and digitizing the process of taking a product from design to production. The increasing adoption of digital manufacturing technologies and more powerful software will lead to a greater need for Model-based Definition (MBD) and strengthen the link between design, production and inspection.

2.2.1 PMI Classification

The typology of a PMI is determined by the information type it contains, thus, PMI can be of a very different nature:

- Text comments: usually clarifying notes for the author himself or for facilitating the understanding, or simply for communicating something to the manufacturer.
- Material definition: definition the characteristics of the material that should be used.
- Surface finish: definition of the nature of a surface.
- Geometric tolerances: allowance for a specific variation of the geometry of the part.
- Dimensional tolerances: allowance for a specific variation of the size of the part.

2.2.2 PMI Benefits

In order to fully appreciate the perks of PMI, just consider that a simple dimensional or GD&T error can cost a company thousand or even hundreds of thousands of dollars if incorrect parts are produced. Recent studies found that companies using PMI and MBD spent significantly less time on engineering documentation each week, had fewer emergencies each month, and had fewer cases of parts not properly fitting together each month (Lifecycle Insights study on Quantifying the Value of Model Based Definitions).

- Enables product teams to incorporate product and process information during the design phase: design cycle shortens, there are better communications, fewer errors, streamlined design/manufacturing processes and faster change management.
- Removes Drawings from the supplier communication chain and replaces with persistent, associated 3D product data that can be deployed across multiple life-cycle processes and used anywhere.
- Reduces cost by ensuring that design intent is completely captured and associated to the model.
- Reduces rework associated with inaccurate or incomplete manufacturing information.
- Reduces manufacturing errors caused by manual translations and enforces "characteristic accountability" for the final product definition.

- Increases productivity and quality by documenting the information once and reusing it everywhere, with no more need for redundant data for downstream applications.
- Supports concurrent engineering by facilitating the documentation of models earlier in the design process.

2.2.3 PMI and Inspection

From the discussion in the first part of this chapter, is quite clear the importance that PMI covers in the manufacturing fields, since it links the product design directly to producers' requirements, avoiding inefficiencies and mistakes.

Nevertheless, they can change also the dimensional measurement process. Before PMI, quality control was done starting from the design specifications on 2D drawings. But since PMI are attributes of the 3D model features, the part program can be generated directly from the CAD, where all information needed are stored already. Therefore, what is obtained is a tolerances-based inspection, where the machine measures only model features a tolerance PMI is associated to.

Moreover, quality control usually was a way to verify that the realized part was compliant with the design specifications. With the introduction of PMI concept, also the inspection acquires a more integrated meaning: since a PMI is not linked just to the design but also to the manufacturing fields, the conformance or not conformance stated by the inspection program has a broader character: the quality assessed is more credible because it is not related only to what was designed, but, coming from PMI, it is the quality measure of different integrated processes.

3 Standard Languages

In the last years, information technology is playing a more and more fundamental role in the manufacturing enterprise. Effective information sharing and exchange are a critical issue in product life cycle management, and, in particular, for interoperable dimensional metrology, clear and unequivocal metrology information needs to flow across all the process steps. Formal information modeling languages that unambiguously outline information requirements together with unambiguous specifications for modeled data enable the development and integration of a networked and consistent computer environment.

Information modeling is a technique for specifying the data requirements that are needed within the application domain: it is a representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse.

There are different methods for developing an information model: the entity-relationship (ER) approach, the functional modeling approach, and the object-oriented (O-O) approach. The ER approach deals with the application of the concepts of entities and relationship in describing information requirements; its basic constructs are the entity type, the relationship type and the attribute type, and it uses a graphical notation technique. The focus of functional modeling technique is specifying and decomposing system functionalities, by representing the flow of information from one process to another with data-flow diagrams. Lastly, the O-O approach identifies in blocks objects from the application domain, and then operations and functions; it provides easier modeling of complex objects, better extensibility and easier integrability of O-O database models and O-O programming code. Each information model has a specific emphasis that represents the viewpoint of the organization; choosing the appropriate methodology is a decision that must be taken at the beginning of the modeling work. A good-quality information model should be complete, sharable, stable, extensible, well-structured, precise, and unambiguous; its main contents are scope, information requirements, and a specification.

Information modeling needs a formal syntax able to capture data semantics and constraints: this is what an information modeling language does. Some of the most commonly used are UML, IDEF1X, EXPRESS and XML Schema.

UML [6] specifies, visualizes, constructs and documents the artifacts, rather than processes or software systems. It is a graphical application based on the object-oriented paradigm. UML organizes a model in a number of views for different aspects of a system; the contents are described in diagrams.

IDEF1X [21] is an extended version of IDEF (Integration Definition for information modeling). It was developed for designing relational databases with a syntax intended to support the semantic constructs necessary in developing a conceptual schema. It is most useful for logical database design after the information requirements are known and the decision to implement a relational database has been taken. EXPRESS is created as ISO 10303-11 [13] for formally specifying the information requirements of a product data model. The language is part of a suite of standards known as STEP (Standard for the Exchange of Product model data). EXPRESS is a textual representation and it has also a graphical representation available, EXPRESS-G. It is based on several programming languages (Ada, Algol, C, C++, Euler, Modula-2, Pascal, SQL) and on the O-O approach. It is designed as a language for communicating information concerning data; it consists of language elements that allow an unambiguous object definition and specification of constraints on the defined object. EXPRESS maintains separate information modeling task with programming or database design tasks, and it is not specific for a system.

XML [2] schemas serve as design tools establishing a structure where implementations can be built. It can be used to express the set of rules to which an XML document must conform to be considered valid according to that schema.

There are multiple standards and specifications for each element of dimensional metrology system. Different information modeling languages are also chosen for different standards, which may also include interoperability issues.

3.1 Product Data Models and Standards

For the product definition process, end-users can choose from a wide variety of CAD vendors. Each type requires a different mindset for the customer to use it and to design virtual components. Moreover, each of the commercial CAD systems has its own proprietary data format, hampering the data exchange between different CAD software systems. This imposes one of the key-interoperability issues among computer-integrated manufacturing systems.

STEP is developed by ISO Technical Committee as ISO 10303 [10] and it is intended to support data exchange, data sharing and data archiving. For data exchange, STEP defines the form of product data to be transferred between two applications; each application holds its own copy in the preferred form. The data conforming to STEP is transitory and defined only with the aim of exchange. STEP supports data sharing by providing access to a single copy of the same product data by more than one application, potentially at the same time. The structural elements of STEP may be used to support the development of the archived product data itself: archiving requires that the data to be exchanged is kept for use at some other time. Another essential concept for the STEP architecture is that the content of the standard is to be completely driven by industrial requirements.

STEP consists of many integrated resources, application protocols and parts. Before discussing design data modeling in STEP application protocols, an overview of STEP architecture is given.

1. Components of STEP: decomposition of the standard into several series of parts, which contains one or more type of ISO 10303 parts.
2. Description methods: common mechanism for specifying the data constructs of STEP. They include the formal data specification language developed for STEP, EXPRESS.
3. Implementation methods: standard implementation techniques for the information structures specified by application protocols. Each of them specifies how descripted data constructs are mapped to that implementation method.
4. Conformance testing.
5. Data specification.
6. A STEP file.

Application protocols are the implementable data specifications of STEP. AP 203, AP 214 and AP 242 will be described in their functions and scopes [16, 17, 19].

STEP Application Protocol 203 (Configuration Controlled 3D Designs of Mechanical Parts and Assemblies) provides the data structures for the exchange of configuration-controlled 3D design of mechanical parts and assemblies. AP 203 edition 1 has quite complete definitions of product design information; however, it does not provide semantic association between GD&T and design geometry, requirement fulfilled by edition 2.

STEP Application Protocol 214 was developed for the exchange of information between the application that supports the development process of the mechanical aspects of automated vehicles. In addition to AP 203, it offers information for process plan and configuration control, references, kinematic structures, tolerance data and data related to the documentation of design change process, approval, security, classification. However, it did not receive main acceptance among CAD vendors.

STEP Application Protocol 242 (“Managed Model Based 3D Engineering”) is a convergent AP from AP 203 and AP 214, especially motivated by the needs of long-term archiving of CAD data. Its strength is the completion to PMI, allowing the definition and exchange of “machine-readable” representation of tolerances. AP 242 strengthens manufacturing acceptance and support by establishing a single universal brand and introduces new capabilities common to many industry sectors, such as tessellation (allowing STEP to efficiently support a light visualization) composite structures, domain of PDM, product data quality and mechatronics.

4 Computer-Aided Inspection Planning

Measurement process planning, here defined also as CAIP (Computer-Aided Inspection Planning) [5, 8, 22, 23, 25], is an integral part of the design and manufacturing activities: it defines what characteristics of a product are to be inspected, where and when. The overall CAIP activity is normally divided into high-level and low-level process planning. High-level process planning describes the measurement scope, a dimensional measurement equipment (DME) list, a sequence of high-level measurement operations, that includes the accessibility of features to be inspected, the probes and the orientation of the part. On the other hand, the low-level process planning activity decides the number of measurement points, their allocation, measurement paths, and addresses the generation of an executable code. The efforts towards interoperability studied in this work are addressed to inspection operations performed on CMMs.

The low-level process plan activity is closely associated with the chosen measurement devices; hence, there is a significant overlap between low-level measurement process planning and measurement execution activities. Even though CMMs are quite flexible, sometimes the measurement devices offer limited low-level measurement process plan capabilities. It is the exchange of information on high-level that is opposing the interoperability barrier.

4.1 High-Level Dimensional Metrology Process Planning

Standard organizations are aware of interoperability issues and have made several efforts in developing a suitable data model for the exchange of high-level measurement process plans. These data models include HIPP data model for AP 238 and the QMP model data.

Dimensional measurement information is defined in AP 238 [15], also known as STEP-NC, since it is the application of STEP methods to Numerical Control machines. Tolerance data are formalized in the Geometric and Dimensional Tolerancing (GD&T) model developed for AP 203 and AP 214: this allows an application program to pass the data from a feature, to the faces in that feature, to the design tolerances on those faces, to the datum defining tolerances, to the plane defining datum, etc. Nonetheless, the incompleteness of the inspection-based data model and the need to harmonize STEP-NC with some specification like DMIS and I+DME were recognized. NIST (National Institute of Standards and Technology) developed a new AP 238 ARM model for the High-level Inspection Process Planning (HIPP). ARM stands for Application Reference Model and it is a model of the data needed for a particular application. AP 238 ARM combined the information requirement models for machining defined by previous standards and was also upgraded with product data management information necessary to align the inspection feature descriptions with the STEP manufacturing application protocols and link to data. The objectives of HIPP data model include:

- Standard means of transmitting high-level metrology objectives from one part to another (e.g. from automotive manufacturer to a supplier).
- Standard means of embodying a detailed high-level metrology process plan that can be translated into a machine in a language like DMIS or can be executed directly by a smart machine controller.
- Executable model suited to the machining models so that it is feasible to write process plans that include both machining and dimensional measurement on the same machine.

HIPP brought a harmonized dimensional measurement feature definition from major dimensional metrology data models, even if dimensional measurements features are half associative in the HIPP data model: associativity to manufacturing features should be added.

DMSC (Dimensional Metrology Standards Consortium) introduced a Quality Information Framework (QIF) [3] to develop a set of four standards to address the major aspects of manufacturing quality systems: Quality Measurement Plan (QMP), Measurement Resource Information (MRI), Measurement Execution Program (MEP), and Quality Measurement Results (QMR). The QIF project is intended to develop a common vocabulary and data definitions for the entire set of quality management systems. It captures the natural structure of information flow related to part geometry: from the initial description and supplemental information all the way to the statistical analysis of inspection results for multiple workpieces. At each step along the way, the necessary information is captured in a standard format, allowing flexibility in choosing tools for the next step. The standard format is defined using XML. In detail, the scope of QMP is defined as "the pre-requisite for the science-based downstream generation and execution of integrated measurement processes and for the fullest utilization of acquired measurement data". Its purposes are:

- Consolidate existing standard and specifications related to the quality measurement process planning activity.
- Define the unique facets of QMP within QIF.
- Ensure the flexibility and scalability of the QMP data model to support additional data genres.

To sum up, these standard efforts have made relevant achievements in defining core information for high-level measurement plan. Some information is fairly exhaustive, such as dimensional measurement feature definitions and GPS/GD&T definitions, even if the most pressing issues include developing non-proprietary data formats for CAD + PMI data downstream to inspection process planning and adequate data model to include quality requirements from the production point of view. QIF process is an effort in this direction, with the purpose of consolidating the standardization work and develop a neutral data library for the aspects of quality measurement systems, included the data model for high-level measurement plans.

4.2 Low-Level Dimensional Metrology Process Planning and Execution

The interoperability issue in low-level dimensional process plan creation and execution becomes relevant in large enterprise-level corporations, where a single-vendor solution is unfeasible. An equipment-independent data format for representing both high and low-level measurement processes is necessary and critical for big corporations; nonetheless, there is not such standardization in the industry.

Low-level dimensional process plans are embedded in programs that can be executed by the controller of a CMM. There is only one standard language for such programs: Dimensional Measuring Interface Standard (DMIS). The semantics of the standard and the syntax for programs are given in DMIS Part 1, whereas Part 2 puts the semantics of Part 1 into a collection of objects interfaces that provides interoperability between DMIS client applications, a DMIS server, a DMIS mathematics module and a DMIS equipment module. There are distinct interfaces between CAD/CAM/CAE software that define the program and the metrology software that controls the machine, and between the latter and the machine itself. The two software systems are generally built by different companies and run on different computers. Their interface usually consists of dynamically generated messages that are sent back and forth over a communication system, through DMIS. The interface between the metrology software and the CMM is the I++DME Interface Specification. This last interface can also directly connect CAD/CAM/CAE software with the machine.

There are great deals to be gained by using a standard messaging specification between a CMM program execution system and the equipment controller. If two different execution system run the same language, it may be possible to execute a given program on either one. This allows a CMM user with multiple CMMs to use the same program for different machines and gives to the CMM buyer flexibility in his choice. Moreover, if a standard is used, different execution systems can be plugged in the same CMM hardware, and different hardware can be controlled by the same execution system.

An overview of DMIS and I++DME Interface Specification is given below.

DMIS is a large statement-based language. The DMIS specification actually describes both a language for writing executable programs and a language for writing output reports about what was done during the execution and the related results. The programming language will be outlined in this section, whereas the output language will be addressed in the next one, talking about quality data analysis and reporting.

The specification for DMIS programming language divides statements into 18 types, compressed here into seven: program, geometry, metrology, equipment, motion, miscellaneous and output (covered in the section below).

Programs consist primarily of one-line statement, each of which tells the executing statement to do something; they can declare and use variables, may be constructed by combining several files, and are executed in the order in which they occur.

Geometries are treated as features, defined as ideal ("nominal") forms; once defined, a feature can be measured or constructed. All DMIS features represent points, curves or surfaces in three dimensions.

Metrology statements in DMIS provide tolerances, datums and coordinate systems, measurement uncertainty, simultaneous requirements and key characteristics.

The core of DMIS programming is a single-arm CMM. This includes articulated arm as well as cartesian machines. DMIS is developed for using a sensor that is a touch trigger probe or a scanning probe. Motion can be in free space or for measuring specific points or points along a scanning path. DMIS offers different modes to do this.

In order to solve the dimensional equipment interoperability problem, major European automakers supported the development of I++DME (I++ Dimensional Measuring Equipment Interface Specification). Its goal is to allow automakers, and any other manufacturers, to select the best software and equipment for their objectives and budgets and ensure that they work together seamlessly out of the box.

I++DME is a messaging protocol between measurement plan executors and measurement equipment. It uses TCP/IP sockets as the communication mechanism and defines a message set and a client-server architecture. Clients are measurement plan executors, and servers represent the equipment that carries out the measurements. For instance, a client could read DMIS measurement plans generated by an upstream application, interpret the DMIS statements, send I++DME messages to the measuring equipment, accumulate the measurement results that return as I++DME messages from the server, and give as output a DMIS or DML report. An I++DME test suite has also been developed by NIST to enable testing of conformance to the specification. Despite this, in a real implementation, I++DME files are not used. I++DME files are only used for testing purpose.

4.3 Quality Data Analysis and Reporting

The quality data analysis and reporting activity is a fundamental element of dimensional metrology. To face the essential need for quality management, the traditional reaction has been the creation of local quality measurement structures designed for users' specific needs: this prevented the accurate and clear flow of quality measurements information from each new data source: therefore, the need for a standard format emerged. The proposals are STEP AP 219, QMD, DML, and DMIS output data.

ISO 10303 AP 219 [14] specifies an application protocol for the exchange of information resulting from the inspection of solid parts: its focus is the analysis and reporting activity for dimensional inspection. It is the first and only standard trying to provide semantic associations between tolerances, measurement features, dimensional measurement results and analysis. It also connects the measurement process with features, later connected to other manufacturing information from different APs. Nevertheless, AP 219 is inadequate in providing complete definitions of dimensional measurement features, results and analysis methods, and its storing model is too complicated to see obvious advantages. Moreover, portions of AP 219 (primarily features, tolerance and datum definitions) overlap with DMIS, and harmonization is still missing.

QMD (Quality Measurements Data) XML [4] Schema intends to provide a data structure for the exchange of data between different applications that serve quality control efforts in the manufacturing industry. It describes a non-proprietary and open standard for variable, attribute and binary quality measurements. It does not define any process, but only the quality measurement export format.

DML (Dimensional Markup Language) [7] is an XML format definition conceived for the needs of dimensional results for discrete manufacturing. The goal of DML is to haul the results between applications that generate or use dimensional information. Compared to QMD, DML is able to carry more information on dimensional measurement resource, devices, cloud points and raw data. Nonetheless, features and tolerances defined in DML have not been fully validated and they overlap with those defined in DMIS and STEP AP 219; also, some of the information defined in DML overlaps with the one defined in QMD. Although DML is the first standard effort in standardizing dimensional measurement result data, several problems have been found by industrial users.

The DMIS output has several levels of control. One selects one or more destination types for the output and the language to use for it. The most important output is the results of the measurement: this applies specially to features and tolerances. In order to provide a standardized measurement data format, harmonization between DMIS, AP 219 and DML is essential.

5 Case Study

To understand the current industrial state of the interoperability in metrology, a case study has been analyzed involving commercial software packages. To avoid disclosure, the two packages considered will be referred to as "CAM software" (CAMSW) and "CMM software" (CMMSW).

The global idea of the process is to develop a part solid model together with its PMI on the CAMSW, pass the information to the CMMSW which can operate a CMM to perform the measurement, and then send back the measurement results to the CAMSW, so that they can be stored in the PLM system[1]. This return of the measurement information to the CAMSW is required by the lack of direct integration of the CMMSW into the PLM. Interoperability issues arise then in the transmission of the information from the CAMSW to the CMMSW and vice versa.

The aim of the study is to investigate which information can be shared by the software packages, using different data format for the transmission of the information. Different reference solid models have been considered to perform this test.

- The standard specimen defined in ISO 10791-7:1998 [11] for the test of machining centers (Fig. 4). This part has been considered for all those PMI typical of prismatic parts.
- An impeller blade (Fig. 5). This parts is representative of free form parts and their typical PMI.
- All the simple parts described as examples in ISO 1101 [20]. These simple parts have been considered to cover all the possible geometric tolerances from the same ISO 1101 standard, and to check the behavior of the software when in the simplest cases.

[1] It is worth noting that the CAMSW manufacturer declares that its software can operate a CMM directly, avoiding the interoperability issue. This scenario has not been analyzed.

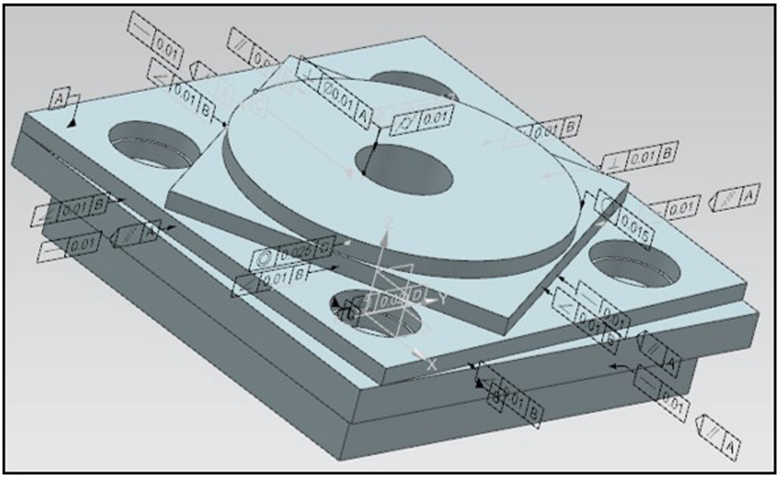

Fig. 4. ISO 10791-7:1998 standard part for machining center test, and its PMI in 3D annotation

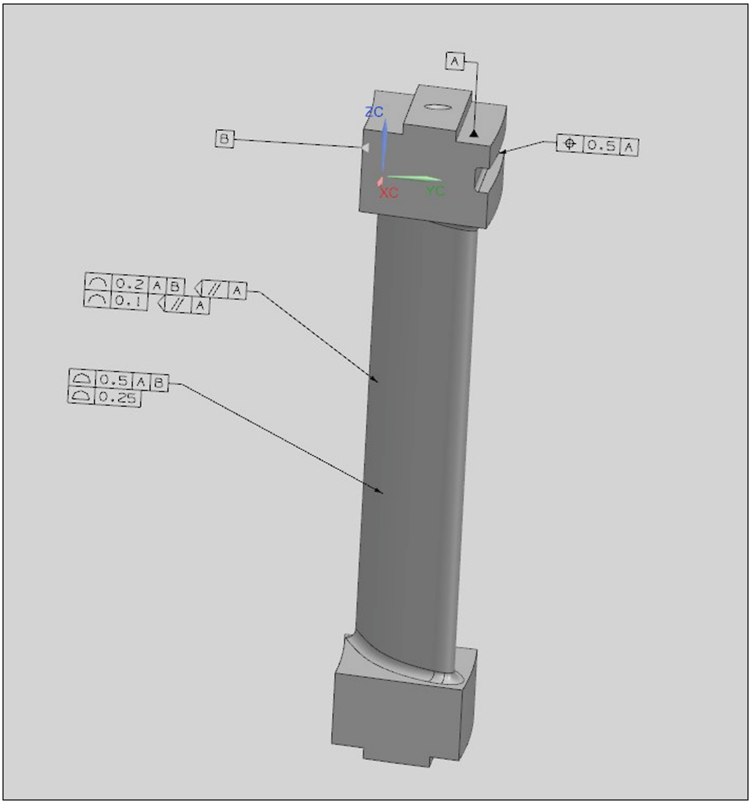

Fig. 5. An impeller blade, and its PMI in 3D annotation

5.1 From the CAMSW to the CMMSW

Both the CAMSW and the CMMSW can generate inspection plans (part programs) for CMMs. In the case of the CMMSW, as it is also the control software of the CMM, the inspection plan is immediately operated on the CMM itself. In the case of the CAMSW, the inspection plan must be exported as part program and then loaded by the CMMSW which can operate the CMM. This situation opens two possible scenarios.

5.1.1 First Scenario: The CMMSW Generates the Inspection Plan

This scenario is the most common in industry, as the vast experience of CMMSW software developers in measurement (who are often the CMM manufacturers as well) has made CMMSW specialized systems for inspection plan development, and most CMM operators are trained in the use of the CMMSW for developing the inspection plan.

In this scenario, the solid model together with the PMI is developed on the CAMSW, then it is exported in some file format, and loaded by the CMMSW, which can then generate the inspection plan (Fig. 6). The standard file format for the transmission of the solid model plus PMI is the STEP AP 242.

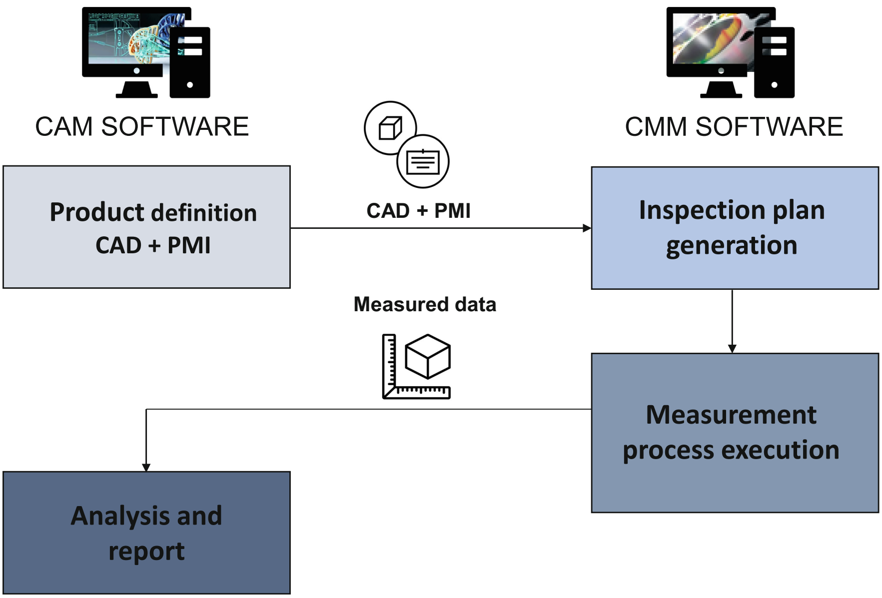

Fig. 6. First scenario: the CMMSW generates the inspection strategy.

The results obtained varied. While the ISO 10791-7 part was correctly exported from the CAMSW and imported into the CMMSW, in the case of the impeller blade the CMMSW failed in importing correctly the line profile tolerance, which is converted into a surface profile tolerance. Similar problems have been faced for all those tolerances in which a profile must be extracted from a surface, given a specific datum (line profile, straightness, roundness, etc.). This problem in general shows up when an intersection plane, as defined in ISO 1101 §13, is found. The 3D annotation of intersection planes, although required for all those tolerances based on the extraction of profiles from surfaces, has been introduced only in the 2012 revision of the ISO 1101 standard. Although STEP AP 242 is capable of representing it, software developers are still working on how to manage it. Minor issues have also been found in the correct identification of datum features.

For sake of completeness, as the considered CMMSW is capable of loading the CAMSW proprietary solid model format, the possibility of transferring information through this format as been investigated as well. The obtained results were similar to those obtained using the STEP AP 242 format.

5.1.2 Second Scenario: The CAMSW Generates the Inspection Plan

This scenario is currently seldom seen, as only recently CAMSW has gained the capability of generating inspection plans, and as such the experience of the operators in this field is limited.

In the second scenario, the CAMSW generates an inspection plan that is exported in a part program file. The part program is then loaded in the CMMSW which operates the CMM (Fig. 7).

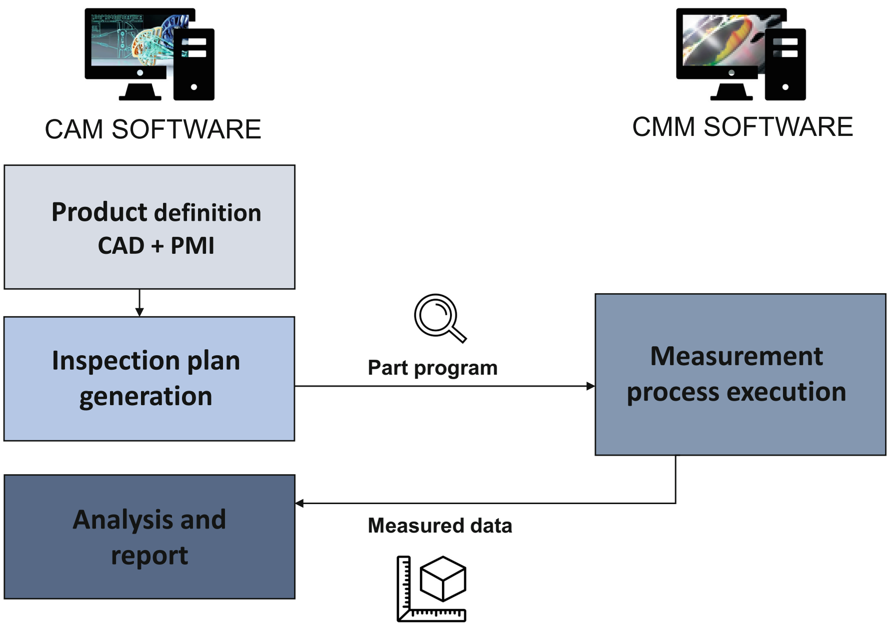

Fig. 7. Second scenario: the CAMSW generates the inspection strategy.

The only format available for the export of the part program is the standard DMIS. It is worth noting that, although most CMMs are capable of measuring in scanning probing, DMIS, in its standard form, and in particular in the form handled by the CAMSW, can handle only discrete points probing, which limits the possible inspection strategies.

The result of this scenario is, in general, a failure. Although the inspection strategy is correctly transferred from the CAMSW to the CMMSW (i.e. the CMM will be commanded to probe the expected points), the definition of the geometric features and the geometric tolerances are not correctly transferred. In particular, the geometric parameters see their parameters altered (they are translated by some amount). The geometric tolerance are not transferred, with the sole exception of position tolerances.

Currently we are not able to state whether the problem is in the DMIS export form the CAMSW or import into the CMMSW. The generated DMIS are semantically correct, but this does not mean the geometric features and tolerances are correctly represented. It is possible to state that currently this scenario cannot be considered feasible.

5.2 From the CMMSW to the CAMSW

Once the measurement has been performed by the CMM, the measurement results obtained are in most cases not yet integrated in the company PLM software, as usually the CMMSW is not integrated. To integrate the measurement results into the PLM, the possibility of sending back the measurement results to the CAMSW, which is integrated in the CMMSW, has been investigated.

Only DMIS can be chosen as file format to be generated by the CMMSW including the measurement results and then loaded into the CAMSW. However, the CAMSW failed in parsing the DMIS files generated by the CMMSW. This is consistent with the results obtained when testing the generated DMIS files with the NIST DMIS test suite [1], which reports a number of syntax error in the file. As such interoperability is currently impossible.

6 Conclusion

Interoperability is a requirement in an Industry 4.0 context. In the field of metrology, the tools are partially available: neutral languages have been defined to represent solid models, PMI, and measurement result. However, the implementation in commercial software is still poor, and requires improvements. If passing the information from CAM software to CMM software is possible, even if with some limitations, the inverse passage for the measurement results, which would allow the inclusion of quality data into the PLM system, is still almost unfeasible.

As a conclusion, it is possible to say that, perfect interoperability, still far from being reached, implies the necessity of a standard language that should be the only way of communication and interpretation from both sides. Indeed, having the same standard managing both information flows, would be a significant step towards interoperability. This idea is what lays at the basis of the “digital twin” concept. Digital twin is a new approach, perfectly inserted inside Industry 4.0 environment, that consists in creating a bit model of the product under realization, on which it is possible to make tests, as wear or duration, without the need of physical prototypes. Only at the end, bits are converted into atoms. Often, a final product is the assembly of components produced by different companies. If all companies of the supply chain create the digital twin of the component (bit model), each of them can consign it to the downstream company, which assembles its own model with the one received. At the end of the chain, the final digital twin is obtained and, after tests are passed, all companies can physically produce the part they have to. Shifting this idea inside dimensional metrology environment [24], PMI and machining information are information that enrich the CAD model through STEP language. It is the same of having different components of an object assembled together: the different digital twins can be integrated. What is still missing is a language that can represent inspection strategy and results as CAD + PMI are, or vice versa. In the considered case study there are STEP representing CAD + PMI information on one side, and DMIS representing inspection strategy and results on the other side. Thus, a solution toward interoperability could be enhancing one of the two standard languages, so that it can represent all information needed and therefore it can be used as the digital twin representation language. Should one of these be realized, every software would receive from the other a digital twin, represented by a language that it can decode. Considering for example the case of STEP enhancing, the CMMSW would receive from the CAMSW the CAD + PMI, in the form of a digital twin represented by STEP. At this point, the software could add its information on the digital twin in STEP (e.g. the CMMSW adds an inspection program and relative results) and resend it to the CAMSW, which, in turn, could insert additional information (e.g. measurement analysis), and then store the overall digital twin in an integrated database. This, in the end, would mean a perfect integration and the optimal achievement of interoperability in dimensional metrology system.

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The Paradigm of Pit - Stop Manufacturing

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Abstract. The context in which manufacturing companies are operating is more and more dynamic. Technological and digital innovations are continuously pushing manufacturing systems to change and adapt to new conditions. Therefore, traditional planning strategies tend to be inadequate because both the context and short - term targets are continuously changing. Indeed, one of the goals of manufacturing companies is to keep manufacturing systems efficiently running, and reduce and control the impact of disruptive events, that may originate from different sources, not always known or well defined. In order to do so, manufacturing systems should be kept relatively close to the current optimal condition, while, at the same time, taking into account information about future possible events, which may require new optimal conditions. In fact, the reaction time to the change must be short, in order to remain competitive in the market. In addition companies to be competitive should lead the introduction of changes therefore they have to be both reactive and proactive. From this analysis, the new paradigm of 'pit - stop manufacturing' is introduced, in which the overall goal is to dynamically keep the manufacturing system close to an improvement trajectory, instead of statically optimizing the system. It is shown how the 'pit - stop manufacturing' deals with various aspects of current manufacturing systems, therefore providing novel research questions and challenges.

Keywords: Manufacturing systems · Industry 4.0 · Control · Variability

1 Introduction

The context in which manufacturing companies are operating is more and more dynamic. Technological and digital innovations are continuously pushing manufacturing systems to change and adapt to always new conditions, in order to remain competitive [1–3]. Indeed, manufacturing systems can be seen as racing cars: in car races, though the overall goal is to be as fast as possible, the winning team is the one capable of mastering a strategic approach and use and minimize the impact of pit - stops during the race, by grounding on team cooperation, advanced technological solutions and information exploitation. Similarly, in manufacturing systems, the ability to timely deliver the desired quantities of products that are conforming to the customer expectations, strongly depends on how the manufacturing system is capable to deal with unpredicted events such as machine failures, delays, lack of material [4, 17, 21].

Strategies for manufacturing system improvement involve decisions at different levels having impact on different time horizons. For example, if a machine breaks down, short term production planning should adapt immediately, while maintenance

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should focus on the reduction of the repair time, in order to bring back the system to its full operational mode. On a medium term, increasing the reliability of the machine, by means of technological actions on the machine, may entail specific investments. Alternatively, the implementation of advanced maintenance policies, such as condition-based maintenance or predictive maintenance could be considered. This last option however requires additional information coming from data sources such as sensors. Therefore, decisions should be taken on the redesign of the sensory networks (i.e.: how many sensors should be installed? What is the acquisition frequency? How much data should be stored? [16]) However, by the time the decision has been taken, the context could have already changed, therefore the optimal decision needs to be continuously redesigned.

1.1 Why 'Pit - Stop Manufacturing'

In order to answer to the situation presented above, a new paradigm is introduced, 'pit - stop manufacturing'. Pit - stop manufacturing aims at considering manufacturing systems as continuously changing and evolving objects, for which optimal targets change accordingly. Therefore, the overall goal becomes to be able to react to unpredicted and disruptive events or to take disruptive decisions by acting on different decision levels and exploiting innovative technologies, novel modeling techniques and advanced digital tools:

- On the *short term*, keep the system running, by performing the required actions in the best possible way;
- On the *medium term*, develop control strategies to minimize the impact of disruptive events and stoppages on the system;
- On the *long term*, understand and translate into decisions the information about the changing context in order to proactively change and remain competitive.

Indeed, this resembles what happens for racing cars. People involved on the routine operations, such as pilots, mechanics, telemetrists in the control room, should be well prepared and highly skilled to perform their tasks at best. In fact, in the end they are the ones performing the concrete job that allows the system to keep on running. Then, the off-line efforts should be on the optimization of these operations, by providing the best possible conditions to operate.

Therefore, manufacturing systems should be characterized by *agility* and *mutability*. On the one hand, *agility* represents the ability to act quickly and easily, both mentally and physically. Therefore, agile manufacturing systems are characterized by short reaction time to disruptions [21], as well as a good control structure. On the other hand, *mutability* represents the ability to change. For manufacturing systems, *mutability* can be considered the ability to adapt to new and changing situations, by having the intuition about what to do even if it had not been done before.

Agility and *mutability* enlarge the concepts of flexibility and reconfigurability by including control actions. In fact, a manufacturing system can be flexible, but until the flexibility is not used properly, it cannot be considered agile. Similarly reconfigurability allows the system to change but only when system design and redesign is available mutability can be attained.

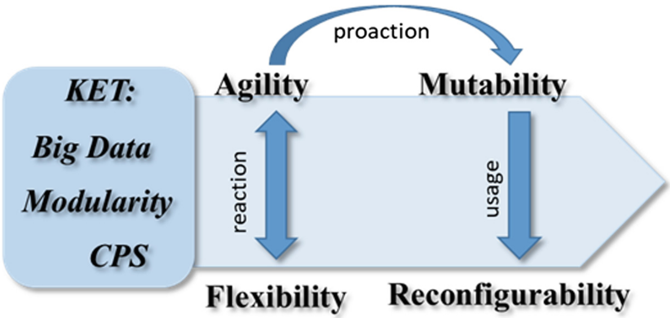

Fig. 1. Graphical representation of the key drivers for manufacturing systems in pit - stop manufacturing

1.2 Agility by Learning and Mutability by Modeling

Increasing the ability of being agile can be attained by practicing more and more when doing something. This means that, grounding on the experience and a solid control design, agility is reached by reiteratively learning how to perform the same action better and better. Indeed, data-driven techniques such as neural networks, reinforcement learning, genetic algorithms consists in learning from a defined data set how to optimally perform an action chosen in a predefined solution space [5]. The more data is available, the more the network can be easily trained to do what it is designed for. Moreover, the more the network is trained, the more it learns how to perform better its task. For instance, neural networks for image recognition after a preliminary training phase, they become quite efficient at recognizing predefined features in pictures. However, if a picture with a new feature is presented, the neural network assigns that feature to the most similar one among the set which is already known. The only way to have a correct identification is to train the neural network again by adding to the solution space the new feature. This happens because data-driven methodologies work well when the solution space is already known. By grounding on available data and available feedback about implemented actions, data-driven methodologies are capable to efficiently identify the best action in the known solution space.

However, when dealing with continuously changing conditions, it may happen that a decision has to be taken, in a new situation, for which no data is available [1]. This means that the problem moves out of the known solution space, for which the behavior of the variables involved in the decision has not been registered yet, and therefore there are not known feedbacks. As explained above, this is a fair common situation in in manufacturing systems, that are in the need to proactively change in order to remain competitive.

Hence, abstraction becomes a key factor when looking for the ability to change and adapt. In fact, models can support this situation, because they provide decisional support by formalizing existing knowledge in structures that are valid even out of the validation space. Indeed, model-based methods allow what-if analysis, as well as evaluation of situations which have never been observed in practice. Therefore, the use of models to proactively take tactical and strategical decisions represents a key characteristics of competitive manufacturing systems. Obviously, developing a model, such as a performance evaluation model of manufacturing systems, or a process control model, requires some efforts. Nevertheless, the main advantage is represented by the fact that, if the model has been well-developed, can give suggestions even out of the validation space, i.e. it is general.

1.3 Factors Considered by Pit - Stop Manufacturing

In the following, three factors that are relevant for the definition of pit - stop manufacturing strategies are presented.

1.3.1 Variability as a Central Issue

Manufacturing systems are characterized by intrinsic variability. Variability comes from different sources at different levels of the system [1, 31]. Therefore, it has an impact on different time horizons. If variability did not exist, the management of manufacturing systems would have been based on *plan*, rather than *control*. With *plan*, we mean the timed set of actions that are decided in advance in order to make the system operating, whereas with *control*, we mean the set of actions that need to be done based on some system condition in order to keep the system operating.

Variability cannot be completely deleted from manufacturing systems. Therefore, the goal is to reduce it as much as possible the variability, and to find the best strategies to cope with it.

1.3.2 Information Uncertainty

Information is not always certain. On the contrary, in most of the cases information is available with some level of uncertainty. When information comes from data sources as sensors, the efforts can be put in determining which piece of information is the most relevant one for the considered problem [8]. For instance, when dealing with the definition of maintenance strategies [32], precise information about the degradation of machines could be useful. On the other hand, other types of information do exist and play a relevant role in the overall manufacturing strategy, such as non-structured information about the changing context, weak signals from situations that require intuition in order to be understood, expertise and previous knowledge.

1.3.3 The Role of Humans

Manufacturing systems without people is still a quite un-realistic situation. Indeed, even if manufacturing systems are more and more automated, and capable of self-managing, i.e. self-detection and solving of failures, the probability of occurrence of unpredicted events remains always relatively high, due to the variability descending by the physics of the system. Therefore, though humans might represent a relevant source of randomness within the system, they are capable, if well - trained, to react, and to solve, issues that have not been completely identified, or that they have never happened before [1].

1.4 A Real Case from an Italian SME

In the following, a real case from an Italian SME is presented. Indeed, it is a representative case for manufacturing analysis, and the factors presented above can be noticed. Therefore, it serves as example for the validity of the paradigm of pit - stop manufacturing, since all considerations made above do apply to it.

Cosberg SpA is an Italian company leader in the automation sector. Cosberg makes assembly machines and assembly systems to automate the production of a great variety of products ranging from furniture fittings, to braking –systems for cars and motorcycles, to gears for wrist-watches, and more. More than 50% of the turnover of the company comes from export all over the world, warranting unique solutions and a tailor-made product for each customer.

The collaboration between the company and customers is very strong, and often they develop together strategies for the plant improvement. Therefore, usually Cosberg operates on ‘brown-field design’. Once the manufacturing line has been designed, there is a continuous process of optimization of the current line configuration with respect to its efficiency (reduction of time losses due to maintenance, reduction of set-up time for product changes, increase of product quality by selective inspection, root-cause analysis for most frequent failures) where Cosberg supports the customer, and operators are actively part of the improvement plan by suggesting actions. At the same time, reconfiguration actions are planned, tested and then implemented on the customer’s line.

In fact, the manufacturing line is continuously evolving. For instance, the manufacturing line in Fig. 3, designed for the assembly of drawer slides of ready-to-assembly kitchen drawers depicted in Fig. 2, used to have hydro - pneumatic actuators, well known for being reliable but slow.

Fig. 2. Drawer slide for ready-to-assembly kitchen furniture

Therefore, the management of the operating line has been optimized taking into account the current cycle time. At the same time Cosberg and the customer jointly worked on the implementation of electrical actuators, that allow a better control as well as a shorter cycle time than the hydro-pneumatic ones. Indeed, the optimization that had been carried out for the previous line configuration had to be reviewed, in order to consider new – and better – performance goals.

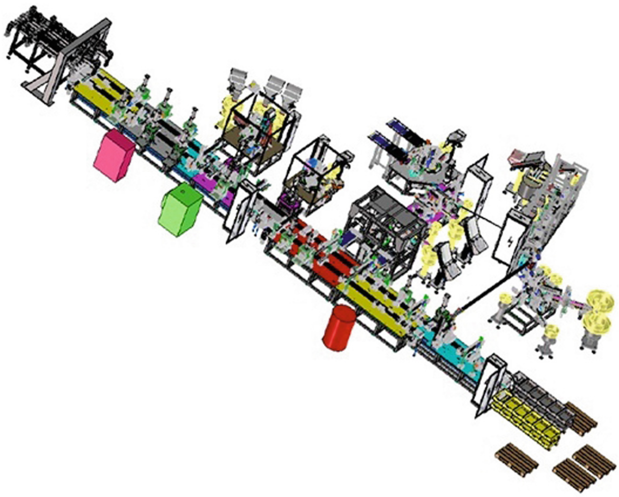

Fig. 3. Drawer slides manufacturing line as example of modular automated line provided by Cosberg

2 Challenges for Research Guidelines

2.1 Design of Manufacturing Systems

Traditionally, the design of manufacturing systems includes a set of decisions involving the elements of a manufacturing system, such as layout, machines, buffers, handling systems [15, 24]. Now, an additional element should be considered: sensors and data management. The data acquisition and management can be seen as 'a system within the system'. Its design involves questions similar to the design of a traditional manufacturing system: how many sensors? Which layout? How much storage capacity [34]? Indeed, the data management system has a direct influence on the uncertainty of the gathered information.

Moreover, the design of manufacturing systems cannot avoid to take into account considerations about the control of manufacturing systems. Not only manufacturing systems should be *flexible*, but also *agile*. Similarly, the design of manufacturing systems should take into account its necessary and unavoidable evolution and requirements to adapt to new situations [22] and therefore be *mutable*.

2.2 Ramp - Up Management

In a continuously changing context, the ramp-up of a manufacturing system should be as short as possible. Ramp-up represents a challenge for manufacturing companies because they have to deal with disruptions coming from various and unknown sources [7]. Indeed, after a change, the manufacturing system is not well-known and therefore optimization is done with respect to partial information rather than complete knowledge or sufficient data [33]. Therefore during this phase, the problem becomes to prioritize certain actions to maximize the production gains, and trying to reduce and control the variability coming from different sources. Effective strategies combine proactive and reactive actions: proactive strategy includes the anticipation of potential problems during the design phase, reactive strategy includes the ramp-up management by data gathering, bottleneck identification and analysis, system modeling and improvement.

2.3 Integrated Control Policies of Logistics, Maintenance and Quality

Quality, maintenance and production planning strongly interact and jointly determine those aspects of a company's success that are related to production quality, i.e. the company's ability to timely deliver the desired quantities of products that are conforming to the customer expectations, while keeping resource utilization to a minimum level [4]. What are the relevant information needed to take integrated decisions? For instance, both maintenance and quality policies are based on the identification of process degradation patterns, and therefore on the same set of data. Current performance evaluation models are capable to deal with logistics, maintenance and quality. The design of control policies, however, should be directly integrated within the design of the manufacturing system [18, 29], so that *agility* exploits system flexibility to its full potential.

2.4 Robust Model - Based Strategies

Dealing with model - based strategies implies the estimation of model parameters from real data. However, data might be insufficient, especially in the ramp-up phase, or completely absent. Moreover, models may consider restrictive assumptions. In order to implement model-based strategies in reality, robustness should be investigated and analyzed, with respect to the uncertainty of the information [8]. Indeed, if there is no awareness of uncertainty, control strategies may be useless or even counterproductive [9]. Robustness helps also when dealing with variability: if a control strategy is robust with respect to variability of system conditions, not only agility has been pursued, but also mutability.

2.5 Key Enabling Technologies (KET)

The following Key Enabling Technologies (KET) allow a successful development of the afore-listed research challenges in the framework of pit-stop manufacturing. They represent existing technologies that still have a consistent margin of improvement and advancement.

2.5.1 Big Data

Data come from different sources in great amount. For instance, data are not only measures, but also images, or sounds. Data can be clustered according to classification, see for instance the 3 V's model [2]. However, what is the value of the data? In order to define the value, we have to go through the identification of the meaning of the data, and then of the information [19, 27]. Interpretation plays a relevant role. Therefore, a relevant question when dealing with Big Data is whether it is possible to formalize the interpretation with the goal of an effective extraction of knowledge from the data. Indeed, Big Data are necessary for data-driven techniques that prove to be useful when aiming at agility, and also the knowledge extraction becomes essential when aiming at mutability.

2.5.2 Modularity

Modularity is the degree to which a system's components may be separated and recombined, often with the benefit of variety in use. Modularity is useful at all levels in manufacturing systems: in product design, modularity allows an effective and sustainable management of the product lifecycle [10, 11]; in manufacturing system design [23, 30], it supports easier configuration and reconfiguration decisions [20], hence leading to the agility of reacting to disruptive events. Moreover, modularity is directly linked to the development and use of models, and therefore to aim at mutability.

2.5.3 Cyber - Physical Systems

Cyber - Physical Production Systems (CPPS), rely on the latest, and the foreseeable further developments of computer science, information and communication technologies on one hand, and of manufacturing science and technology [6]. Information coming from different sources at different levels are used to close the control loop and take decisions on different time horizons [25, 26]. Indeed, manufacturing systems should be kept as close as possible to an operational trajectory. Therefore, the architecture of the control system [28], that starts at physical level up to the system level, should be coherent to the decisions that are going to be taken and the information flow that is relevant for the control loop.

3 Examples from Ongoing Projects

In the following, three examples are presented in which considerations presented above for pit-stop manufacturing do apply. The three projects have different background and come from different scenes: the first one is a European project focused on zero-defect manufacturing solutions for manufacturing systems, the second one is a huge European project focusing on the overall supply chain of semiconductors, and the third one is an Italian initiative for Industry4.0 that has put the basis for the paradigm of pit-stop manufacturing.

3.1 ForZDM: Integrated Zero - Defect Manufacturing Solution for High Value Multi-stage Manufacturing Systems

The H2020 ForZDM project "Integrated Zero - Defect Manufacturing Solution for High Value Adding Multi-stage Manufacturing Systems" was launched to propose a new production quality system specifically targeted to small lot, large variant productions, subject to frequent reconfigurations [12]. The key architecture of the system proposed in the project is represented in Fig. 4. At lower level, a multi-sensor data gathering system is implemented, enabling to collect process variables, part quality, machine state, and part tracking information as well as codified and un-codified human feedback, through intuitive and user-friendly Human-Machine Interfaces (HMIs). This heterogeneous data set is collected and organized into a data management platform, that prepares data for higher level analyses. At middle layer, a set of data-analytics methods and tools are implemented, targeted to the identification of (i) correlations among the observed heterogeneous variables, (ii) correlations among different system stages, and (iii) non-ideal part variation patterns along the system stages. These models can be used to design specific model-based control systems to be implemented at shop floor levels. Moreover, at higher level, an analytic system-level model is implemented, with the goal to identify priorities of intervention, dynamic bottlenecks, and to verify that local improvement actions that are detrimental for the overall production quality performance are avoided. Within the ForZDM project, this architecture has been being developed, tested and validated in three complex application domains, dealing with the production of engine shafts in the aeronautics industry, the production of axles in the railway industry, and the production of micro-catheters in the medical technology industry.

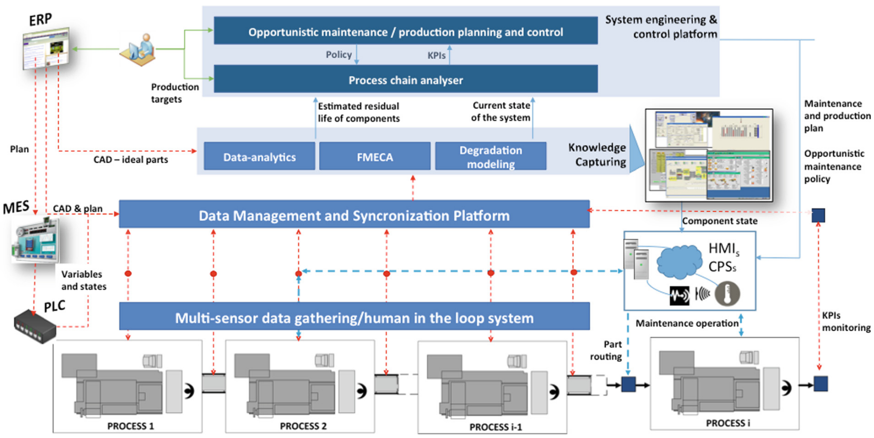

Fig. 4. Reference architecture for short - run production quality improvement proposed within the ForZDM EU project

3.2 Productive4.0: ECSEL Project

The semiconductor sector is undergoing one of the fastest market growths. Demand is increasing and market forecasts are optimistic. New markets are emerging and product portfolios are broadening significantly. Dynamic supply chains are developing with increasing number of customers, products, suppliers and manufacturing partnerships. Up to now due to modeling complexity and computation time constraints, disjoint systems are used for local supply chain control and optimization. For efficient control, these complex semiconductor supply chains require a global approach for simulation and optimization. In the ECSEL project Productive4.0, novel model aggregation approaches are introduced by means of innovative hierarchical modeling concepts. Bosch Semiconductor provides one of the use-cases. The overall goal in the Bosch use-case is the coupling of disaggregated analytical and simulation models to systematically improve overall model validity [13]. This requires a deep analysis of which data are available and significant at which level (Production Unit, Plant and Supply Chain levels). Moreover, it means investigating how data and information should pass from one level to another in order to bring value to the overall control model. Indeed, the model-based approach has been chosen by the partners in order to develop a general digitalization strategy that can adapt to changing conditions (Fig. 5).

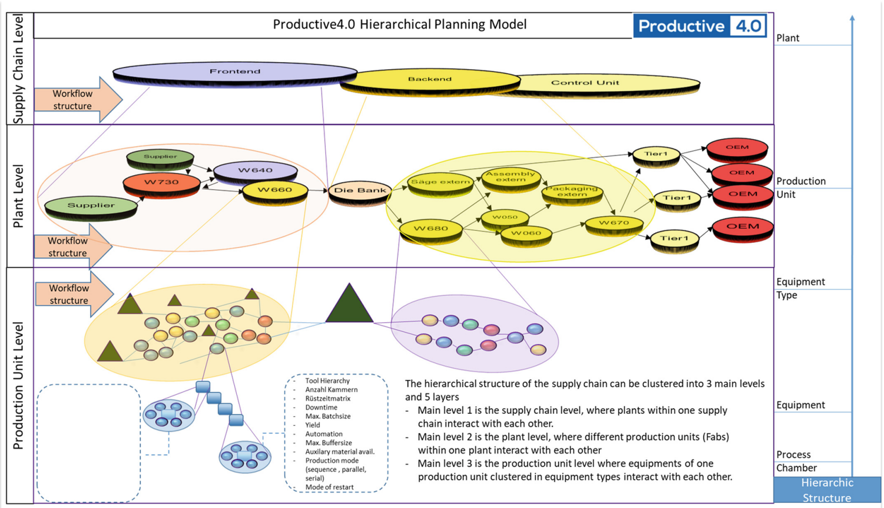

Fig. 5. Hierarchical architecture of the productive4.0 planning model.

3.3 The Italian Initiative: Lighthouse Plants

A Lighthouse Plant (LHP) is an infrastructure that aims at creating a reference production plant, owned by a company and operating in a stable industrial environment, based on key enabling technologies whose benefit was previously demonstrated (e.g. in Lab-scale or Industrial-scale pilot plants). The aim of the LHP is twofold: on the one hand, to demonstrate on a long-term basis novel technologies in operation, thus supporting the continuous uptake by industry; on the other hand, to trigger the development of industrial research and innovation activities to continuously improve manufacturing solutions according to the progress of technology [14].

LHPs are conceived as evolving systems and are realized ex-novo or based on an existing plant deeply revisited, where collaborative research and innovation, partially funded by public institutions, is carried out by the owner of the plant together with universities, research centers, and technology providers. The results of research and innovation activities are meant to be readily integrated into the plant.

The LHPs concept as presented in the previous section has been defined by Italian Cluster Intelligent Factories (CFI) to further boost the National Plan Enterprise 4.0 designed by the Ministry of Economic Development in Italy (MISE) in 2017. This plan included incentives for super- and hyper - depreciation as a way to support the implementation of advanced technologies in Italian manufacturing companies (Fig. 6).

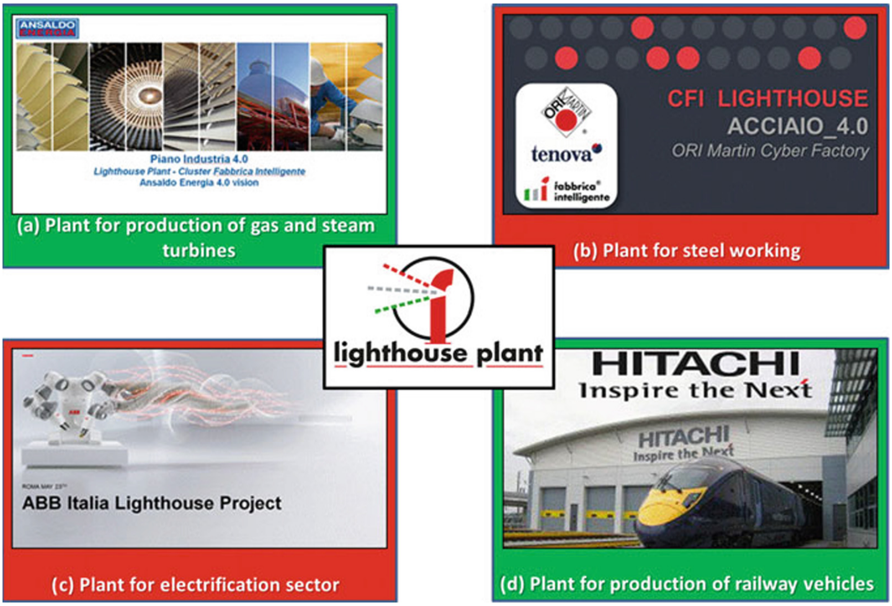

Fig. 6. Lighthouse plants approved by MISE: (a) Ansaldo Energia, (b) ORI Martin and Tenova, (c) ABB, (d) Hitachi

4 Conclusion

This work introduces a novel paradigm for manufacturing, named pit-stop manufacturing. Pit-stop manufacturing sees manufacturing systems as continuously changing and evolving objects. The reasons for the evolution are manifold: on the one hand, manufacturing systems are pushed to continuously proactively improve in order to remain competitive, on the other hand disruptive events may happen that force the manufacturing system to adapt. Therefore, control should be included into the design and management of manufacturing systems as capability to be considered for an effective manufacturing strategy. Two characteristics are defined as relevant for pit-stop manufacturing: agility and mutability, where the first one represents the ability to act quickly and easily, and the second one represents the ability to evolve and to adapt to new and changing situations.

Model - based strategies are presented as the right approach to address the evaluation of situations out of the existing solution space, rather than data-driven methodologies that perform well for given conditions. Indeed, the factors having an impact on the definition of such strategies are represented by variability, uncertainty in information and the relevant role of human.

Research challenges and relative Key Enabling Technologies are provided, and research guidelines depicted with respect to the proposed paradigm of pit-stop manufacturing. Some examples from on-going projects illustrating the main points of pit-stop manufacturing show the validity of the proposed paradigm, that aims at representing a novel approach for solid and successful manufacturing strategies.

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Design of the Codes Structure for Information System Working on I4.0 Principles

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Abstract. The paper deals with a design of codes structure for Information system working on principles of Industry 4.0. There are also describe the base aspects of information system related to the requirements for computer aided process plans design in the manuscript. The higher efficiency of processing big amount of data requires to make the code inside of a software application clear and therefore as simple as possible. On the other hand, it has to include all the information about the subject that is being coded. Within the proposed information system as such coded objects can be not only the manufactured components, but also the manufacturing facilities and operations needed to process the product (manufacturing operations, transport, handling, …). In the article is explained a proposed method of coding of individual types of objects along with a demonstration of code structure that is well-processable and identifiable with computer support.

Keywords: Information system · Classification · Code · Industry 4.0

1 Introduction

In One of the most toilsome and time-consuming phase of manufacturing process is the Process planning. It contains many of partial tasks and it has great impact on new product development time and on the cost decreasing, what expresses in the product price. It influences not only economics and time aspects of the manufacturing, but also the precision and quality of parts, too. The analyses of technical-engineering activities in process planning show that most of these activities have routine character, and only a little part of them has intuitive character. It is possible these monotonous and mentally labored works to effective, to speed up, to make objective by means of algorithmizing and sequential computer aid, and so to respond on varied conditions not only customer, but to manufacturing, too. There are many types of software or information systems for computer aid of process planning in the world, but every of them have their advantages and disadvantages.

The idea of using computers in the process planning activity was discussed by Niebel (1965) [1]. Other early investigations on the feasibility of automated process planning can be found in Scheck (1966) [3] and Berra and Barash (1968) [2].

Many industries also started research efforts in this direction in the late 1960s and early 1970s. Early attempts to automate process planning consisted primarily of

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building computer-assisted systems for report generation, storage, and retrieval of plans. A database system with a standard form editor is what many early systems encompassed. Formatting of plans was performed automatically by a system. Process planners simply filled in the details. The storage and retrieval of plans are based on part number, part name, or project ID. When used effectively, these systems can save up to 40% of a process planner's time. A typical example can be found in Lockheed's CAP system (1981). An example of a modern version is Pro/ Process for Manufacturing (launched in 1996 and since discontinued). Such a system can by no means perform the process- planning tasks; rather, it helps reduce the clerical work required of the process planner [4, 5].

2 Some Aspects of Information System - State of the Art

Basic current problems of production companies from the view of production information systems (IS) can be covered by their requirements: availability for usage in wide areas of production approach, simple implementation in entrepreneurial surroundings, modular concept for covering all necessary areas, reliable and secure data formats and structures, possibility of flexible bilateral data sharing, possibility of a trouble-free extension of IS, securing the possibility of a relatively fast transfer to higher level of IS and reasonable price. Generally, production companies can use for selection of production software all variations between two extremes: Complex systems or Independent solution for every application field of enterprise activity. First one is for many small enterprises inaccessible by reason of system complexity, fixed structure, expensive price, large and complicated adaptation, time-consuming maintenance etc. Second of them generally dispose only by flat possibility of interconnection to other information systems.

The statistical studies show that European micro companies constitute a substantial part of the European market as they comprise 92% (17.82 million business units) of the overall number of companies and employ 39% of the employees. Small and medium size companies together comprise 7.5% of the overall number and employ 30.3% of the employees. The rest ((0.2% production unites and 30.2% employees)) is covered by large companies [6]. Other results of this same study show that micro companies have the disposal of a free potential of 20% of the productivity and 15% profitability. These are very important characteristics which describe a distinct ability of the dynamic growth production and the possibility of effective evaluation of micro company instruments basically ‘over a night’.

The procuration of suitable integrated CAPP system can be for little and some middle plants expensive, sometimes inaccessible investment with the long recoupment period. On the other hand, also for these plants it is fundamental to be the manufacturing information saved digestedly and to be used in various forms (for example for the generation of technological information or NC programs) with the possibility to successive complement, editing and modification of necessary data. Considering requirements of Industry 4.0, the specifications of this type of enterprise units imply diametrically different demands on information systems from the normal setting of IS appropriate for large and medium size companies. The first very important is a data storage security. Next requests for IS are [7]:

- the system has to be able to work with the possibility of the user view on the production process from several angles,
- enterprise subject should be limited when launching new products to the production process as little as possible,
- it should be applicable for a wide range of business,
- it should be modular.

Basic problems that authors deal with in the research related to the development of Manufacturing Information System (MIS) are:

- Autonomous reasoning for wide variety of technological approaches,
- Flexible structure of data for optimizing procedures,
- Arrangement for obtain of advantages of both extreme - Complex systems vs. Independent solutions,
- Integration, association and connectivity of MIS with environs of specialized systems (CAD/CAM, salaries, financing, materials, accounting …),
- Very good possibility of data sharing by external applications and co-operators.

The presented research is focused on a new computer aided process plan philosophy and data structure conjunction for wide spectrum of technological approaches that Industry 4.0 brings. New designed information system aids the multivariant creation of process plans with the optimization according to the selected criteria, the creation of technological documentation and NC programs on the basis of hybrid approach, compendious production data holding and its processing with time and cost manufacturing savings. The basic Menu of new system is shown in the Fig. 1.

The system was built on the basis of the following technological approaches:

- Individual technology,
- Type technology,
- Group technology.

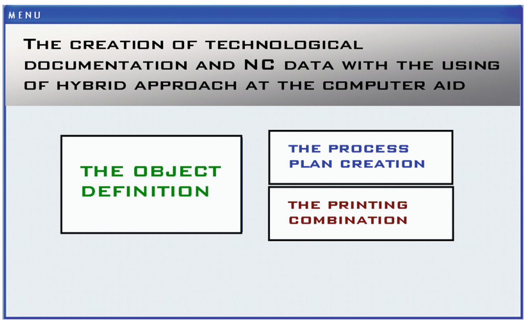

Fig. 1. The basic application Menu

The Individual approach includes the creating of manufacturing documentation for each component individual without the possibilities to use the same repeated operations for certain set of manufacturing objects (from parts through subassemblies and assemblies to final products). It can be said that his approach is not connected with standardization of technological processes and with the activities linked with them.

The term *Type technological process* represents the specific technological process for group of parts with the equivalent technological characteristics. This process is suitable for specific group of parts and defines the type and the sequence of main technological operations. The important term for Type technology is the Type Representative. It's real or abstract object of manufacturing, which technological process contains all basic and auxiliary operations existed in this group of parts. The typification of technological processes can be realized by two methods that are varying in the usage and in the objects of classification. They are:

- Typification of technological processes as the series of technological operations, by means of which all parts of the specified group can be made.
- Typification of the items within technological processes. By means of such processes the specified operations, occurred on the dedicated group of parts, can be realized.

The following steps are typical at the typification of technological processes:

1. parts' classification (or the elementary surfaces),
2. projection of the Type technological process (operation),
3. specification of individual technological process phases,
4. development of technological process for the Type representative,
5. transmission of Type technological instruction to specific part.

The sequence of works on the typification is started by development of a design-technological classification list of parts. The importance of the classification list lies in the analysis of part basis and technological processes, which are used currently in the company or which will be used in a future.

The last type of technological processes standardization is *Group technology*. It is manufacturing philosophy and strategy that assists a company in understanding what it manufactures and how those products are then manufactured. In manufacturing engineering, Group technology focuses on similar machining operations, similar tooling, machine setup procedures and similar methods for transporting and storing materials. By identifying similarities in manufacturing (machines, tooling, process sequences, etc.), similar workpieces parts (geometric shape and size) can be grouped into distinct families and processed together in dedicated workcell. Some parts may look similar to each other, but because of differences in materials, tolerances or other production requirements, they have different manufacturing conditions and so don't create "manufacturing family of parts" [8].

In contrast to Type technological processes, the Group process is always specific and it serves as technical instruction to realize individual operations. The approaches to Group technology are today based on the fact that all technical and organizational evolutions inside specific manufacturing unit contain activities or data with some degree of similarity. So, they can be combined with the groups for which common solutions and methods are used. The methodological tools for the sorting parts are different classification and coding systems.

3 Classification and Coding System Within IS for I4.0

The objects in machine engineering as are the parts, machines, equipment and other; it is possible to model on the various stages with various goals. These objects can be represented by models (physical, simulation, computer, mathematical and other). Every of these objects it is possible to consider as system, which consists of other features, respectively as the feature that is part of some system [9].

The mathematical model represents the substantial object properties expressed by the numbers or symbols. In regard to a large number of parameters that are variable in consequence of the varied manufacturing process conditions, it is most suitable to use the type of code at which are the starting positions reserved for the characteristic properties of the object [10]. Other positions are attached to the attribute part of code according to the need to define the classification of the object. On the basis of this structure, it is possible to consider manufacturing system as a set, which is unification of subsets, also marked as subsystems (Fig. 2).

The created system can be expressed by the relation [11]:

$$MS = S \cup E \cup O, \tag{1}$$

where MS - manufacturing system, S - Segment, O - Operation, E - Equipment.

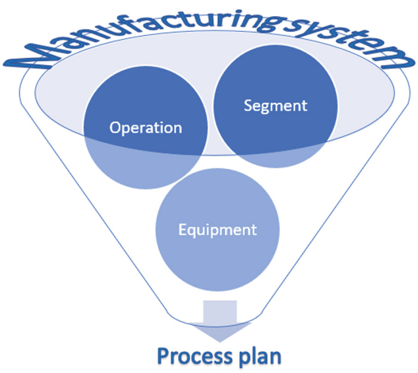

Fig. 2. Mathematical model of the manufacturing system

The Subsystem Segment

The basis of subsystem "Segment" is the classification code for the segment description, which represents the start point of whole system. The suggested coding system keeps the space for the process plans creating not only for cutting technology but also for other technologies.

The codes cover the following characteristics:

- the geometrical shape,
- the class of part,
- the manufacturing characteristics,
- the class of dimensions.

The example of the selected surface coding system with the possibility to manufacture surfaces by individual technological operations is shown on the Fig. 3 [11]. Numbers 0 or 1 describes the true or false of this manufacturability.

The surface type					Code	The technological method						
						grinding	tooling	milling	drilling	gilling	slotting	planning
	external	smooth			01	1	1	1	0	1	0	0
		step			02	1	1	1	0	0	0	0
		shaped	developed		03	1	1	1	0	0	0	0
			undeveloped		04	1	1	1	0	0	0	0
Rotary surfaces	internal	semi-enclosed	smooth		05	1	1	1	1	0	0	0
			stepped		06	1	1	1	1	0	0	0
			shaped	developed	07	1	1	1	1	0	0	0
				undeveloped	08	1	1	1	0	0	0	0
		passed	smooth		09	1	1	1	1	1	0	0
			stepped		10	1	1	1	1	0	0	0
			shaped	developed	11	1	1	1	1	0	0	0
				undeveloped	12	1	1	1	0	0	0	0

Fig. 3. The example of the surface coding [11]

During the creation of software application, it was suggested several manners of the segment classification, for example according to the types of surfaces that didn't comply from the view of the classification complexity. The example of generated code and its structure are shown in Figs. 4 and 5 [11].

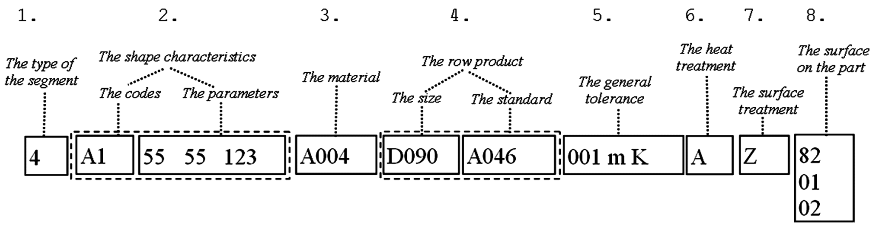

Fig. 4. Structure of individual code parts in subsystem Segment [11]

In this code, for example, the 4-th part of code describes the raw product size. This part of code is created by 4 positions. The first position is defined by alphabet letter, which determined the kind of raw product (for example into the group "A" fall the sheets, steel strips…). The second, third and fourth position give the standard sequence for specific kind of raw product in database module. It is possible for the plant to register till 1000 standards for one kind of raw product.

Sequence	characteristics	code format	code meaning
1.	Segment type (defines the level of segment complexity from the part to finished product)	0	1. segment type
2.	Shape of part	A0	1. basic shape 2. specification of shape
	Segment dimensions	000x000x000	
3.	Material (STN – include additional digits)	A000	1. kind of material 2. } material 3. } sequence inside material kind
4.	Row product size (e.g.: L 25x25x4)	A000	1. kind of raw product 2. } dimension 3. } sequence in 4. } specific kind of row product
	Row product standard (STN – include additional digits)	A000	1. kind of material 2. } dimension 3. } sequence in 4. } specific kind of material
5.	General tolerances of geometry and dimensions (e.g.: ISO 2768)	000aA	1. } order of 2. } general 3. } tolerances, size and geometry sign 4. general size tolerance 5. general geometry tolerance
6.	Heat treatment	A	1. mode of part heat treatment
7.	Surface treatment	A	1. mode of surface treatment
8.	Type of surface	00	Surfaces complex segment forming

Fig. 5. Structure of individual code parts in subsystem Segment [11]

The coding of segment in this software application goes out from the assumption that the data registered in this module will next be used at the creation of technological or drawing documentation and the parameters already once defined will be possible to record by another database module. Segment code can to appear too difficult at the first sight, but its creation is very simply at the work in user interface and it is aided by already partially charged by data bank. New code is formed by 8 parts. Basic characteristics of individual parts are shown in the Fig. 4.

The Subsystem Operation

On the basis of suitable code definition for subsystem Structure of operation it is possible to determinate three stages [11, 12]:

- class of the machining,
- type of the machining,
- process of the machining.

It is possible to specify the concrete machining operation by means of these three stages. The example of the Structure of operation coding is shown on the Fig. 6, which shows the code meaning.

	1.code digit **The class of the machining**	2.code digit **The type of the machining**	3.code digit **The process of the machining**
0	*rotary machining*	*autom. lathe work without thread*	*thread cutting internal*
1	*facing*	*lathe work without thread-cutting*	*thread cutting external*
2	*drilling and boring*	*grinding*	*thread milling internal*
3	*manual work, generally*	*treading*	*thread milling external*
4	*surface treatment*	*autom. lathe work with thread*	*thread rolling internal*
5	*inspection, checking*	*lathe work with thread*	*thread rolling external*
6	*heat treatment*	*gear cutting*	*thread grinding internal*
7	*non-cutting processes*	*vacant*	*thread grinding external*
8	*metal joining*	*vacant*	*worm machining*
9	*casting, etc.*	*vacant*	*other*

Fig. 6. The example of the Structure of operation coding [11]

Inside the created software application also other technologies are considered and so this subsystem is expanded to the stages [13]:

- technology,
- technological class,
- technological type,
- technological process.

The Subsystem Equipment

The term "Equipment" is, in this case, used for the cover of wide spectrum of various product equipment, such as [11, 12]:

- production spaces (the halls, workshops, …)
- equipment for the energy production and energy distribution
- machining equipment
  - tools
  - jigs and fixtures
  - machines
  - machining equipment
  - equipment for the workshops of manual operations
  - equipment of assembly plants
- measuring and testing equipment
- conveying devices
- equipment for storage
- other devices (for example computer techniques, …)

The subsystem "Equipment" represents very large, rugged and heterogeneous structure of individual objects. Therefore, it was used at the suggestion of the coding the hybrid type of code.

Machining equipment can be divided for example as following:

Machines
The machines it possible to divide from various aspects, the most advantageous is the classification on the basis of used technology. In this case we can speak for example about the machines for:

- Machining
  - turning,
  - milling,
  - drilling and boring,
  - machining centres
  - other.
- Moulding,
- Casting,
- Welding,
- Assembly and other.

Tools
Tools are very important part of production process. For exact coding it is necessary to regard:

- technological operation that the tools are able to execute,
- technological and geometrical limitation,
- maximal and minimal values of the working parameters,
- type of the work holding,
- environment, which can be tools used in.

Jigs and Fixtures
It is needed to determinate at the coding of jigs and fixtures:

- devices, which can be used on,
- maximal and minimal values of the working parameters,
- environment, which can be jigs and fixtures used in.

Accessory Equipment
The accessory equipment is often essential and necessary for a flow of some operation. It was possible to choose the hybrid type of code in regard to the ambiguity of its used definition (for example the same medium can be sometimes used as the cooling mixture and some other time as oil).

4 Conclusion

Process planning acts as a bridge between design and manufacturing by translating design specification into manufacturing process detail. Hence, in general, process planning is a production organization activity that transforms a product design into a set of instruction (sequence, machine tool setup etc.) to manufacture machined part economically and competitively. The information provided in design includes dimensional specification (geometric shape and its feature) and technical specification (tolerance, surface finish etc.). CAPP is the application of computer to assist the human process planer in the process planning function. In its lowest form it will reduce the time and effort required to prepare process plans and provide more consistent process plan. In its most advanced state, it will provide the automated interface between CAD and CAM and in the process achieve the complete integration with in CAD/CAM) [14].

The suggestion of new philosophy and the development of new software product for the creation of multivariant process plans is the intent of submitted project. This approach enables to increase effectivity already at the beginning of its design and to improve the process of technological documentation creation without of the influence on its complexity. Generated codes within designed software application has been built in modular way to allow flexible adapt data structure to user specific conditions and to satisfy the specification of simple implementation into already existing information structure of the plant. The output data of the system will be able to utilize not only for the generating of technological documentation but also to the processing of details for manufacturing, store, economic and wage records, thereinafter for the creating and archiving of NC programs and for the data registration, too. It is assumed the practical verification of the final product in real conditions of manufacturing plants.

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A Critical Evaluation of Current Machine Tool Designs in the Digitalized Global Production Networks

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Abstract. Machine Tools are mother machines. They are necessary for the creation of any product. There is a correlation between machine tool capabilities and industrial achievements. The history shows that new innovative designs of machine tools led to remarkable technical as well as monetary results. Digitalization is changing our daily life in all aspects. A new "On demand economy" is coming up. No more an economy based on fixed plans is essential but an economy which is reactive to changes in daily life on time. Consequently also new production systems and machines are necessary for making it possible to adapt to new demands. This new era requires as well changes in machine tool design for taking benefit of the possibilities forwarded by digitalization. A paradigm change is necessary. In this paper a systematic review of machine tool developments will be given and requirements on up to date machine tools will be worked out. Finally, some examples for potential future design ideas will be presented.

Keywords: Machine tools · Digitalization · Reconfigurable · On demand economy · Paradigm shift

1 Introduction

Machine tools have an essential role for every industry. They are mother machines and are at the first stage of the manufacturing of a product [1]. Basis of a strong national industry is a powerful machine tool industry. Thanks to capabilities of machine tools industrial performance can be affected.

On the other hand there is also a correlation between mechanical design of machine tools and surrounding game changing technologies. The invention of numerical controls (NC) and their utilization in machine tools increased the capabilities tremendously thus contributing to higher productivity and flexibility [2].

Digitalization is the current game changer. The impact of it is huge in many respects. Thanks to it global production networks is reality [3]. But it also changes individual demands as well as industrial demands. Digitalization changed the fundamental plan economy to an "on demand economy" [4].

This kind of economy is changing the whole way of production as well as work-life balance. This unstoppable transformation requires also new types of production units and manufacturing systems.

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2 Review and State of the Art of Machine Tools

The invention of NCs had remarkable impact on the capabilities of machine tools. The implementation of NCs enabled the designers to create new designs of machine tools and year by year to include additional functions. Figure 1, [2].

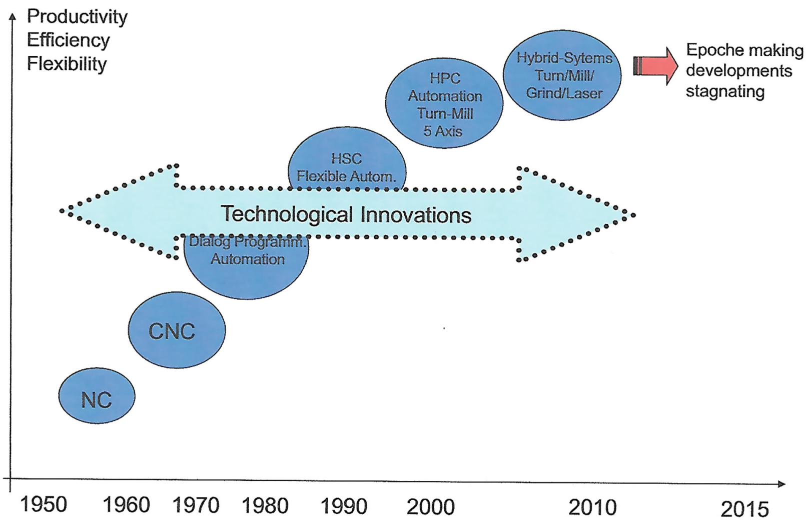

Fig. 1. Technological innovations after invention of numerical controls (NC) [2]

Thanks to NCs it was possible to drive each axis of a machine by individual motor thus being able to control more than two or three axis what was the case in conventional machine tools. This broadened the view of developers how to view the production process. Analyzing the value chain in a production process it was realized that additional operations could be included in a machine tool thus reducing the number of machines, reducing the number of setups. Consequently the lead time for an order could be reduced [5].

The inclusion of additional operations into one machine increased the productivity but also the flexibility of a machine tool. It was possible to use the enriched capabilities for frequently changing orders.

After NC technology maturely was applied in machine tools, handling of work pieces, loading, unloading was automated by industrial robots [6]. Initial industrial applications delivered encouraging results. Consequently automation of work piece handling was pushed forward throughout several industries. Step by step additional manual operations and setup operations such as tool changing, check changing, chuck jaw changing were automated [7].

The powerful the controls became the more processing functions could be added to a single machine. A lathe could execute much more operations than just turning. Milling, boring, gear cutting and grinding operations as well as measuring enabled the full machining of a workpiece in one setup. So the productivity and flexibility in the production of a user could jump up.

After having included almost all cutting operations in a single machine tool it was realized that the impact on productivity and flexibility was diminishing. Further step was to include laser technology. This opened new fields for the utilization of a machine tool, but huge timely and financial efforts was necessary for achieving some minor benefit.

Furthermore the increasing functions of a machine tool led to higher complexity of them. More functions meant also higher sensitivity. The high sophisticated production units had also high price. Any idle time or setup time was very costly. Highly educated and skilled operators were looked for efficient use of machines.

In 80ies after the declaration of Sustainable Development Goals (SDGs) [8] by United Nations additional efforts were done for creating environment friendly machine tools. These efforts delivered remarkable discoveries what could be improved in terms of energy efficiency and environment protection [9]. The results contributed to cost savings at user' sight. The contribution to productivity was limited.

3 Game Changer Digitalization

The Needles to emphasize, digitalization opened a new chapter in many means. The affect of digitalization encircled not only the single machine tool, but also entire production environment.

Digitalization eliminated the distances, locations and time differences in our thoughts. It enabled mankind to break the walls in his thinking, in his imaginations. A great door was opened for engineers to enter a new world of ingenuity and creativity.

Regardless the size of machine tool, regardless its capabilities it could be considered purely as a unit in an ICT environment. But this unit could communicate with other stakeholders of a production process regardless where they are and regardless time constraints.

Digitalization changed also total production philosophy of enterprizes. It gave path to globalization. Instead of focusing on main base for production companies could consider more suitable places for producing their goods, they could produce at places where their main customers are located and they could go to markets where they realize more markets potential.

The profile of the individual demands is also changed. The easy connectivity and the flexibility in production initiated an "On Demand Economy" which has impact in many areas of individual and business life resulting in a board product and service range. Companies must be ready to identify market demands, to flexibly produce a unit and to deliver it at a time when the customer requests it.

This is a totally different state of the art than the times when people could select a product out of a published catalogue with a certain delivery time.

Digitalization became also a key political issue for governments. They realized the potential as a game changer and supported the local academic and industrial activities with individual specific titles. In Germany the new era was identified as the fourth industrial revolution. Consequently the focus on digitalization was named as Industry 4.0 which has a well acceptance all over the world [10].

Thanks to connectivity of machines and even its components suppliers are able to receive extensive field data. Analyzing these data manufacturer can gain valuable knowledge about the performance of their machines as well as about the manner of the customers using the machine. This transparency could lead to a more fruitful communication between user and manufacturer. Furthermore new business models could be created, Fig. 2.

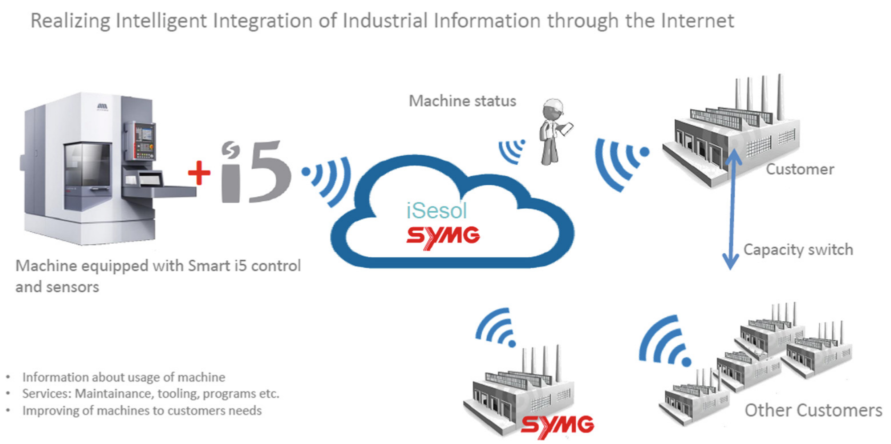

Fig. 2. Integration of a machine tool in the digital world [2]

The deeper utilization of the big data collected from the field will lead to artificial intelligence (AI) which is expected to become a further game changer in future.

Connectivity thanks to digitalization will upgrade developing and emerging countries to areas at the same eye level on communication aspect. This could speed up their development and probably they could become important basis for new production networks [11].

4 Impact of Digitalization on Manufacturing Systems

After benefits by technology have diminished Industry 4.0 was supposed to become the new source for productivity and flexibility. Several estimations are made what kind of effects Industry 4.0 could have in an entire production process. These estimations are not yet proven by extensive feedback from the field. On the other hand on academic field new formula are necessary for measuring the effects of digitalization on productivity as well as on GDP [12, 13].

One of the reasons why the impact of Industry 4.0 couldn't be quantified substancially yet could be lack of manufacturing systems matching with the advantages delivered by Industry 4.0. Digitalization will be considered as an essential game changer but there is no corresponding change in manufacturing philosophy. Breaking down the philosophy to individual machines there is also no game changing design of machine tools.

As to manufacturing strategies Global Production Networks were created thanks to connectivity by digitalization. Key point for establishing these kind of strategies was organizational point of view. New footprint was set up based on existing machine tool designs. The classification of manufacturing systems was based on variety and volume, Fig. 3, [14].

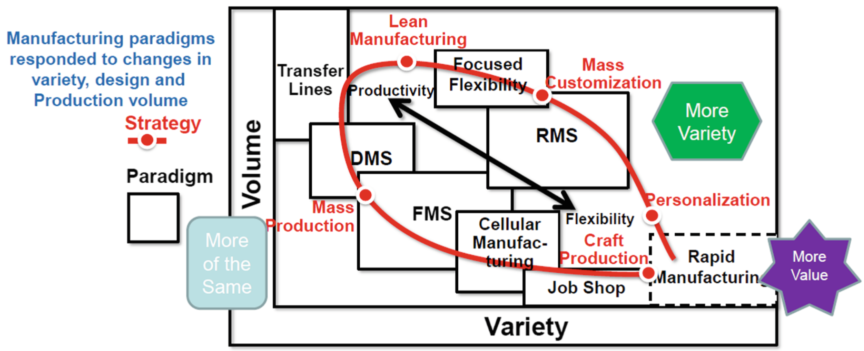

Fig. 3. Classification of manufacturing systems [14]

Regardless the connectivity it is obvious that machine tool industry does not deliver design concepts yet which could be considered as game changer as well. A paradigm change is taking place at academic level, [15]. Figure 4 shows attempts to classify manufacturing systems following new up-to-date and future oriented criteria.

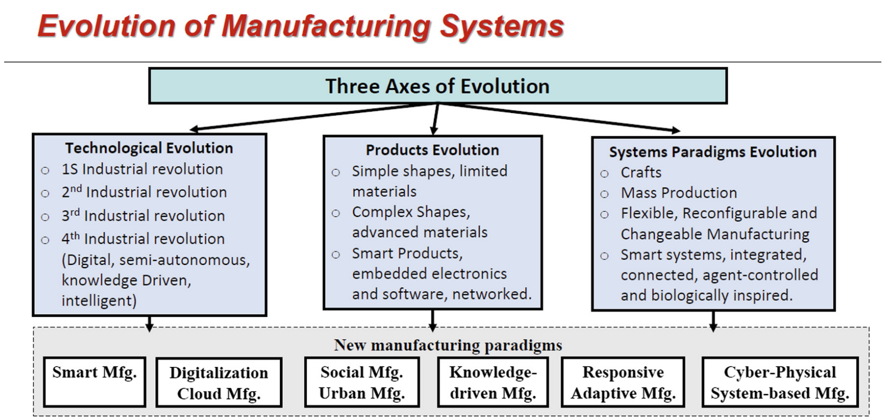

Fig. 4. Evolution of manufacturing systems [15]

In the past the term "Reconfigurability" was used for a machine tool of which the modules could be put together following the manufacturing operations [16]. Final stage of a reconfigurable machine tool could be a high sophisticated, complex and sensitive unit. It is a rather engineering dominated approach.

An "On Demand Economy" which could extend even to an individualization of a product requires machine tools which are able to immediately respond to changes of market demands. This attribute cannot be achieved by state of the art design of machine tools. Following characteristics should be fulfilled: Simple, maintenance friendly, affordable, reliable and timely to market. The company of the author uses the strategic brand name "SMART" taking the initial characters of the five attributes, Fig. 5, [17]. Considering the industrialization of developing and emerging countries as well as their improving digitalization SMART machines represent not only the proper aids for On Demand Economy but also for the mentioned category of countries the suitable machine tools for their economic development. So far a big market could be forecasted for machines fulfilling SMART criteria.

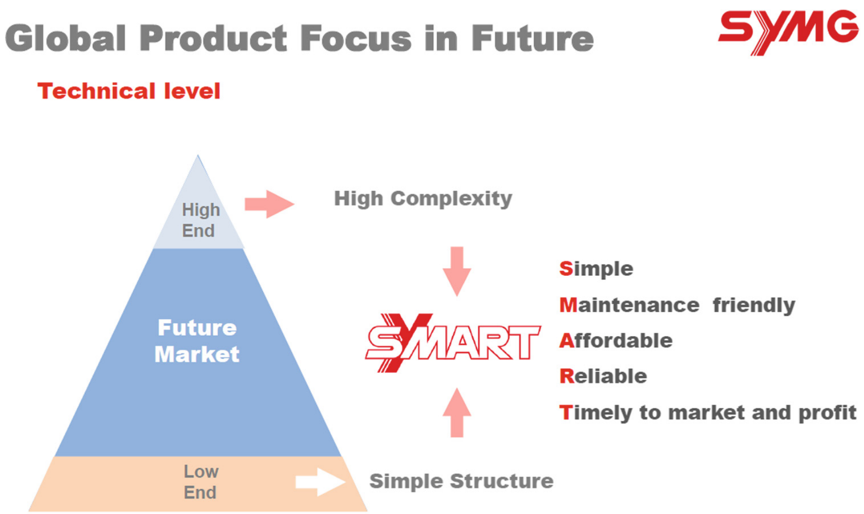

Fig. 5. SMART – future attributes for a machine tool [14]

For immediate response to changing demands simplicity is essential. Simplicity of single machine tools enables manufacturing systems to easy reconfigurability, a more market oriented attribute.

Simplicity means a reverse of state of the art of machine tool design in developed countries. Instead of including several operations in a single machine for every operation an individual module will be put. For every kind of manufacturing operation a module can be used. Module can be created for turning, boring, milling, gear cutting, grinding, laser operations and even for simple assembly work. Figure 6 shows a module for turning. Figure 7 shows a system comprising several modules. Like the elements of a chain modules can be put together depending of market demand.

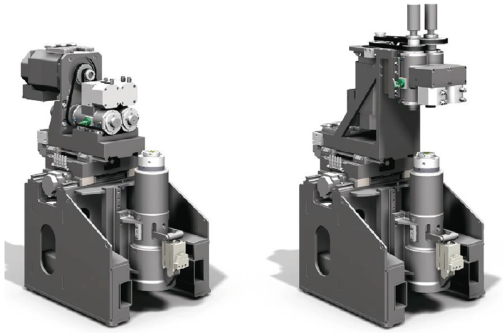

Fig. 6. A module of CATENA system for turning operation [18]

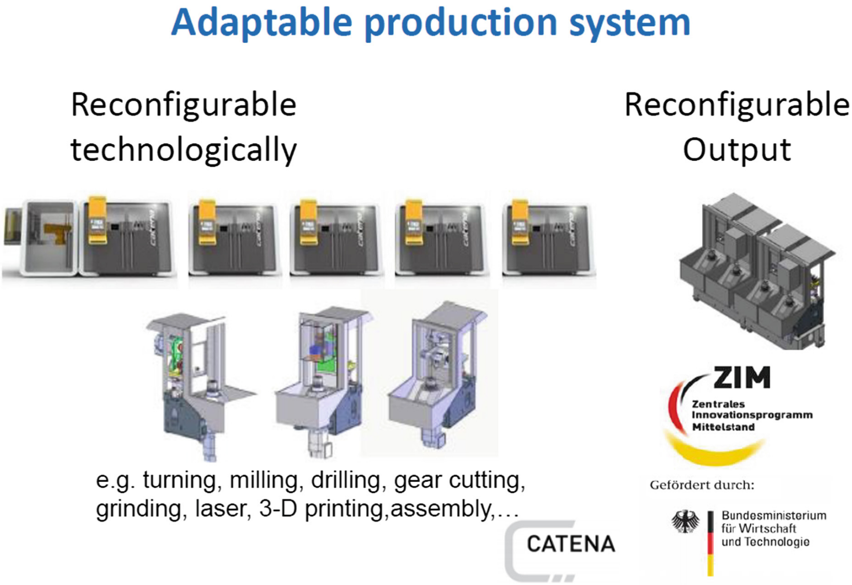

Fig. 7. Adaptable production system following CATENA principle [18]

The solution shown here has been realized as a prototype in Germany. The project was funded by the German Government within the program ZIM [18]. The machine is named as CATENA which means a chain in Latin language.

Indeed, the manufacturing system will be considered as a chain of modules for fulfilling a manufacturing order. The elements of the chain can be put together depending on operations and units. Changing the job or the volume the chain can be adapted easily.

CATENA fulfills all first four attributes of SMART thus leading to quick response to market demand and fulfilling the fifth attribute Timely to Market. Breaking down a manufacturing process into individual operations and allocating them to single modules represents a fundamental paradigm change in machine tool industry as well as in entire manufacturing. For transferring parts from module to module conveyor system with individual grippers will be used. The automatic transfer of work pieces is part of total CATENA philosophy. All set up operations at modules can be executed parallel to running process so that the changeover to a new manufacturing order is only the replacement or reorder of modules. Thanks to standardized electrical and mechanical interfaces the change over time could be kept within few minutes.

Last but not least CATENA could be an enabler of future Smart Factories thanks to its attributes derived from SMART. Various new business models can also be realized.

The utilization of reconfigurable manufacturing systems such as CATENA requires fundamental change in engineering. After having applied the current way of engineering over centuries it may be a matter of generations to switching to new philosophy. The characteristics of the markets of the future could accelerate the realization of reconfigurable manufacturing systems following CATENA philosophy.

5 Conclusion

The paper elaborates the development of machine tools since the introduction of numerical controls. The innovations were dominated by technological considerations. Key point was how to enhance the sophistication of a machine tool so that complex parts could be produced with single chucking without additional setups.

Digitalization changed the market attitude of individuals as well as companies. The current century is dominated by On Demand Economy. This new market characteristic requires easy adaptable, so called reconfigurable manufacturing systems. In the paper the necessity of a paradigm change will be worked out. SMART machines following CATENA philosophy will be introduced.

The new approaches could also initiate further improvements in developing and emerging countries thus contributing to Sustainable Development Goals (SDGs) of United Nations.

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Statistical Study of Parameters in the Process of Orthogonal Cutting Surface Hardness

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Abstract. This paper is a development of the study of hardness of workpiece surface layer, case of C45 steel orthogonal cutting, as function of cutting regime parameters and forces and geometry of the cutting tool [1]. The size of the experimental data imposed an extended use of computer assisted statistical applications. The influence of cutting parameters and radius of the cutting tool on hartness was modeled with all variables and their interactions, seven factors, based on a multivariate regression function. The model with three factors was a sinthetic application for this dependence and we established that the mainly influence on hardness is due to the factor radius of tool, which explained reliability. The dependence of hardness from cutting forces, modeled with a bivariate copula, proved a strong dependence of the variable HV.

Keywords: Hardness · Experimental design · ANOVA

1 Introduction

The Big Data generated by Cyber Manufacturing Systems [3] should be analytically processed and managed by Cyber-Physical Manufacturing or Cyber Physical Systems with functional entities, like intelligent data management, analytics and computational capability, which construct the cyber space. The extended use of computers and software supposes the application of the advanced statistics, as example in manufacturing [7]. The present paper applies on a large scale such tools in the study of hardness of workpiece surface layer, in steel orthogonal cutting, as function of cutting regime parameters and forces and geometry of the cutting tool.

2 A Preliminary Data Analysis

For a preliminary statistical evaluation of the experimental data it was chosen a random sample [1]. It is important to study the hypothetical dependence of the hardness from the three factors: cutting speed, depth of cut and tool radius, each at two levels (Table 1). In the Table 2 it is described an orthogonal design of experiments [5]. In the Fig. 1 it is illustrated main effects and interactions of the chosen factors [14]. It is

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obvious that the factor radius has the biggest influence on hardness and, in a less measure, the factor depth of cut.

Table 1. The levels of the three factors

Factor name	Factor letter	Low setting	High setting
Cutting speed	vc	15	60
Depth of cut	ap	0.1	0.4
Radius	r	0.1	0.4

Table 2. The orthogonal design of experiments

	Run Order	vc	ap	r	AxB	AxC	BxC	AxBxC	HV
1	6	15	0.1	0.1	1	1	1	-1	268
2	8	15	0.1	0.4	1	-1	-1	1	307
3	1	15	0.4	0.1	-1	1	-1	1	286
4	4	15	0.4	0.4	-1	-1	1	-1	315
5	2	60	0.1	0.1	-1	-1	1	1	277
6	5	60	0.1	0.4	-1	1	-1	-1	276
7	3	60	0.4	0.1	1	-1	-1	-1	291
8	7	60	0.4	0.4	1	1	1	1	316

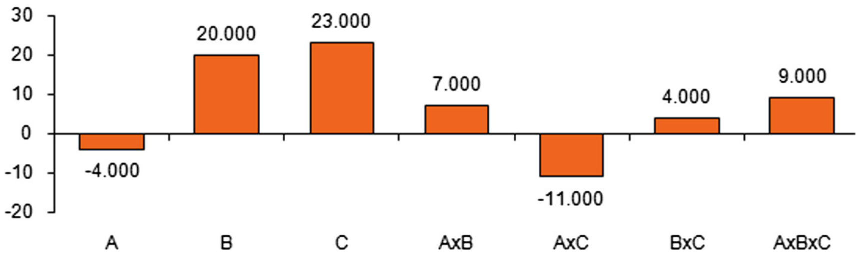


Fig. 1. Main effects and interactions

As example, using [14] it was detailed the case of the interaction between the cutting speed and the depth of cut (Fig. 2), showing a small interaction.

A x B Interaction

		B LO	B HI
A LO	1	268	288
	2	307	315
	Avg	287.5	301.5
A HI	1	277	291
	2	276	316
	Avg	276.5	303.5

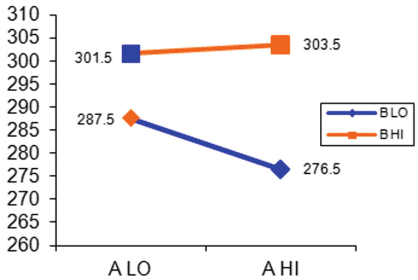


Fig. 2. Interaction A $\times$ B

3 A Regressional Data Model

It was supposed that the hardness depends of three factors, each with two levels, for a total of eight experiments. For the three factors the smallest factorial design has 2^3 treatments, with three degrees of freedom of main effect, three degrees of freedom for two-interaction factors and one three-interaction factors (Table 3).

Table 3. The values of the regression factors

Vc	ap	r	vc * ap	vc * r	ap * r	vc * ap * r	HV
15	0.1	0.1	1.5	1.5	0.01	0.15	268
15	0.1	0.4	1.5	6	0.04	0.6	307
15	0.4	0.1	6	1.5	0.04	0.6	286
15	0.4	0.4	6	6	0.16	2.4	315
60	0.1	0.1	6	6	0.01	0.6	277
60	0.1	0.4	6	24	0.04	2.4	276
60	0.4	0.1	24	6	0.04	2.4	291
60	0.4	0.4	24	24	0.16	9.6	316

For this design an adequate model would be:

$$x_{ijl} = \mathrm{m} + \alpha_i + \beta_j + \gamma_l + \alpha\beta_{ij} + \alpha\gamma_{il} + \beta\gamma_{jl} + \alpha\beta\gamma_{ijl} + u_{ijl}, \tag{1}$$

where $\alpha_i, \beta_j, \gamma_l, \alpha\beta_{ij}, \alpha\gamma_{il}, \beta\gamma_{jl}, \alpha\beta\gamma_{ijl}$ are real effects (for example $\alpha_i = (m - m_\mathrm{i})$ and the indices i, j and l run up to the number of levels of factors.

The following function should be determinate from the experimental data:

$$\mathrm{HV} = \mathrm{a} + \mathrm{bv_c} + \mathrm{ca_p} + \mathrm{dr} + \mathrm{ev_c} + \mathrm{fv_c a_p} + \mathrm{ga_p r} + \mathrm{hv_c a_p r}, \tag{2}$$

where the coefficients a, b, c, d, e, f, g, h will be calculated [8].
The numerical equation is:

$$\begin{aligned}\mathrm{HV} = {} & 238.7 + 0.62\mathrm{v_c} + 88.9\mathrm{a_p} + 198.9\mathrm{r} - 1.185\,\mathrm{v_c r} - 3.8\,\mathrm{v_c a_p} \\ & - 244.4\,\mathrm{a_p r} + 8.9\,\mathrm{v_c}\,\mathrm{a_p r}.\end{aligned} \tag{3}$$

The interpretation of the obtained parameters is: the growth with one unit of $\mathrm{v_c}$ implies a increasing with 0.6148 of the HV, while the growth with one unit of r implies a increasing with 198.9 of the HV, etc. We see that the variable r is the most significant factor. Therefore it will insist on the dependence of HV by r.

For a better analysis it should calculate the correlation matrix of the chosen factors. The results are presented in the Table 4.

Table 4. Correlation matrix with interactions

	vc	ap	r	vc * ap	vc * r	ap * r	vc * ap * r	HV
vc	1							
ap	−0.167	1						
r	−0.167	−0.167	1					
vc * ap	0.575	0.575	−0.34	1				
vc * r	0.575	−0.34	0.575	0.0246	1			
ap * r	−0.34	0.575	0.575	0.0246	0.0246	1		
vc * ap * r	0.445	0.445	0.445	0.59	0.59	0.59	1	
HV	−0.39	0.477	0.586	0.0676	−0.154	0.78	0.36	1

It is clear that r, a_p have the biggest correlation values with HV, and therefore their interaction, ap * r, too. The correlation matrix of these three factors is illustrated in Table 5.

Table 5. Reduced matrix correlation

	ap	r	ap * r	HV
ap	1			
r	0	1		
ap * r	0.650945	0.650945	1	
HV	0.574485	0.660658	0.848884	1

It follows regression analysis: HV versus ap, r, ap * r (Table 6).

Table 6. The results of analysis of variance

Source	DF	Adj SS	Adj MS	F-value	P-value
Regression	3	1890	630	4.72	0.084
a_p	1	94.12	94.12	0.71	0.448
r	1	141.24	141.24	1.06	0.362
a_p * r	1	32	32	0.24	0.650
Error	4	534	133.5		
Total	7	12424			

The model summary gives the following values:

$$S = 11.5542; \text{R-sq} = 77.97\%; \text{R-sq(adj)} = 61.45\%; \text{R-sq(pred)} = 11.88\%. \quad (3)$$

The regression coefficients are: constant 261.7, a_p = 52.9; r = 54.4; a_p * r = 89 and the regression equation is:

$$HV = 261.7 + 52.9a_p + 54.4r + 89a_p r \quad (4)$$

This equation confirms the major influence of the selected factors, but the main variable remains the radius r.

4 Analysis of Hardness's Dependence from Tool Radius

The above calculi proved that the factor radius has the main effect on the hardness. Therefore it is proposed a practical model as following: the dependence of HV only of the independence variable r, an easier way to estimate the hardness variation.

In the beginning of this paragraph it will analyzed if it exists significant differences between the 4 levels of the factor radius with one-way ANOVA method. In this case the null hypothesis is:

$$H_0 : m_1 = m_2 = m_3 = m_4 \quad (5)$$

versus the alternative hypothesis:
H_a: It exists minimal two different averages, $m_i \neq m_j$, i, j = 1, 2, 3, 4, $i \neq j$ (Table 7).

Table 7. The results ANOVA for different radius levels

Anova: Single factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
r = 0	6	1607	267.8	49.3		
r = 0.1	12	3377	281.4	154.6		
r = 0.2	10	2976	297.6	315.8		
r = 0.4	12	3651	304.25	824.2		
ANOVA						
Source of variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	6844	3	2281.2	5.92	0.00215	2.866
Within groups	13856	36	384.9			
Total	20700	39				

Because:

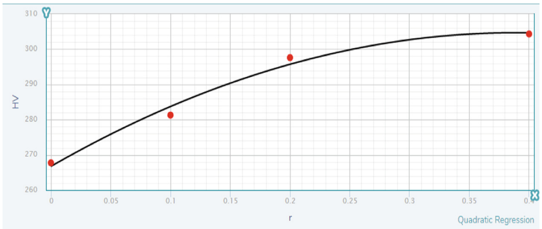
$$F_{empiric} = 5.926713 > 2.866266 = F_{critical} \quad (6)$$

and simultaneously

$$P\text{-value} = 0.00215 < 0.05 = \alpha, \quad (7)$$

thus there is a strong evidence that the levels of radius are different influences on hardness.

It results that alternative hypothesis is not rejected with a 0.95 confidence level. With other words, the measure of hardness depends of the value of the radius. In the Fig. 3 are given the experimental values of the independence variable, radius, r, and values of the dependence variable, hardness, HV.



r	HV
0	267.75
0.1	281.29
0.2	297.61
0.4	304.34

Fig. 3. Fitted curve and values of r&HV

The fitted curve is a parabola:

$$y = a + br + cr^2 \tag{8}$$

The obtained function for the experimental data has the expression:

$$y = 266.8159 + 194.6705r - 250.2045r^2 \tag{9}$$

The goodness of fit is represented by the high value of $R^2 = 0.9869 - 1$, which gives the ideal fit. With other words the explained variation by the parabola represents 98.69% to the total variation. Simultaneously p-value = 0.1144 > 0.05 = α proved the goodness of fit.

The root - mean - square of the residuals has a small value, SE = 3.266, and thus the regression curve explains much of the variation.

The 0.95 - confidence intervals for the coefficients are:

$$\begin{aligned} &263.6869 \le a \le 269.9449, \\ &154.9505 \le b \le 234.3905, \\ &-342.3045 \le c \le -158.1045. \end{aligned} \tag{10}$$

5 Hardness's Copula as Function on Cutting Forces

To study the dependence of hardness from cutting forces it was taken a sample of size 20 treatments from the experience design [1] (Table 8), with the values of the main components of the cutting force F_z, F_y and of the dependence variable HV. The chosen model for the link between forces is the bivariate Nataf copula [2, 4], because their Pearson correlation coefficient has a big value, $\rho = 0.875401$.

Table 8. Experimental values of forces and hardness

Fy	482	506	817	1599	676	685	637	757
Fz	891	776	1853	3448	1359	1347	992	937
HV	262	271	276	269	257	272	260	287
FempHV	0.11	0.274	0.405	0.228	0.054	0.298	0.082	0.709
Bi(Fy,Fz)	0.086	0.080	0.243	0.724	0.162	0.163	0.119	0.128

Fy	1091	1866	1300	1457	1596	2760	1362	1284
Fz	2440	3109	1438	1328	2821	3563	1880	1757
HV	278	285	290	292	290	311	286	280
FempHV	0.461	0.658	0.778	0.819	0.778	0.988	0.684	0.518
Bi(Fy,Fz)	0.407	0.822	0.296	0.265	0.7	0.953	0.441	0.391

Fy	846	819	1620	2379
Fz	1206	997	3005	3487
HV	267	267	291	296
FempHV	0.187	0.187	0.799	0.885
Bi(Fy,Fz)	0.183	0.144	0.724	0.936

As a necessary preliminary condition was first tested the normal distribution of the force components and of their bivariate distribution with Lilliefors (Kolmogorov-Smirnov) test [12]. For F_y:

$$D = 0.17474, \text{p-value} = 0.1321 > 0.05 = \alpha, \tag{11}$$

For F_z:

$$D = 0.18837, \text{p-value} = 0.07457 > 0.05 = \alpha, \tag{12}$$

It is obvious that the forces should be modeled by normal distributions. The hypothesis of the normality for the bivariate copula [6] was proved with Mardia test.

Similarly was tested the normality of HV values (row 3 in Table 8).

The results of the calculi of the values of the binormal distribution [9], copula function, are given in row 4 of the Table 8.

The concordance between values of the empirical distribution function of the hardness, FempHV, and the values of the bivariate copula, Bi(Fy, Fz), (rows 4 and 5 in Table 8) was analyzed with different correlation coefficients [10, 11]:

- Pearson correlation coefficient r = 0.6647 p-value = 0.0014
- Spearman correlation coefficient r_S = ρ(rho) = 0.6764 p-value = 0.0011
- Kendall correlation coefficient $\tau = 0.5185$ p-value = 0.0015.

Similarly was calculated the Pearson correlation coefficient for pairs F_y and HV (0.823688), and $F_{z,}$ HV (0.594773). It is confirmed the strong dependence between the force, F_y, perpendicular on the surface, and hardness, what permits the estimation of hardness based on the values of the force. Another remarkable result is the stronger link between the copula values, Bi(Fy, Fz), and of the force F_y (r = 0.94). An illustration of this concordance is reproduced [13] in the Fig. 7. The bivariate kernel density plot is illustrated in the Fig. 4. In the Figs. 5 and 6, respectively, are ploted the empirical values of the functions HV(Fy, Fz), respectively C(Fy, Fz).

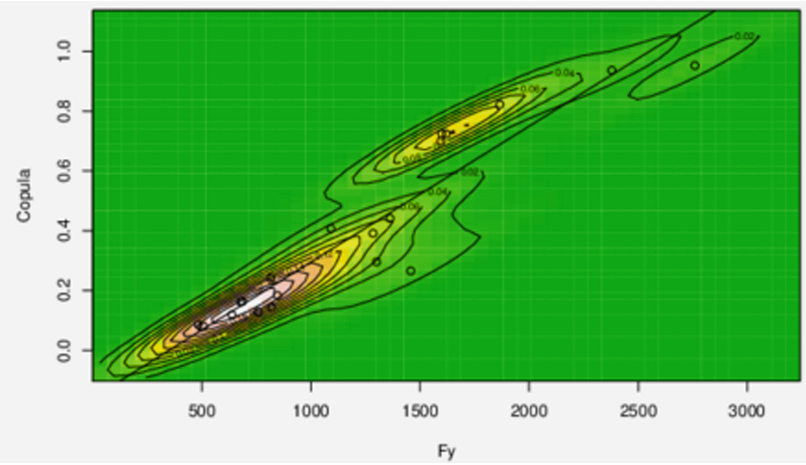


Fig. 4. Bivariate kernel density plot

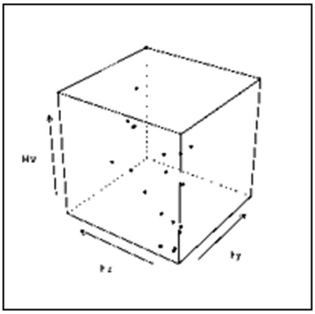


Fig. 5. The values of the HV(Fy, Fz)

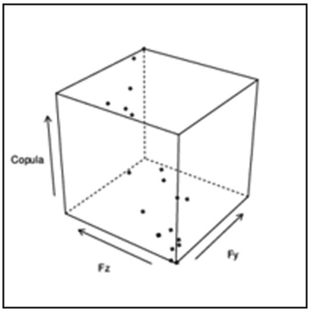


Fig. 6. The values of the C(Fy, Fz)

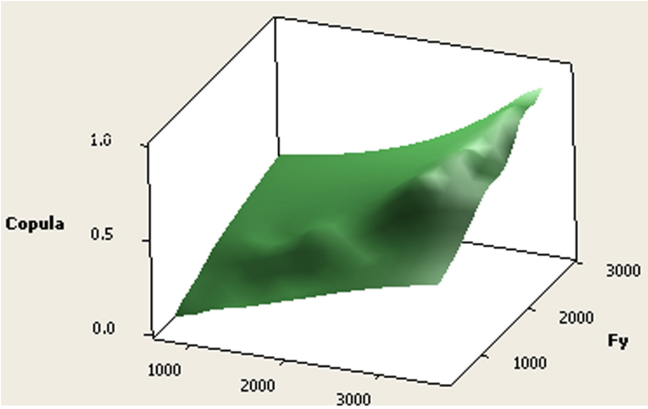


Fig. 7. Responce surface of the Bi(Fy, Fz)

6 Conclusion

This paper has presented a sequel of the article [1] with statistical processing of the experimental data. The dependence of hardness of piece surface layer from cutting regime parameters and forces, and geometry of the cutting tool is the kernel of the study. The size of experimental data requires an extended use of computer assisted statistical applications. In the beginning it was applied a model with all variables and interactions, seven factors. At the first glance seems that a_p, r, $a_p * r$ are statistical significant with more influence of radius. The model used is a linear regression function with these three factors. It is clear that the dominant factor is the radius too. As consequence, it was applied a quadratic model with variable r and it was concluded that this factor indeed is dominant. A bivariate copula modeled the concordance between hardness and cutting forces. The correlation coefficient of the empirical disarranged values of the hardness distribution function and the values of obtained copula function, r = 0.6647, proved a good concordance.

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Industry 4.0 Programs Worldwide

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Abstract. Since 2011, when Industry 4.0 has entered the scene, national programs for its development and application in national industries have been launched around the world. In the meantime, this Program has begun to develop in different countries, until now thirty seven worldwide. Industry 4.0 is Program initiated by German Government and industry as a new model of automatization of manufacturing technologies. Cyber-Physical System (CPS) is the key element of Industry 4.0. In this paper, a detailed analysis of the current level of development of the Industry 4.0 program has been made in globe. Also, overview of the Industry 4.0 program in Serbia is given as well.

Keywords: Industry 4.0 · Programs · Analysis

1 Introduction

In the currently rapidly changing industrialized world, globalization, product customization and automation are playing an imposing role in the development of the manufacturing industry. The manufacturing industry is on the top of the Industry 4.0, bringing with it advanced technologies and techniques that will change the products, processes and supply chains involved in every aspect of industry. This technology ushers in even greater connectivity that will allow manufacturers to maintain their competitive edge in a rapidly changing world, and respond flexibly and quickly to customers' requirements [1].

Industry 4.0 in manufacturing sector, there are three areas where it will support [2, 3]: (a) smart supply chains – greater coordination and real time flow of information across supply chains and relationships allows better tracking of assets and inventory and integrated business planning and manufacturing. This unlocks new ownership and collaboration models across supply chains; (b) smart manufacturing – the use of data analytics and new manufacturing techniques and technologies (such as autonomous robots, multi-purpose manufacturing lines and augmented reality) helps to improve yield and speed up manufacturing. This allows new business models to be pursued such as mass customization, and (c) smart products – rapid innovation and a faster time to market is enabled by data collected from products along with user feedback, whether direct or collected via social sentiment on the internet. This data also allows remote diagnostics and predictive maintenance.

Industry 4.0 is the information-intensive transformation of manufacturing and other industries in a connected environment of data, people, processes, services, systems and Internet of Things (IoT) - enabled industrial assets with the generation, leverage and

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utilization of actionable information as a way and means to realize smart industry and ecosystems of industrial innovation and collaboration.

Industry 4.0, a German strategic initiative, is aimed at creating intelligent factories where manufacturing technologies are upgraded and transformed by cyber-physical systems (CPSs), the IoT, and cloud computing [4–6].

This paper has three parts: basics of concept Industry 4.0, I4.0 programs worldwide - comparative analysis and I4.0 program for Serbia.

2 Industry 4.0 Framework and Basic Pillars

Original definition of Industry 4.0 is:

> *"Industry 4.0 is a German-government-sponsored vision for advanced manufacturing. The underlying concept of Industry 4.0 is to connect embedded systems and smart manufacturing facilities to generate a digital convergence between industry, business and internal functions and processes. Industry 4.0 refers to a fourth industrial revolution (following water/steam power, mass manufacturing and automation through IT and robotics) and introduces the concept of "cyber-physical systems" to differentiate this new evolutionary phase from the electronic automation that has gone before"* [7].

This definition contains several key words, and the most important is – advanced manufacturing. This means that advanced manufacturing is the basis for the fourth industrial revolution, with industrial manufacturing being integrated into digital technologies on the Internet. Industry 4.0 is the original German term. In the same context, the following terms are used worldwide: a smart factory, a factory of the future, intelligent manufacturing.

Industry 4.0 defines a methodology to generate a transformation from machine dominant manufacturing to digital manufacturing, by Cyber Physical Systems (CPS), cloud system, Big data and data mining, Machine to Machine (M2M) interfaces, Enterprise Resource Planning (ERP) and business intelligence, IoT, Augmented reality, simulation, Virtual Manufacturing and intelligent robotics, but also includes some additional features such as; facilitating system monitoring and diagnostics, the system is environmentally friendly and sustainable through resource saving behaviors, more efficiency systems [8].

Today, eight years after the official presentation of the German Industry 4.0 concept, we can talk about the two most important aspects of this model: practice and research. The first aspect is characterized by 37 national programs around the world, which is thoroughly analyzed in Sect. 3.

The nine pillars and forty two elements of Industry 4.0 will transform isolated and optimized manufacturing cells into a fully integrated, automated, and optimized manufacturing flow and the same time leads to greater efficiency and change in traditional manufacturing relationships among suppliers, producers, and customers as well as between human and machine [6, 8].

2.1 Cyber Physical Systems (CPS)

CPS has been defined as the systems in which natural and human made systems (physical space) are tightly integrated with computation, communication and control systems (cyber space) [5]. Decentralization and autonomous behaviour of the manufacturing process are key characteristics of CPS. The continuous interchanging of data is carried out by linking CPSs intelligently with the help of cloud systems in real time, and digital shadow (digital twins) of manufacturing is defined as the representation of physical object in virtual world [9]. Used by proper sensors in CPS should find out the failure occurring in machines and automatically prepare for fault repair actions, and also finds the optimum utilization of each work station with the help of cycle time required for the operation performed on that station. For control, the 5C structure uses cloud computing to communicate with the machines (machine with machine or human with machine) [1, 5]. In Industry 4.0 model we have the increased connectivity and use of standard communications protocols, which the need to protect critical elements of industrial and manufacturing systems from cyber security threats increases dramatically. As a result, secure, reliable communications as well as sophisticated identity and access management of machines and users are essential [7].

2.2 The Industrial Internet of Things (IIoT)

The Internet of Things (IoT) is a novel paradigm that is rapidly gaining ground in the scenario of modern wireless telecommunications. The basic idea of this concept is the pervasive presence around us of a variety of things or objects – such as Radio – Frequency IDentification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals [10]. By IoT a worldwide network of interconnected and uniform addressed objects that communicate via standard protocols. Today we have several approaches IoT should also know as Internet of Everything (IoE) which consists of Internet of Service (IoS), Internet of Manufacturing Services (IoMS), Internet of People (IoP), an embedded system and Integration of Information and Communication technology (IICT) [7]. In Industry 4.0 model usually we used term – IIoT. Context, omnipresence and optimization are the three key features of IoT in which context refers the possibility of advanced object interaction with an existing environment and immediate response if anything changes, omnipresence provide information of location, physical or atmospheric conditions of an object and optimization illustrates the facts that today’s objects are more than just connection to network of human operators at human-machine interface. The value chain should be intelligent, agile and networked by integrating physical objects, human factors, intelligent machines, smart sensors, manufacturing process and lines together across the boundaries of organization [11]. Near Field Communications (NFC) and Wireless Sensor and Actuator Networks (WSAN) together with RFID are recognized as “the atomic components that will link the real world with the digital world”.

2.3 The Cloud Computing

It is a general term that refers to delivering computational services through visualized and scalable resources over the Internet [12]. Based on recommendations from the National Institute of Standards and Technology (NIST), an ideal cloud should have five characteristics: on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service. This cloud model is composed of four deployment models public, private, community, and hybrid and three delivery models "software as a service," "platform as a service," and "infrastructure as a service" [13]. Organizations of all types and sizes are adopting cloud computing to increase their capacity with a minimum budget and without investing in licensing new software, incorporating new infrastructure, or training new personnel [7]. Cloud manufacturing refers to an advanced manufacturing model under the support of cloud computing, the IoT, virtualization, and service-oriented technologies, which transforms manufacturing resources into services that can be comprehensively shared and circulated [8]. In Industry 4.0 model, organization needs increased data sharing across the companies and supply chains, achieving the reaction times in milliseconds or even faster.

2.4 Big Data and Analytics (BDA)

Big data typically stems from various channels, including sensors, devices, video/audio, networks, log files, transactional applications, the web, and social media feeds [7]. The collection and comprehensive evaluation of data from many different sources manufacturing equipment and systems as well as enterprise and customer-management systems will become standard to support real-time decision making. Therefore, for organizations and manufacturers with an abundance of operational and shop-floor data, advanced analytics techniques are critical for uncovering hidden patterns, unknown correlations, market trends, customer preferences, and other useful business information. In most industries, putting customer relationship management (CRM) data into analytics is considered to be an effective way to enhance customer engagement and satisfaction [14]. Moreover, a deeper analysis of various data from machines and processes can realize the productivity and competitiveness of organizations. In the manufacturing flow of biopharmaceutical production, have hundreds of variables must be monitored to guarantee the accuracy, quality, and yield.

2.5 System Integration: Horizontal and Vertical System Integration

Integration and self-optimization are the two major mechanisms used in industrial organization by Industry 4.0 model [1]. The paradigm of Industry 4.0 is essentially outlined by three dimensions of integration: (a) horizontal integration across the entire value creation network, (b) vertical integration and networked manufacturing systems (c) end-to-end engineering across the entire product life cycle [9]. The full digital integration and automation of manufacturing processes in the vertical and horizontal dimension implies as well an automation of communication and cooperation especially along standardized processes [11].

2.6 Simulation

In this case used more extensively in plant operations to leverage real-time data to mirror the physical world in a virtual model, which can include machines, products, and humans, thereby driving down machine setup times and increasing quality [2]. 3D simulations can be created for virtual commissioning and for simulation of cycle times, energy consumption or ergonomic aspects of a manufacturing facility. Uses of simulations of manufacturing processes can not only shorten the down times and changes it but also reduce the manufacturing failures during the start-up phase [5]. Decision making quality can possibly be improved by easy and fast way with the help of simulations, also.

2.7 Autonomous Robots

In Industry 4.0 concept robots are becoming more intelligent, autonomous, flexible, and cooperative, interact with one another and work safely side by side with humans and learn from them [7]. An autonomous robot is used to perform autonomous manufacturing method more precisely and also work in the places where human workers are restricted to work. Also, autonomous robots can complete given task precisely and intelligently within the given time limit and also focus on safety, flexibility, versatility and collaboratively [15].

2.8 Additive Manufacturing

With Industry 4.0, additive-manufacturing methods will be widely used to produce small batches of customized products that offer construction advantages, such as complex, lightweight designs. High-performance, decentralized additive manufacturing systems will reduce transport distances and stock on hand [7]. The manufacturing should be faster and cheaper with the use of additive manufacturing technologies like fused deposition method (FDM), selective laser melting (SLM), and selective laser sintering (SLS) [16]. Decreasing product life cycles in combination with the growing demand of customized products asks for the further transformation towards organization structures which lead to increased complexity [7].

2.9 Augmented Reality

Augmented-reality-based systems support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices. Industry can use of augmented reality to provide workers with real- time information to improve decision making and work procedures by augmented reality glass. Workers may receive repair instructions on how to replace a particular part as they are looking at the actual system needing repair [7].

As you see, the discovery of new technologies has made industry development from the early adoption of mechanical systems, to today's highly automated manufacturing/assembly lines, in order to be responsive and adaptive to current dynamic market requirements and demands. Challenges like embedment, predictability, flexibility and robustness to unexpected conditions [17]. In summary there are some challenges and fundamental issues occurs during the implementation of industry 4.0 in the current manufacturing industries are given as:

- *Modularized and Flexible Physical Objects*: When processing a product, equipment for machining or testing should be grouped and worked together for distributed decision making [17]. So there is a need of creating modularized and smart conveying unit that can dynamically reconfigure the manufacturing routes.
- *System Modelling and Analysis*: In system modelling, to reduce dynamical equations and conclude appropriate control model, systems should be modelled as self-organized manufacturing system [17]. The research is still going on for complex system.
- *Manufacturing Specific Big Data and Analytics*: It is a challenge to ensure high quality and integrity of the data recorded from manufacturing system. The annotations of the data entities are very diverse and it is an increasing challenge to incorporate diverse data repositories with different semantics for advanced data analytics [2].
- *Intelligent Decision-Making and Negotiation Mechanism*: In smart manufacturing system needs more autonomy and sociality capabilities as key factors of self-organized systems whereas the today's system have 3C Capabilities i.e. lack of autonomy in the systems [17].
- *High Speed IWN Protocols*: The IWN network used today can't provide enough bandwidth for heavy communication and transfer of high volume of data but it is superior to the weird network in manufacturing environment [17].
- *Cyber Security Data*: With the increased connectivity and use of standard communications protocols that come with Industry 4.0, the need to protect critical industrial systems and manufacturing lines and system data from cyber security threats increases dramatically [18].
- *Investment Issues and Aspect*: Investment issue is rather general issue for most of new technology based initiatives in manufacturing. The significant investment is required for implementing industry 4.0 is an SME initially. The implementation of all the pillar of industry 4.0 requires huge amount of investment for an industry [19].

As the implementation of the industry 4.0 increases new research streams should be discovered like transparent and organized supply chain and industrial management, data collection from the manufacturing lines and optimization of that data for the use of effective machines, energy saving, optimized maintenance scheduling and increasing product and process quality.

3 Industry 4.0 Initiatives Worldwide

This naturally requires a philosophical change in setting up new manufacturing facilities and leads to a new manufacturing vision to be based on Industry 4.0 basic concepts including intelligence, products, communication, and information network. In

[20] clearly outlines this progress and suggests the following recommendation for better transformation towards Industry 4.0 application:

- Starting point is the "*vision*". Industry 4.0 is a part of smart networked world and the philosophy includes novel business, new social infrastructures and real time enabled Cyber Physical System platforms. These factors should definitely be taken into account in generating the road maps for digital transformation.
- Second point is so called the "*dual strategy approach*". Since leading supplier strategy and leading market strategy are becoming important day by day, the manufacturing strategy is said to be based on these two.
- Third point is the capability of the companies to outline their "*requirements*". Firms should determine their needs by an in-depth analysis and see their strong and weak points.
- Fourth point is determining the "*priority areas*". A ranking should be made to strengthen the weak spots. All problems must be resolved in sequence with the available resources and the time schedule given. Managing complex systems, delivering infrastructure for industry, safety and security factors, regularity framework is to be the main body of road map for implementing Industry 4.0.

In this chapter we show the I4.0 programs worldwide - comparative analysis.

3.1 Programs of Industry 4.0 in EU Members

Members of EU - I4.0 Programs Facts and Figures can be defined as:

- Total Countries – 18 (from the 27 members), support by Government/Ministries.
- Leaders by developing and application Program (Germany, Italy, France, Spain, Sweden).
- Total budgets for all countries – 2014/2019, app 34 b Euros.
- Policy Industry 4.0 is overarching framework strategy, of the *research, innovation and industrial policies,* especially for manufacturing.
- Focus on delivering next-generation technologies (Italy, Sweden), developing new products and improving industrial processes (Germany, Holland), providing support to SMEs for innovation and commercialisation (France and Spain) feature amongst the prominent goals.
- Sectoral focus – no, Internet of Things (IoT)/Cyber - Physical Systems (CPS) are the most common technology focus areas.
- While the major national I4.0 policies significantly rely on public funding.
- Results and outcomes: France, more than 800 company loans and 3400 diagnoses have been realized; the Swedish P2030 funded 30 projects with participation of over 150 businesses; the German I4.0 initiative, the transformation of research into practical applications and the creation of the platform's reference architecture with 150 members.
- While the majority of this collaborations is between different actors and across various governance levels.
- Last but not least, the initiative of public authorities in pushing forward the I4.0 policies is also among the key drivers (Table 1).

Table 1. Established programs for I4.0 in EU for 18 Member States - state of March 2018.

Country	*Launched / Responsible*	*Target audiences*	*Concepts and focus areas*	*Approach*	*The heart of the measures*	*Funding model*
 **1.Austria** / Industrie 4.0 Osterreich Produktion der Zukunft / Plattform Industrie 4.0 for Intelligent Production [1,2].	Launched in 2014 / Ministry for Transport, Innovation and Technology.	Companies; research organisations; universities; policy-makers at national and regional level; trade unions; employees' associations	Norms and standards; Research, development and innovation; Qualification and skills for Industry 4.0; Regional strategies; The human in the digital factory; Smart logistics.	Creating a common national model of industry 4.0 and exploit its benefits for everybody. Bottom – up.	App 100 Enterprises.	App 500 m euros per year, support of public and private sector.
 **2.Belgium** / The Made Different – Factories of the Future [1,2].	Launched in 2013 / The Government of Belgium	Companies; research organisations; universities.	A strong innovation and design competence; Customer orientation and networking; Energy - and material-efficient technologies; Creative human potential.	Transform manufacturing companies into ´Factories of the Future´. Bottom – up.	Manufacturing companies from all economic sectors, in particular SMEs.	No dedicated funding scheme; several public grants available; participating companies need to cover a share of participation costs.
…  **18.Sweden** / "Produktion 2030" [1,2].	Launched by VINNOVA, Sweden's innovation agency, and industry, on 2013.	Strategy for new industrialization. The Swedish Production Academy, representing ten universities, Swerea IVF, an industry research group.	Sustainable production, flexible manufacturing processes, virtual production, human-centered production, product and production-based services, and integrated production and production development.	Bottom-up approach. Industry and research stakeholders with an emphasis on innovation, research and industrial challenges in production.	Funded 30 projects, involved over 150 businesses, set up a PhD school and obtained 50% industry co-financing.	€25 million offered by VINNOVA for 2013-2018 period complemented by approx. €25 million from industry.

Source: [1] https://ec.europa.eu/growth/tools-databases/dem/monitor/category/national-initiatives; [2] https://ec.europa.eu/futurium/en/implementing-digitising-european-industry-actions/national-initiatives-digitising-industry.

3.2 Programs of Industry 4.0 in Non-members EU

Non - members of EU - I4.0 Programs Facts and Figures can be defined as:

- Total countries with I4.0 Program in practice from Europe – 21 (18 + 3).
- The UK's national initiative to business, industry and research organizations.
- Developing large scale projects (LSP).
- Developing cross center capability and competence.
- Creating collaborative relationships with universities.
- Manufacturing sector businesses - SMEs or large companies.
- €203 million budget in 2015/2016 (Table 2).

3.3 Programs of Industry 4.0 in America and Africa

Facts and Figures for I4.0 program in these geographical areas can be defined as:

- Total Countries number – six (North America - 2, Central America -1, South America - 2, Africa - 1).
- Leader: USA.
- Industry 4.0 platform, big companies in the USA initiate the start:
  - in March 2014 AT&T, Cisco, General Electric, IBM and Intel founded the Industrial Internet Consortium (IIC) in order to coordinate the priorities for the industrial Internet, and to enable the technical applications required for this,
  - meanwhile 250 companies have joined the movement, including some from Germany, and
  - the aim of the Industrial Internet Consortium is to bring together "operational systems".
- Industrial Internet Consortium and Platform Industry 4.0 are collaboration for Interoperability, based on:
  - RAMI 4.0, the focus is on manufacturing in depth and IIRA crosses multiple application domain,
  - industry as a whole and must work across domains; manufactured goods are one of those domains, and
  - interoperability by Vertical – Horizontal approach.
- Support for programs by Governments/Ministries (Tables 3 and 4).

Table 2. Programs for I4.0 in non-EU countries - state of March 2018.

<table>
<tr><th>Country</th><th>Launched / Responsible</th><th>Target audience(s)</th><th>Concepts and focus areas</th><th>Approach</th><th>The heart of the measures</th><th>Funding model</th></tr>
<tr><td>
UK / The High Value Manufacturing Catapult (HVMC) [1].</td><td>The UK's national initiative to increase the competitiveness and value added of its manufacturing industry, Established on 2012.</td><td>Business, industry and research organisations.</td><td>Developing large scale projects (LSP) to transform major manufacturing markets and supply chains; Developing cross centre capability and competence; Creating collaborative relationships with universities.</td><td>Improve the competitiveness of UK businesses by providing novel and effective technology solutions across the manufacturing sector.</td><td>Manufacturing sector businesses - SMEs or large companies - and research organisations including private and public organisations.</td><td>€203 million budget in 2015/2016.</td></tr>
<tr><td colspan="3">
Swiss
[2,4]</td><td colspan="4">The unique national Program for I4.0 just defined.
Faculties, research organizations, large companies and consulting organizations work on individual projects to implement the I4.0 model in practice.
In [2] was show a neutral and independent initiative for a smart Swiss and promotes sustainability the digital economics dvelopment in Swiss, established 2016.
Since 2016, an international Conference on Industry 4.0 is being organized.</td></tr>
<tr><td colspan="3">
Norway
[3,4]</td><td colspan="4">The unique national Program for I4.0 just defined.
Faculties, research organizations, large companies and consulting organizations work on individual projects to implement the I4.0 model in practice.
Since 2017, an international Conference on Industry 4.0 is being organized.</td></tr>
</table>

Source: [1] https://ec.europa.eu/futurium/en/implementing-digitising-european-industry-actions/national-initiatives-digitising-industry; [2] https://www.digitaleschweiz.ch/; [3] https://ec.europa.eu/digital-single-market/en/scoreboard/norway; [4] https://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-innovation-outlook/.

Table 3. Programs of I4.0 in North/Central America – state of March 2018.

Country	***Basic facts and figures***
 **USA** [1,2]	Big companies in the USA triggered the start: In March 2014 AT&T, Cisco, General Electric, IBM and Intel founded *the Industrial Internet Consortium (IIC)* in order to coordinate the priorities for the industrial Internet, and to enable the technical applications required for this, and meanwhile 250 companies have joined the movement. The White House released the quadrennial *Strategy for American Leadership in Advanced Manufacturing*, which describes how Federal agencies, state and local government, the full spectrum of educational institutions, large and small private industry, large and small investors and, most importantly, our citizenry can achieve a national vision of U.S in I4.0. ***Digital Manufacturing & Design Innovation Institute (DMDII)***, whose mission is to "establish a state-of-the-art proving ground for digital manufacturing and design that links IT tools, standards, models, sensors, controls, practices, and skills, and transitions these tools to the US design & manufacturing industrial base for full-scale application on I4.0 .
 **Canada** [3]	*The National Research Council-Industrial Research Assistance Program (NRC-IRAP)* is Canada's premier innovation assistance program for small and medium-sized enterprises (SMEs). The Canada-Germany Industry 4.0 Partnering Mission in Berlin, Germany from February 26 to March 2, 2018. The Canadian delegation, consisting of small and medium-sized enterprises (SMEs) & academic researchers active in the development or deployment of Industry 4.0 technologies will join leading players in German Industry 4.0 adoption. The aim is to establish collaborative applied research and development opportunities in Industry 4.0 sectors between Canadian and German companies and their academic partners, leading to future economic benefits for Canada-Germany.
 **Mexico** [4]	In 2019 and 2021, *Mexico will build up two hyper-flexible manufacturing clusters*. The clusters will develop an I4.0 framework and a Manufacturing Operating System. *a. I4.0 cluster framework* - A general framework must be developed in order to support the creation of a hyper-flexible manufacturing operating systems, this will be the platform for systems integration and applications development. These clusters should be supported according to the regional productive vocations and using the current infrastructure and capabilities, as well as the existing projects and collaboration mechanisms which include: price clubs; supply information systems; shared infrastructure; and technology packages; among others. *b. Innovation Campus replication for I4.0* - Identifying regions that fulfill the requirements to reply the innovation campus model developed by Continental and Volkswagen in Mexico whose main objective is to establish a collaborative environment between the academy and the private sector to develop innovation projects in Industry 4.0.

Source: [1] https://www.manufacturing.gov; [2] https://dmdii.uilabs.org/; [3] https://remapnetwork.org/2018/02/12/canada-germany-industry-4-0-partnering-mission/; [4] https://www.clusterinstitute.com/.

Table 4. Programs of I4.0 in South America and Africa – state of March 2018.

Country	***Basic facts and figures***
 **Argentina** [1]	In 2018. year, 8 out of 10 Argentine businessmen believe that digitizing their companies is critical aspect to carry out their innovation processes, however less than half (43%) have a team dedicated to digital innovation. In this complex scenario, Argentina has the unique opportunity to boost its digital transformation with the realization of strategic Program. For this reason, Chamber of Commerce Argentina organizes Alliance of the Industry 4.0 as Forum that will convene national and international experts. A main focus on the gradual technological integration of state-of-the-art digital systems, and activities on cross-cutting issues such as digitization, smart technologies and business models within the framework of Industry 4.0 Program in Argentina.
 **Brazil** [2]	The Brazilian government in March 2018 to start implementing a national I4.0/IoT plan, according to the country's Ministry of Science, Technology, Innovation, and Communications. The plan seeks to advance Brazil's I4.0/IoT ambitions across the four verticals of smart cities, agriculture, manufacturing, and healthcare. Increasing awareness of the benefits of Industry 4.0 and creating a strategy for implementation of 4.0 technologies will help drive the success of Industry 4.0 in Brazilian manufacturing.
 **South Africa** [3]	South Africa, the Trade and industry Chamber and Commerce starting with the Manufacturing Indaba 2018 to be set amidst the exciting backdrop of Industry 4.0 which aims to open a gateway of opportunities for existing and prospective manufacturers in the SA. More than a quarter (27%) of the industrial companies in SA have rated their level of digitization as high, and this value is expected to rise to 64% within the next five years.

Source: [1] http://www.ahkargentina.com.ar/eventos/foro-industria-40/; [2] https://internetofbusiness.com/brazil-national-iot-strategy/; [3] https://www.itweb.co.za/content/o1Jr5qxEX8ZvKdWL.

3.4 Programs of Industry 4.0 in Asia, Australia and New Zealand

For I4.0 program in these geographical areas can be defined as:

- Total Counties numbers: 8 (Asia) +2 (Australia and NZ).
- Those Support by Governments/Ministries.
- Leaders in application and context are: Japan, China and Australia.
- Japan realize its "Super Smart Society 5.0" strategy, the Japanese government initiated the "*5th Science and Technology Basic Plan*" in 2015-2020, to support Japan's manufacturing sector.
- The Japanese government has Plan for promote the development of technologies for *IoT, big data analytics, high-speed processing device, AI (artificial intelligence), networking, edge-computing and cyber security*.
- The Chinese government started the "*Made in China 2025*" (MIC 2025) Strategy together with the "*Internet Plus*" plan, which priorities ten fields in the manufacturing sector.
- The MIC 2025 initiative also includes ten key sectors that receive special attention: Next generation IT; High-end numerical control machinery and robotics; Aerospace and aviation equipment; Maritime engineering equipment and high-tech maritime vessel manufacturing; Advanced rail equipment; Energy-saving vehicles and NEVs; Electrical equipment.

In conclusion we can say that 37 countries in the world have a National Program for Industry 4.0 of 192 countries, UN members (Europe - 21, America - 5, Africa - 1, Asia - 8, and Australia/NZ - 2) (Tables 5 and 6).

3.5 Programs of Industry 4.0 Initiatives on Global Level

On global level, until 2016, we have joint activities regarding Industry 4.0 initiative, as:

- World Economic Forum – Davos, Swiss [21]:
  - The World Economic Forum, in collaboration with McKinsey and Company, has identified 16 "Manufacturing Lighthouses"; production sites which are world leaders in the successful adoption and integration of the cutting-edge technologies of the Fourth Industrial Revolution.
    Big data decision-making
    Democratized technology on the shop floor
    Agile working mode
    Minimal incremental cost to add use-cases
    New business models
    IoT architecture built for scale-up
    Capability-building through acquiring new skills
    Workforce engagement
- International Center for Industry 4.0 [22]:
  - Global network of Industrie 4.0 Digital Capability Center, Aachen (Germany, Singapore, China, the US and Italy.
- Alliancie:
  - Germany - Austria, G - Hungary, G - Holland, G - Brasil, G - Argentina, G - South Africa, G - Malaysia, G - Australia.

Table 5. Programs of I4.0 in Asia – state of March 2018.

Country	*Basic facts and figures*
 **Japan** [1]	Japan realize its "Super Smart Society" strategy, the Japanese government initiated the "*5th Science and Technology Basic Plan*" in 2015-2020, to support Japan's manufacturing sector. The Japanese government by Plan promote the development of technologies for *IoT, big data analytics, high-speed processing device, AI (artificial intelligence), networking, edge-computing and cyber security* as the "fundamental technologies necessary to build the super smart society service platform", as well as such technologies as those for *robotics, sensor and human interface* as the "fundamental technologies that are Japan's strengths, which form the core of new value creation."
 **China** [2]	To accelerate industrialization in Chinese manufacturing, in 2015, the Chinese government started the "*Made in China 2025*" (MIC 2025) Strategy together with the "*Internet Plus*" plan, which priorities ten fields in the manufacturing sector. In March 2015, Premier Li Keqiang formally announced the 'Made in China 2025' ("MIC 2025") initiative which aligned with the 13th Five Year Plan ("FYP"), Internet Plus and outbound focused policy of the Belt & Road Initiative ("BRI") is centred on reforming and modernising China's manufacturing sector. Influenced by the Industry 4.0 roadmap set out by Germany in 2013, Premier Li commented at the official announcement that 'Made in China 2025' will "upgrade China from a manufacturer of quantity to a manufacturer of quality". This roadmap has been established to build a thriving innovation led economy through to 2025 and beyond.
 **South Korea** [3]	To ensure competitiveness and continuous innovations in South Korea's manufacturing sector, in 2014 the South Korean government started the *"Innovation in Manufacturing 3.0"* initiative.Officially launched in June 2014, the Manufacturing Industry Innovation 3.0 strategy is part of the Park Geun-hye administration's flagship policy of the Creative Economy that aims to introduce innovation to the manufacturing process, including expanding the use of smart factories and developing core technologies related to the Internet of Things (IoT), 3-D printing and Big Data. Big Data refers to data processing, data collecting and data sharing that can be used for data analysis and prediction.
	The "*RIE2020*" Plan is the Singaporean's governments' commitment to *research, innovation, and enterprise (RIE)*. The initiative has a funding budget of S$19 billion from 2016 to 2020 and includes activities in four strategic technology

 **Singapore** [4]	domains that is supported by three cross-cutting programmes. To maximise impact, funding will be prioritised in four strategic technology domains where Singapore has competitive advantages and/or important national needs: *Advanced Manufacturing and Engineering (AME), Health and Biomedical Sciences (HBMS), Urban Solutions and Sustainability (USS), and Services and Digital Economy (SDE).* Activities in the four strategic technology domains will be supported by three cross-cutting programmes to ensure excellent science, a strong pipeline of skilled manpower, and value creation: *Academic Research, Manpower, and Innovation and Enterprise (I&E).*
 **Malaysia** [5]	The Ministry of International Trade and Industry, 2018, has taken the proactive measure to develop this *National Policy on Industry 4.0*, with the objective of transforming the Malaysian manufacturing industry and its related services to be smart, systematic and resilient. The goal for the future of manufacturing industry is not only to "make better things" by creating innovative products and services, but also to "make things better," by improving design, engineering, service planning and execution, management and production processes. This Policy, in essence, outlines 13 broad strategies for Malaysia to embark on a journey that will transform the manufacturing industry landscape over the next decade. MITI believes that this journey towards Industry 4.0 adoption is anchored on three shift factors: People, Process and Technology.
 **Thailand** [6]	The government created the *Thailand 4.0 plan* in May 2016, a holistic economic development program, which aims to evolve the economy from Industry 3.0, whilst also addressing social issues such as inequality. By introducing Thailand 4.0, the government had set their target to modernise SMEs into innovation-driven SMEs, with clear indicators such as to initiate creative and innovative business models, encourage technology usage with research and development (R&D) support, as well as to increase SME's responsiveness toward the world market demand. Many SME-related agencies and science/technology-related agencies have setup plans for encouraging innovation in SME toward the "Thailand 4.0" scheme such as: Formulating SMEs promotion plan as the main strategy and upgrading technology, innovation, and

	productivity; Providing grants for entrepreneurs to create innovation; and Organising events once a year such as Thailand Synergy for Thai SMEs, STI Thailand Award and Science Technology and Innovation Association.
 **Israel** [7]	In Israel was founded *Start-Up National Centar*, we provide deep knowledge of the relationships and rapidly evolving trends in this ecosystem that are necessary for global corporations, investors, NGOs and governments to navigate this competitive landscape. Industry 4.0 (Industrial IoT) handles technologies that aim to connect physical industrial assets with digital insights, while digitizing the entire chain of production. As the name suggests, companies and technologies targeting this sector view various industrial verticals as their main target markets, such as manufacturing, energy, construction, oil & gas and so on. As yet, these verticals have not fully realized the value that data can bring to industrial business processes.
 **India** [8]	Prime Minister of India, launched the '*Make in India*' program to place India on the world map as a manufacturing hub at 2018. The Manufacturing Sector especially SMEs play a pivotal role in the Indian economy and provide the largest share of employment. Government of India has launched *Digital India Programme* with a vision to transform India into a digitally empowered society and knowledge economy. National Productivity Council, New Delhi has been designated by the Asian Productivity Organisation (APO) as a *Centre of Excellence on IT for Industry 4.0* (CoE: IT for I4.0)".

Source: [1] http://www.tillvaxtanalys.se/; [2] https://www.made-in-china.com/; [3] http://www.businesskorea.co.kr/; [4] https://www.nrf.gov.sg/rie2020/; [5] http://www.miti.gov.my/; [6] https://asean.org/; [7] [8] https://finder.startupnationcentral.org; http://www.npcindia.gov.in/;

Table 6. Programs of I4.0 in Australia and New Zealand – state of March 2018.

Country	*Basic facts and figures*
 **Australia** [1]	In 2016, the Prime Minister's Industry 4.0 Taskforce was announced with the support of the Australian Government. The Taskforce's initial role was to connect Australian and German industry leaders to collaborate and share information on Industry 4.0. The activities of the *Industry 4.0 Testlabs Workstream* were supported by the Department of Industry, Innovation and Science, the Australian Industry Group (Ai Group) and the Australian Advanced Manufacturing Growth Centre (AMGC). Taskforce and leading its Industry 4.0 Testlabs Working Group I have had the privilege to discover how important it is to establish innovative learning platforms and facilities in support of model Industry 4.0 is about digitalization of the entire manufacturing process.
 **New Zealand** [2]	The New Zealand Government has been created a new policy platform to promote *Industry 4.0*, the next iteration of manufacturing enabled by the *Internet of things*. This document launched by the Ministry of Business, Innovation and Employment at 2018.

Source: [1] https://www.industry.gov.au/; [2] https://www.computerworld.co.nz/.

The above facts show that Industry 4.0 has become a global movement for new industrial development.

4 Program Industry 4.0 for Serbia

In Serbia, at Mechanical Engineering Faculty, Belgrade, since 2006 different kinds of EU initiatives are introduced, related to Advanced Manufacturing, such as [23–25]:

4.1 Manufacture Program

Manufacture Platform in Serbia was established in 2007. In meantime held five International Conference "Manufuture Serbia" (2009/'11/'13/'15/'17), on same topic. Prof. Dr. Francesco JOVANE, "FATHER" EU Manufacture Program, participating on Serbian Manufacture Conference 2011, was held Introduction Plenary Presentation – Manufuture Vision 2020. Also we established Consortia on national level – 28 members (Faculties, Institutes, SME, …), since 2008, and participating on EU Manufacture events (Conferences, Panels, …), more of ten times in this period. Also on this meetings presenting five papers – case studies from Manufacture Program in Serbia. Established Regional Initiative – Manufacture Village (Romania, Hungary, Serbia) – held for Conferences/Panels in Romania and Serbia (2010/’12/’14/’16), and finally three Joint Projects support by EU – Leading by Microelectronica, Bucharest by subject of Manufacture Program.

4.2 World Manufacturing Forum – WMF

Those Conference was establishing since 2010 – Conference in Cernobbio, Como, Italy, and Conferences: 2012 – Stuttgart, 2014 – Milano, 2016 – Barcelona, was held. From Serbia we are participating each time – with paper, and representative from Serbia and Member of few Tasks Group. Finally, Prof. Dr. Marco Taisch, Founder and Chairman on WMF, participating with Plenary presentation 2013 on Serbian Manufacture Conference.

4.3 Factory of the Future – FoF

Establishing since 2008 – EU Program/support industry excellence, and we are participating from Serbia and member few tasks group. Also representatives this Program participating three time on Serbian Manufacture Conference, 2011 and 2013. Program Industry 4.0 was introduced in Serbia, when the First International Conference was held in Belgrade, on 31st May - 2nd June, (AMP Conference 2016), with the main topic: Advanced Manufacturing Program - INDUSTRY 4.0 model for Serbia. As a result of this Conference, the Program - Advanced.

Industrialization of Serbia and Industry Policy, horizon 2020/2030 [24], was created. After this, the Project - Advanced Industrialization of Serbia - Industry 4.0 model for Serbia [25] was also defined. Next year, Second International Conference USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, 7th–9th June, 2017, Serbia – Smart And Intelligent Products (AMP Conference 2017) was held. So the central theme was - the output from the Industry 4.0 model - Smart And Intelligent Products. As a result of this conference, Position Paper - Smart And Intelligent Products - case study from Serbia. Finally, for 2018, Third International Conference USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, 5th–7th June, 2018, Serbia - Industry 4.0 model for SMEs (AMP Conference 2018) was held. A paper on the main topic of the Conference - Industry 4.0 model for SMEs, case study from Serbia [26], is also produced. For 2019 will planning at title – The 4th Conference on the Industry 4.0 Model for Advanced Manufacturing, *INDUSTRY 4.0 and Internet of Things for Manufacturing*, 3rd–6th June, 2019, Belgrade, SERBIA.

After the first AMP Conference, organized by the Faculty of Mechanical Engineering in Belgrade, fourteen Panels were held on different topics regarding Industry 4.0 model: New Industrial Policy of Serbia, Education of Mechanical Engineers for Industry 4.0 model. Faculty of Mechanical Engineering positioned as a leading higher education and scientific institution for Industry 4.0 model in Serbia and the region [26].

4.4 Program Industry 4.0 for Serbia [27]

Industry 4.0 is emerging as a unifying vision across our diverse industry sectors, giving us a clearer focus and a roadmap for digital transformation of advanced manufacturing in Serbia. We hope that this Program will serve as a useful resource for industry, education and research organisations that are engaged with the Industry 4.0 Program.

Serbian's initiatives in Industry 4.0 need from the Government to created of support Serbian's transition to a new economy and connect the nation to the fourth industrial revolution. I4.0 Program for Serbia is a national strategic initiative from the Mechanical Engineering Faculty, Belgrade as representative of Consortia I4.0 Serbia and the Ministry for Economy. The policy levers of the Program include an initial design phase, a visionary and a top-down steering role by the Ministry for National Economy and the Chamber of Commerce and Industry of Serbia in the form of strategy development. The expected results include: innovation acceleration, realisation of industrial solutions, a new generation of trained and highly-qualified professionals and the development of a sustainable and competitive manufacturing system in Serbia.

The main goals of the Program are:

(1) a increase the industrial output-to-GDP ratio from the current 23% to 30% until 2021;
(2) increase the level of R&D expenditures to 0.6% of the GDP by 2021;
(3) a reinforce the growth, export and innovation potential of the domestic companies;
(4) decrease standardised low-skill activities;
(5) increase high - skill activities, planning, control and IT related tasks 3.

They aim to find solutions and formulate recommendations on how to overcome the challenges presented by the practice. The five area in context on I4.0 are:

1. Education and Training
2. Manufacturing and supply chains
3. ICT Technologies
4. Industry 4.0 Cyber-Physical Pilot Systems/Center of Excellence
5. Innovation and Business Models

The Program is presenting as a common and strategic vision for the advanced industrialisation of the Serbian economy. The central role of I4.0 Program is to draft and propose suggestions and policy recommendations for the Government (Table 7).

Table 7. Basic facts about I4.0 Program for Serbia

Key elements	Characteristics
Policy Lever(s)	Bottom-up approach, public financing, equally orientated towards technology and infrastructure and skills
Funding Model	Simple public funding model under negotiations, a possibility to secure private financing through introduction of membership fees
Budget	Operated by the voluntary work contributions of the MEF, Belgrade. Negotiations on obtaining financing from the Ministry for National Economy
Uniqueness factor	Multidisciplinary approach involving stakeholders coming from key industry, academia, social and business backgrounds
Value-added for policy-makers	Cooperation and partnership facilitation, both at national and international level, throughout the entire process of implementation; driven by industry
Expected Impact	Boosting manufacturing and industry transformation in Serbia in the wake of the Fourth Industrial Revolution
Business involvement	150 experts to identify as active members of the Program dividing into five core Working Groups
Bringing together different sectors	Stakeholders from different sectors are brought together to advise and make recommendations on the future of I4.0 in Sebia
Policy strategy	Creation of a strategic policy development plan responding to Industry 4.0 challenges faced by Serbia
I4.0 piloting	Preparatory work undertaken for the initiation of I4.0 pilot systems across the country to be in autumn 2019

Program I4.0 - roadmap for digital transformation of advanced manufacturing in Serbia. Deployment of Industry 4.0 within Sebia has the potential to significantly improve the competiveness of our SMEs. Framework based on full integration of cyber – physical manufacturing systems (CPMS) with intelligent products.

5 Conclusion

The Industry 4.0 program has become a worldwide movement for development and automation of industry on new bases, such as CPM, IoT and Cloud technologies.

This paper has shown detailed development of Industry 4.0 in the most developed regions of the world. We can conclude that this Program Worldwide has become a national priority number one for the industry development. Also, we can conclude that the Industry 4.0 model has been increasingly used in various fields, making its industrial application, with the results achieved, an impetus for others. We can proudly say that our country is one of the few countries in the world (38 of them) that are working on developing and implementing Industry 4.0 model in their industry.

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Illuminating an Economy of the Future: How to Win the Transition to Industry 4.0 with New Economic Rules

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Abstract. The beginning of the fourth industrial revolution was marked with inconsistency between the anatomy of a rapidly changing environment and the way of its functioning. Combinatorial innovations connecting technologies, businesses, industries, and people have pushed the new economy, sometimes called Industry 4.0, into great discontinuity. Double amalgams based on synthesis of innovations from virtual and physical (and/or biological) world as well as products and services have disruptive impact on incumbents. Paradoxically, a quantum leap in technological opportunities is not matched with increase of macroeconomic performance. The reason for that is a legacy of combined crisis (the Great Recession 2008 plus digital disruption) emerged in the period before the start of the fourth industrial revolution. Advance manufacturing is a primer of negative impact of combinatorial innovations on incumbents. Advanced manufacturing is a direct consequence of universal mobility as a new free good and their impact on the value chain. This fact is important because production based on advanced manufacturing is the place where the fourth industrial revolution is happening before spreading out on other stages of the value chain, both downstream and upstream and throughout the whole economy and society as well. We cannot expect greater impact of combinatorial innovations on economic growth within existing economic framework. To achieve managed change, or smooth transition toward the Industry 4.0, the economic system needs new rules. Equally, the new economic model of growth and economic policy platform (macroeconomics) as well as strategy and business model of industry leaders (microeconomics) are being reshaped in accordance with new economic rules. In writing this article, we have been guided by two intentions. First, to map the direction of change as it happens. Second, to provide from a microeconomics (or business economics) perspective a fresh and far reaching insight into new economic rules for macro and micro management, desirable for winning smooth and well managed transition to Industry 4.0.

Keywords: Industry 4.0 · Combinatorial innovation · Advanced manufacturing · Model of growth · Economic policy platform · Economic paradigm · Macro management · Micro management

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1 Introduction

In Discovery of the steam engine and hydraulic power in the late 18th century designated the start of the industrial revolution which entails nothing else than a series of structural changes, or transformation of the way humans work, live and relate to one another. Until now, there were three waves of industrial revolution embodied in mechanical production, mass production based on electrical energy and organized within assembly line, and advanced automation with information technology, respectively. Now we are in the beginning of the fourth industrial revolution [12], sometimes called *Industry 4.0*[1]. In the first three waves of the industrial revolution capital replaced labor, more or less. In the last wave, information has replaced capital. So, today connectivity has become an ultimate free good, instead of land, water and air. Ingeniousness of the new free good is zero marginal cost, after some set-up costs. Connectivity is a principal enabler of massive influx of combinatorial innovations. The best allocation of resources across business organization is impacted by this development.

Combinatorial innovations are a point of view in Industry 4.0 that comes into play through daily practice of business organizations. Production and customer engagement were early adopters, but it didn't take long for other stages of the value chain to climb on board. Their application is growing in complexity at an ever increasing pace. But, they have disruptive impact on incumbents [3]. Namely, combinatorial innovations outperform sustaining technologies causing new entrants to take over business from incumbents. New skillset will make a lot of jobs redundant. As the nature of work evolves, different kinds of professions are needed, including data scientists, service designers and experts for cognitive technology who are great storytellers, turning communication from insight into impact.

Universal connectivity introduces reversibility of an endless network of cyber-physical (or biological) systems of fully decentralized production with connected customers, products and value chains as the new normal. Advanced manufacturing is a typical example of reversibility of conventional embedded system of production technologies influenced by artificial intelligence, cognitive technologies and robotics. Technological revamp includes machine learning, neural networks, rules engines, robotic process automation, natural language processing, etc. Implementation of smart production processes in the production stage of the value chain means entering the territory human activity cannot replicate. Industrial production machinery no longer "processes" the product, but the product (designed in line with customer's needs) communicates with machinery to tell it what to do. Refocusing from cost leadership to value creation actually means a paradigm shift in micro economics.

The last industrial revolution needs new economic rules as well as new tools in micro and macro management. Non-evolutionary change is happening in the business organization, actually in production stage of the value chain and influences primarily changes in micro management. Also, it is spreading out on other stages of the value chain, both downstream and upstream. Radical change in the way of functioning of

[1] "Industrie 4.0", Deutscher Industrie - und Handelskammertag.

business organizations requires adjustments in their behavior (or strategy), business model of industry leaders, rules of competition and macroeconomic rules, as well.

Today, competitive position of companies, industries and nations depends on the level of creativity in implementation of a new free good. In the age of universal connectivity the key question is: what would be the management platform, both macro and micro, supporting the new normal in a way to create and massively spread out combinatorial innovation?

An article by Porter and Millar [10] announced the start of the third industrial revolution. In his book Schwab [12] eloquently explained synthesis of breakthroughs of virtual and physical (and/or biological) world as key characteristic of the fourth industrial revolution. The search for a conceptual platform for management, both macro and micro, for Industry 4.0, is still in the process. Many economics scholars have come around to the idea that a paradigm change needs to happen, but the delivery of this change is still in its infancy.

New conceptual platform has to respect basic economic rules, and, by doing so, not inhibit entrepreneurial habit to create and implement innovation, this time of combinatorial nature. Also, the new platform should respect profound impact of the new normal, particularly its most important component digital disruption. Last but not least, the new concept should respect new planetary requirement for environmental sustainability.

What lies behind the answer to previous requirements? It is a new paradigm in economics which respects not only the growth imperative, but also, and mostly, wellbeing. The shift from growth to wellbeing is related with two more questions. What will the economic model of growth and policy platform look like in the age of universal connectivity? Have we made progress in formulating the conceptual platform for sustainable growth based on combinatorial innovations or does supremacy about the impact of the new normal on growth, external balances (current account and capital) as well as fiscal balance put environmental sustainability below the radar again?

After digital disruption has deepened the negative effects of the 2008 Great Recession, the global economy has entered secular stagnation. It was a crisis within the crisis. Now we are at a tipping point. If such a combined crisis is likely to be more prolonged than in the past, the economic system has to change, if only because the conventional paradigm in economics is breaking down.

But, digital disruption has generate opportunities. In the case of a positive scenario, the new paradigm in economics could change the slope of the recovery trend. Paradigm change could accelerate the speed of research and innovation, particularly in the areas of intersection of cyber and physical (or biological) world, as well as increase the size and scope of digital infrastructure supporting implementation of emerging combinatorial innovations. New technology generating opportunities to preservation and regeneration of nature, rather than creating hidden cost of economic development in the form of externalities [12, p. 2].

Figure 1 portrays two transition curves with different slopes. Dotted curve depicts unmanaged transition based on an old paradigm in economics. Continuous curve depicts managed transition after introduction of the new paradigm.

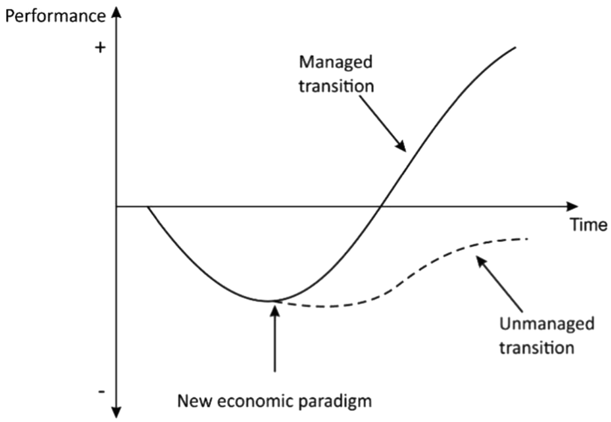

Fig. 1. Two paths of digital disruption: managed and unmanaged transition

2 What Does the Orthodox Economic Theory Offer?

Management, in both technical and social systems, is leading the system in question toward a desirable goal. The purpose is to improve the level of organization of the system being managed, or inversely, to decrease its entropy. The system is adequately managed when the intentions are continuously achieved. Management in an economic system, both on macro and micro level, impacts ultimate economic goals like growth and social prosperity.

Every science, no matter how serious it is, has its paradigm. Paradigm is a set of rules with explanatory power to depict behavior of the system. In economic theory (or economics), the conventional line of reasoning is based on a proposition that the economic system is a result of combined impact of socio-economic context, ideology (including religion), and technological change. Throughout history, the relative impact of factors has been changing. In the age of the industrial revolution, supremacy of technological change over other factors is quite visible. Technology change is a dynamic and cumulative process of alteration of the input transformation (labor, capital, natural resources) into output (products and services). It is an exponential process regularly depicted by “S curve”.

Today’s impact of technology change is stronger than ever before and almost universally dispersed throughout the economy and society. The new mantra for business organizations is: “innovate, digitalize, connect, or go away from the scene”.

With intention to save the planet from rapidly growing influx of negative externalities, the UN recently defined 17 global sustainability goals [14] framing future obligations of companies, industries and nations. The current economic model of growth must be replaced by the new one that gives priority to wellbeing and puts ecological and social goals at the forefront.

Is the orthodox economic theory capable of getting the answers to previous requirements? The most influential school of economics in the core (or industrialized) economies as well as in economies in transition is the *Neoliberal School of Economics*, sometimes called “market fundamentalism”. In this school, like in other most influential schools (*Monetary* and *Post-Keynesian*, primarily), there is consensus that the market mechanism is the primary institutional and policy choice.

What does conventional theory offer in terms of the growth model and economic policy platform? Free market (or free enterprise) economic growth model, sometime referred to as “orthodox” is shown in Fig. 2. The model has three basic premises. First, in nature (or natural capital) there are no limits to growth. Namely, the nature is a “slide show”. Second, the level of GDP is a good proxy for wellbeing. In such sense, more GDP is always better. Third, private property is more efficient than public property. Public property is limited on network technologies, natural monopolies and sectors of economy with prevailing external effects. In this model, the state is a regulator responsible for institutional settings and macroeconomic stability. Namely, the state involvement in economy is quite limited.

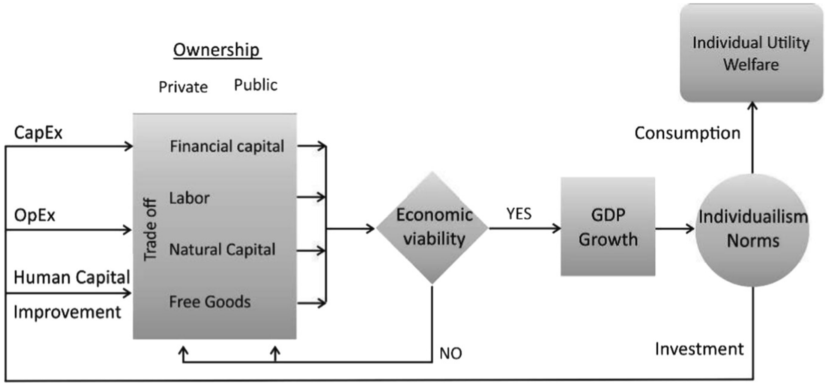

Fig. 2. Orthodox economic growth model. Source: Partially modified in accordance with the idea in [4, p. 354]

Private ownership of factors of production is a pivotal point in free market economy mantra. Goods and services are marketed in a way to match or create the desired needs and thus increase individual welfare for consumers while simultaneously increasing private proprietaries’ utility by increasing value released on the capital market. The return on capital is reinvested with the sole purpose to bring even more value to the proprietaries. To do that, business organizations are primarily concentrated on cost control of massive production. The previous microeconomic concept is not in contradiction with macroeconomic view of the economy, i.e. – that the total market value of all final goods and services (or GDP) is expanding.

The free market model of economy was always obsessed with the growth. To react systematically to change imperative, architects of the economic system try to avoid the so-called “Seneca effect”[2] by searching for alternative variations of the basic free market economy model. When economic growth is slow, social collapse is rapid.

[2] “Fortune of sluggish growth, but social ruin is rapid” (*Lucius Annaeus Seneca).*

From the very beginning of the industrial revolution (first and second wave), the model of growth was manufacturing-based with the focus on the real economy (manufacturing and advanced agriculture) as well as physical infrastructure. In the time of the third industrial revolution, the focus was changed to services, particularly on financial services. In the fourth industrial revolution, focus of the architects of the system and policy makers is going to be combinatorial industries and digital infrastructure.

However, previous model of growth repeated the same fallacies. First, wrong treatment of free goods, in particular water, land and air. Nobody is paying for negative externalities like climate change and environmental deterioration due to uncontrolled exploitation of free goods. Second, exogenous treatment of technology change, as a factor influencing resource allocation inside business organization, but not depending on it. Such treatment of technology change provokes lack of innovation. Third, the ignorance of information asymmetry leads to misuse of resources and emergence of the speculative bubble, primarily in financial sector and related sectors (real estate, for example).

Moreover, as we pointed out in previous papers (see [10], for instance), the premises of the neoliberal economic model of growth no longer hold. Actually, the neoliberal model set of premises is defined for an “empty world” where there are no limits to growth, we live in a world with ample space and resources, where private property is always better and GDP is a preferable proxy for wellbeing.

The problem with such line of reasoning is that maximizing economic capital often derogates natural capital and cultural capital. In the quest for the higher growth (meaning greater wealth) neoliberals forget that the limit of such a world is the existence of the world itself. The exaggerated emphasis on economic systems is to the detriment of natural systems and cultural systems [17]. Also, economic history teaches us that in each economy there are episodes of strong growth followed by a much stronger fall, or overshooting. Namely, exponential growth (CAGR in range 5–7% and more) provokes overshooting, particularly if the economy has structural imbalances.

Neoliberal economic model of growth does not behave as a part of a larger, non-growing ecosystem, but as an ultimate master of the former. In pursuance of higher economic growth, the world itself is brought to the ecological brink of a collapse. There is an obvious conflict between the economic growth and the preservation of the environment. As Daly [5, p. 1] eloquently pointed out, by the first law of thermodynamics, when the economy grows in physical dimensions, it incorporates matter and energy from the rest of the ecosystem into itself. More people, commodities and products means less nature.

The neoliberal economic policy platform is also controversial. The main principles of the economic policy platform (*Washington Consensus*) based on market fundamentalism are: liberalization, privatization, deregulation, and globalization. The ultimate goal of such an economic policy platform is inflation (low and stable). The main policy tool is inflation targeting, mainly based on monetary measures. But, exclusive focus on inflation is not enough for sustainable and inclusive growth. Policy makers could not navigate a complex, multi-dimensional space (financial capital, natural capital, human capital and physical capital) toward sustainable growth with a simple economic compass based on price control. We cannot manage what we do not measure.

Sustainable growth mostly depends on the output gap (low and stable), demographic balance and sustainability of the natural environment.

Without any doubt, in economic theory enlightenment is needed in terms of a paradigm change influencing the model of growth and economic policy platform. More than 40 years of experimenting with neoliberalism is over after the entire wave of influential scholars like [9, 11, 13], both macro and micro, has attacked its basics. In the last decade we are not alone in this observation, particularly after bringing to life the alternative of neoliberal economics called the *New Structural Economics*. According to this way of reasoning, change in the structure of the economy, rather than growth of existing companies, products, and services by itself, could lead to sustainable and inclusive growth, both toward the people and nature. Change in structure of an economy means supporting and allowing development and expansion of tradable sectors or sectors substituting import and/or increasing the export.

Interestingly, the neoliberal economic model of growth continues to act, often with excuse of policy makers that there is no better model. Many policy makers have remained on the side lines, with skepticism about the possible alternative. But, an alternative still exists. Actually, there are four scenarios of possible futures. Two of them are based on the old model of growth, and two are based on the new one (see Fig. 3).

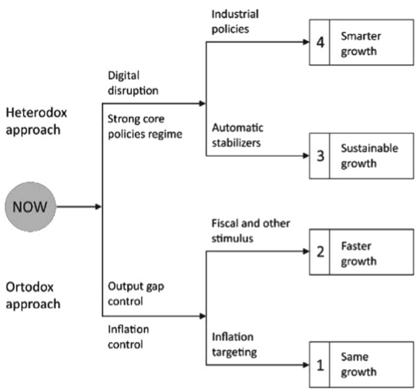

Fig. 3. Four scenarios for future economic development

The same growth (or business as usual) scenario and faster growth scenario are based on conventional economic paradigm. They lead to more violation of planetary boundaries with even more destabilizing income inequality. Intensification of resource consumption, waste increase and climate change following the growth imperative will possibly make growth a door to "illth" in terms of [5, p. 6], instead of wealth (well-being). Only transformational (or smart growth) scenario based on structural economics with the focus on industrial policies in tradable sectors actually rises to the grand challenge of sustainable and inclusive world, both toward the people and nature. Harder growth scenario based on the same approach but with the focus on strong automatic stabilizers in monetary and fiscal policies is the second best solution.

3 New Economic Rules, Both Micro and Macro

Quick transformation of an economy is extremely complex with rapidly rising number of mutually related elements. Previous analysis confirms that the complexity and uncertainty are so strong that a conventional paradigm in economics could not provide the platform to manage the change. When combinatorial innovations dominate environment, industry leaders need to get ahead of the competitive game and ensure they are not left behind. The forth industrial revolution emerged, but the new theory in economics and business management did not emerge yet.

New technology is changing costs (unit cost, infrastructure costs, and marginal cost). Changes in the cost component structure are influencing changes in pricing models. Also, new technology allows a greater analysis of business drivers, using insight and actionable analytics for thinking outside the box. Decision makers can use software-as-service technology which allows access to individual applications with lower set-up cost and greatly improved speed of implementation. Also, customers are more empowered by data and technology too. As a consequence, cost does not bear as much weight as it once did. Time needed for imaginative implementation of combinatorial innovation should also come into consideration.

From a microeconomics standpoint of view, the physical-digital-physical (PDP) loop is a hallmark of Industry 4.0. It enables real time access to data across the whole value chain, giving actionable information for making game-changing decisions. For example, in the production stage of the value chain, advanced manufacturing enables a product designer to create a "digital twin" of the physical product and then uses real time data to optimize design of the product across a number of parameters, before sending a new product into the production process.

A truly digital enterprise takes the PDP loop across all activities of the value chain. The PDP loop has given rise to a move from linear to exponential value chains. It enables incumbents to replace a linear value chain with an exponential one by expanding the scope of general strategy. By entering in new activities or businesses, incumbents could avoid disruptive impact of combinatorial innovation on core business. In an exponential value chain, there are great many of innovative start-ups dealing with emerging technologies and product amalgams based on them.

Scalability of cyber technology solution provides endless opportunities for diversification. Scalability of cyber technology solutions is almost endless. For example, today more than 500 million smartphones have neural network for machine learning on board. In the following years, machine-learning applications are poised to become commodity. It is an opportunity for start-ups development by introducing analytical models connecting demand forecast with construction and design of new products/services. On the company level, the key consequences for the information system design are virtualization of hardware/software and data sharing.

Penetration of niche market is compatible with high diversification. The niche market becomes the norm of a competitive game. Competitors are forced to make products/services for market segment that can win market share locally. But, the competitive advantage on local market segment in time of universal connectivity offers them the possibility to get an agglomeration effect on the global market. Agglomeration effect is the reason why penetration of niche market is a lucrative strategy.

To illuminate an economy of the future, we have to start with some considerations of changes in the way of functioning of the modern business organization. First, customer focus across the whole value chain. To meet rapidly changing customer needs, competitors must: redesign value chain, automatize key activities with core competence, and connect key activities with other companies, or make alliances with them. Competitors following previous rules are able to offer high-end products, operate with superior cost structure, and higher responsiveness based on an almost ideal lean structure.

How to systemize the impact of new micro economics propositions for paradigm change in macro economics? Our line of reasoning has three improvements. First, treatment of the economic system as system dynamics. The main reasons for that are growing complexity and mutual interdependence of highly volatile elements. Second, the contingency principle as a key game changer. Contingency covers bad guesses. It is a new rule of the game under which behavior (or strategy) of business organizations in the competitive game becomes "context free". Under the context, we mean macroeconomic setting and fundamentals as well. Behavior of business organizations depends on uncertainty (both technological and market), complexity of the system, and responsiveness (lead time to react). Instead of relying on a single or core business, a modern company has to be resilient and insist on a whole battery of businesses in the structural portfolio that can deal effectively with changes, reviewing and revising them more frequently. Third, in market positioning collaboration dominates competition. Collaboration is other side of the connectivity coin. The new paradigm could explain the extraordinary success of business organizations in a macroeconomic environment full of fault lines and the collapse of business organizations in the environment with sound macroeconomic fundamentals.

Very essence of macroeconomic heterodoxy is GDP growth (more output is always better). But robust growth sometimes causes overshooting. To reduce the probability of overshooting to a minimum, growth must be intelligent, not only robust. Precisely, in Industry 4.0, robust growth is no more an adequate ultimate goal for macro management. In an "empty world", the political imperative for growth would not outstrip an economy potential. In a "full world", or in the economy with fiscal imbalance, unsustainable debt, high unemployment, security commitments, limited natural resources and climate change it is necessary to respond intelligently on structural changes. To reconsider the conventional approach towards growth, it is wiser to look for ways of enhancing growth in a sustainable and inclusive way, this time toward both people and nature.

Macro management based on the new, sometimes called "heterodox" platform is reaction to malfunctions of the orthodox platform and the new normal as well. It is a balanced view which respects two key institutional choices: market mechanism and industrial policies for the tradable sector. Namely, the "invisible hand" of the market shakes the "visible hand" of the state. Actually, it was a conceptual platform, almost ideology, of fast growing economies from the Asia Pacific region. For a significant number of economies from that region, it was a remedy for the middle income trap these economies had entered in the early 1960s, after the period of rapid industrialization. Double macro deficits (current account and capital balance) and fiscal too, were the main consequences of debt overhang due to the import of technology. To make debt sustainable, these economies reoriented themselves from transfer of foreign technology to internally developed technology as the base of industrialization. In such orientation, industrial policies were unescapable. Besides sound results in macroeconomic stabilization, the heterodox approach enables that these economies today are on the verge of becoming technology leaders in a number of frontier technologies.

The impact of emerging technologies on business organizations cannot be ignored by the state. Today the invisible hand of the market is just an alibi for inert politicians. Free market economy is joining together with technological breakthroughs sponsored by the state. The state should stay agile, move quickly and get on with the change. Agility means not only a certain level of activism in formation of institutional settings and regulation (particularly digital infrastructure), but also support of frontier technologies critical for emergence of combinatorial innovations.

Economies implementing the orthodox approach have successively entered in the service-led growth model. Such orientation not only increases the burden in creation of demand for the real economy and bubble burst, but it also accentuates the distortions in macroeconomic fundamentals like the output gap deepening, uncompetitive foreign exchange and below neutral prime rate. In contrast, in heterodox approach the growth model is manufacturing related. Consequently, the core element of the new approach is an industrial policy for tradable sectors.

Why is industry important in the new growth model? There are several reasons. First, the multiplier effect. Although less than one-fifth of the total value added in OECD economies comes from manufacturing, the effect of manufacturing is stronger than this share shows. The reason for that is the multiplier effect. One job in manufacturing creates from 2.5 to 3.0 other jobs across the value chain, both downstream and upstream. Namely, greater consumer demand for manufacturing activities is bundled with commodities demand (downstream) and services and logistics expansion (upstream). According to [15], manufacturing value added in China is significantly stronger (33%), so the multiplier effect and impact on growth and employment is much stronger. Second, in great number of relevant economies, industry accounts for majority of exports. It is healthy for macroeconomic balances and debt sustainability. Third, in the global economy industry is in the process of recovery after the deindustrialization erupted by the Great Recession. In the post-crisis period, the drop in investment in the real economy is reversing. Fourth, in recent years, the flow of foreign direct investments fell by almost one quarter, particularly in developed and transition economies. This negative trend is a concern for policy makers and input for increasing internally generated investments. Fifth, in the new economy, technology transfer and offshoring towards economies offering cheaper labor become less relevant in the world of increasingly automated manufacturing. At the same time, improving human well-being requires job creation in the service sector which relies heavily on manufacturing. Small open economies face additional pressure due to diseconomy of scale. Sixth, on the global level, manufacturing is undergoing a deep transformation. Digital disruption is everywhere. New technological amalgams need new resource combinations, greater resource efficiency, new business models, greater connectivity, etc.

In the post-crisis period we see growing popularity of the new approach not only in emerging peripheral economies, but also in core economies (for example the EU) and economies in transition. Over 100 countries have adopted industrial development strategies based on industrial policies [16, p, iii]. Different combination of vertical and horizontal industrial policies should be used in different sectors and policy areas ("one size does not fit all"). Figure 4 depicts heterodox economic model of growth. In the new model of growth, environmental sustainability of some investment proposals is the filter preceding the market filter.

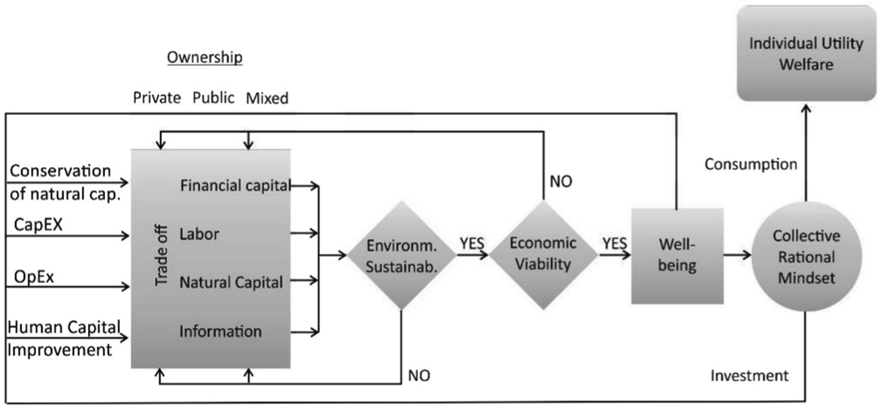

Fig. 4. The heterodox economic model of growth. Source: Partially modified in accordance with [4, p. 354]

In this approach the state has a crucial role to play. An agile state in terms of research and innovation support business development of tradable sectors is an enabler for growth. To stimulate competitiveness on all levels, the state is entering in the open innovation process in terms of Cheshbrough [2] through partnership with companies, research and development laboratories, university and related partners from the innovative ecosystem.

The industrial policy strongly influences micro level, or behavior (means strategy and business model) of business organizations, particularly in tradable sectors. Compatible elements in macro management are automatic stabilizers for core policies like monetary and fiscal [7]. Macroeconomic stability has to come first, again.

4 Conclusion

In Industry 4.0, enormous creativity is a consequence of ever-broader range of requirements. Universal connectivity as a new free good and a synthesis of breakthroughs from different technology fields leaves behind almost endless combinatorial innovations. Advanced manufacturing is a primer of new creativity. It is happening in the production stage and spreading up, both toward the upstream and downstream, across the value chain, industries and economy as a whole.

Besides the changes in microeconomics, in Industry 4.0 the very essence of macroeconomics remains almost unchanged. The growth is in the spotlight again. Today's growth should not be slow, because such growth causes rapid social collapse. Also, growth should not be exponential due to environmental limits to growth and overshooting threat. In Industry 4.0, growth has to be high enough, but intelligent. Intelligent growth has to be inclusive, both toward the people and nature. Achieving such a growth requires paradigm change in economics. In a truly digital environment, competitors continually experiment with combinatorial innovations with the aim to revolutionize the economy and society as a whole. As digital disruption transforms the microeconomics paradigm, the assurance of a new paradigm in macroeconomics has never been more essential. What the global economy really needs after a 40-year old experiment with neoliberalism is the circular economy new deal. The heterodox approach with industrial policies for tradable sectors in the center and automatic stabilizers for core macro policies is a reasonable alternative to neoliberal orthodoxy, maybe. Mindset change toward collective rational also matters.

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Competitiveness of Domestic Enterprises in Changing Markets and Industry 4.0

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Abstract. Globalization inevitably leads to changes on the market. Enterprises have to apply flexible and innovative approaches to management in order to develop sustained competitiveness. Technological advances in a global context create a dynamic economic environment where competition on the market is fierce and constant. Taking into consideration the fourth industrial evolution – Industry 4.0, enterprises have to quickly adapt to changes on the market and they also have to apply technological innovation in order to increase their own competitive ability. When it comes to domestic enterprises in the Republic of Serbia, the overall global competitiveness is quite low. Some of the main reasons behind this is lack of adequate investments in innovative activities. Additionally, there is lack of adequate investment in product and service quality, and low productivity. Now, how is competitiveness achievable? Through the application of modern management techniques and methods, and through investments in innovation, domestic enterprises can achieve higher levels of competitiveness of the global market.

Keywords: Competitiveness · Domestic enterprises · Industry 4.0 · Globalization · Market change · Innovation

1 Introduction

Survival on the market is often affected by the competitive ability of the enterprise. This is more so in today's globalized markets. Fast advancement of technologies further created a gap between innovation-focused and non-focused enterprises. This means that competitiveness is affected by the level of innovation that an enterprise uses for its product and service development. Globalization has majorly contributed to the intensity, activity and visibility of competition on the market. For enterprise who are not prepared, this means trouble. Globalization also led to changes of how

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competitiveness is defined, measured and achieved. The impact of globalization is evident in the list of competitors on the international market. Thirty years ago, West Germany, United States, France, Great Britain, Netherlands, and Japan were the main competitors on the international market. Today, China, India are also becoming economic powers, and South Korea, Taiwan, Indonesia, Singapore and others have a role in the world economy. What does this mean in the context of competition? Well, corporations from developing countries are becoming heavy competition to corporations from developed countries. Before frequent changes were affecting markets due to globalization, companies could establish competitive advantage through new products and services which were based on innovation and new technologies. However, in the today's modern business environments where there is constant change on the market, and where there is heavy competition, competitiveness is based not only on innovation, but on quality and globally acceptable price. The global economic crisis makes new business models a necessity for enterprises. Strategic challenges for enterprises in the next ten years will come from the simultaneous and continuous fragmentation and integration of the world as a whole [1]. Industry 4.0 is a framework that brings new challenges and within which enterprises have to maintain their competitive advantage. Industry 4.0 includes several groups of technologies. These technologies are simulations, autonomous robots, Internet of Value, Internet of Things, additive manufacturing, cloud technologies, cybersecurity, Radio Frequency Identification (RFID), big data and analytics, smart sensors, 3D printing, augmented reality, location detection, machine learning, real time optimization and others. Some of these technologies can be used broadly while others are more narrowly specialized for clearly defined business activities [2]. As for the domestic enterprises there are a few that may compete on the global market. However, the majority of the enterprises lack low technological levels, low productivity, inadequate and insufficient application of knowledge, inefficient organization structure. In addition, Serbia lacks motivated youth who would start their own business. This is due to the lack of starting capital, lack of innovative ideas, and lack of necessary knowledge [3]. Now, in this paper the competitiveness of domestic enterprises in Serbia is analyzed in the context of global markets and Industry 4.0, and guidelines for improvements are suggested.

2 Competitiveness, Globalization and Industry 4.0

Industry 4.0 creates conditions in which the modern economy operates on a global scale. There is a constant evolution of the economy which first focused on production, after that on consumers and individuals and finally it focuses on the integration and convergence of all participants in the economic process. The Indian Prime Minister Narendra Modi noted that society lives in a network that consists of many complex networks. Technology brought many changes as it connects people, and information became an important and big asset. Therefore, it can be assumed that technology is a crucial economic factor that pushes economic development and enterprise competitiveness. Besides new products and services, technology also creates new markets. New industries, new groups, new competitors and enterprises are the result of rapid technological development. The key of new technologies is to increase productivity which will further improve the competitiveness of companies. New technological solutions can increase production capacity, reduce human labor costs, and reduce overall operation costs. Kotler, Kartajaya, and Setiawan discussed that competitiveness will no longer be determined by the size of the enterprise or its country of origin or advantages which it may have brought from the past [4]. Younger, smaller, and local enterprises can develop adequate competitive ability to compete with older, larger corporations that already have a presence on a global scale. One of the important factors that contribute to this is social media. Namely, social media reduces pre-existing barriers between consumers and companies. This lead to a more horizontally oriented consumers. Further, the hyper-linked marketing environments create a good basis for consumers who can move from consciousness (I know about the product), to acting (I buy a product) to advocacy (I recommend the product). Now, some medium-sized companies already compete with large corporations, while small and other medium-sized companies are entering the global market and here the competition rises based on various business and innovation activities. When it comes to Industry 4.0 the speed with which countries generate innovations and adopt new ideas is key to improving competitive ability.

Further, Germany is leader the leader when it comes to innovations [5]. After Germany, there is the US and Switzerland. Some of the factors that determine if a country has the ability to produce innovations include the application of ICT and education quality. Germany's Industry 4.0 project is focused on the goal to establish Germany as leading country and economy when it comes to integrated industry [6].

The Chinese prime minister noted that China will be more actively engaged in stimulating innovation and new directions of development. All this development will be within Industry 4.0 as the fourth industrial evolution brings forward new challenges for enterprises. China has developed its own ten-year "Made-in-China 2025" plan that aims to transform China's status in the world, from the world's workshop to a world manufacturing giant [6]. This approach brings the necessity to take innovation seriously and as an imperative for achieving competitiveness. Certainly, this will push and encourage enterprises, high-tech institutions and scientific institutes to develop innovations and to apply those innovations in business [7].

Table 1 depicts the top ten most competitive countries in the world, according to the list of World Economic Forum (WEF) for 2018. Beside these countries, other strong competitive countries are Finland, France, Taiwan, Australia, New Zealand, Canada, South Korea, Israel, Norway and Luxembourg. China is ranked 28th (last year was ranked 27th). India is ranked 58th (last year it was ranked 40th), Russia is ranked 43rd (last year it was ranked 38th), South Africa is ranked 71rd (last year it was 61st), while Brazil is 72nd (last year it was ranked 80th).

Table 1. Top 10 countries in the world according to competitiveness in 2018

Country	Rank
USA	1
Singapore	2
Germany	3
Switzerland	4
Japan	5
Netherland	6
Hong Kong	7
United Kingdom	8
Sweden	9
Denmark	10

For the Global Competitiveness Report in 2018 an improved methodology was used compared to previous years. This new methodology took into consideration the requirements of Industry 4.0. This included the analysis of productivity and long-term growth in the fourth industrial revolution. Some of the basic global competitiveness index (4.0) indicator groups are:

1. Human capital, with indicators: health, skills;
2. The environment, which includes the analysis of indicators: institutions, infrastructure, ICT acceptability and macroeconomic stability;
3. Innovation and ecosystem, with indicators: business dynamics, innovation capacity.
4. Market, implies the following indicators: product market, labor market, financial system and market size;

Further, the most significant areas of change when it comes to global transformation in the context of Industry 4.0, are:

1. Innovation of products and services, and productivity,
2. Developing need for leaps in business,
3. Agile management models,
4. Integration of technologies and innovation,
5. Increase need for knowledge and skill,
6. Enhancing and improving ethical actions and identity [8].

In addition, it is necessary to make changes to business systems and changes in the domain of improving security, reducing inequality, and reducing conflict.

Experts from the World Economic Forum proposed the ten things that the state administration of the countries should pay attention to are:

- Social and economic development can be improved by investing in people,
- Development and prosperity comes from the use of technology along with other factors,
- Competition should not be viewed as luxury,
- Social protection must part of an open economy,
- Remaining open is a fundamental and crucial factor for developing competitiveness,

- Developing and innovating the economic ecosystem that goes beyond mere development and research,
- Financial systems and it infrastructure are also important,
- Constant agility in times of constant changes is a necessity,
- Proactive action is an imperative for achieving unity and sustainable development.

In order to achieve and maintain competitiveness on a global scale in the context of Industry 4.0, small and medium-sized enterprises (SMEs) have to develop a company-specific Industry 4.0 vision, which would guide the planning and execution process [9]. Industry 4.0 as an approach operates on the grounds of sustainable manufacturing [10]. This can be achieved through the previously mentioned technologies. Further, sustainable manufacturing positively affects and improves competitiveness of enterprises. In the context of globalization, achieving competitiveness is just the first step, maintaining competitiveness in an ever-changing market is a real challenge for SMEs. Therefore, it is evident that applying Industry 4.0 technologies, sustainable manufacturing, globalization and competitiveness are closely inter-affecting concepts. SMEs in emerging economies have to take into consideration the challenges and opportunities that these concepts bring. Also, domestic enterprises have to consider, accept, and apply international achievements in the domain of practice and theory of business standardization [11].

3 Domestic Economy and Competitiveness of Serbian Enterprises

When it comes to competitiveness the domestic economy has a long-standing problem. This problem is evident form the late 1980s. In 2001 the transition began, and the non-competitiveness of the economy in an international contexts became an even more evident problem. Negative effects of the global economic crisis have further influenced the weakening of the competitiveness of domestic enterprises in Serbia. This issue of lack of competitive ability is referred to those enterprises where the only or dominant type of capital is autochthonous domestic capital. Why are domestic enterprises in trouble when it comes to competitiveness? The main issues are the lack of productivity, lack of investments for production revitalization, inadequate qualification of employees, outdated technological and technical basics of conducting business, and overall low quality of products and services. In order to increase competitiveness, enterprises should focus on increasing product and service quality. However, this is not enough if those products are not marketed with a reasonable price, therefore it is important to develop and maintain a sustainable manufacturing business model in order to market good quality products and services at competitive prices.

As mentioned, outdated equipment, or more precisely, equipment aged between 20 and 30 years is a handicap when it comes to achieving competitiveness on the global market. Further, unemployment rates have decreased in the last two years, but this didn’t have a positive impact on productivity, because foreign investors are interested in Serbia mainly due to the financial incentives and the cheap and qualified labor force.

Further, this implies that foreign enterprises don’t bring nor transfer state-of-the-art industrial equipment and technology, thus new jobs don’t contribute significantly to competitiveness. Foreign companies mainly invest in factory buildings and don't equip them with modern technology equipment. These companies focus on labor-intensive activities, and development is not included in the activities. In a new report of the World Economic Forum for 2018, Serbia was ranked 65th in the terms of competitiveness, while last year it was ranked 78th (Table 2).

Table 2. Ranking of Western Balkans countries according to competitiveness in 2018

Country	Rank in 2018
Bosnia and Herzegovina	91
Montenegro	71
Croatia	68
Macedonia	84
Slovenia	35
Serbia	65

Source: http://reports.weforum.org/global-competitiveness-report2018/competitiveness-rankings/ [12]

Furthermore, in the same report Austria is ranked 22nd, Romania is 51st, Greece is 57th, Hungary is 48th, Bulgaria is 52nd, and Albania is ranked 75th. The majority of these countries reported a minor increase in ranks, with the exception of Austria which was 19th the year before. Some of the factors that positively affected the progress and development of the Republic of Serbia on the global list of competitiveness are improved transport infrastructure, low inflation rate, short waiting times to start a new business, and stable financial system. Table 3 gives an overview of the competitiveness of the Western Balkan countries in relation to the main indicators of competitiveness in 2018.

Table 3. Competitiveness abilities of Western Balkans countries according basic competitiveness indicators in 2018

Country	Rank	I 1	I 2	I 3	I 4	I 5
Bosnia and Herzegovina	91	111	89	86	73	52
Montenegro	71	63	86	58	102	55
Croatia	68	74	36	33	106	51
Macedonia	84	85	86	70	70	71
Slovenia	35	35	35	43	1	34
Serbia	65	70	48	60	64	67
Country	Rank	I 6	I 7	I 8	I 9	I 10
Bosnia and Herzegovina	91	87	106	112	83	99
Montenegro	71	52	45	25	51	132
Croatia	68	65	71	96	62	78
Macedonia	84	81	107	78	80	109
Slovenia	35	29	27	43	60	82
Serbia	65	56	66	52	79	75

Source: http://reports.weforum.org/global-competitiveness-report-2018/competitiveness-rankings/ [12]

Label clarification: I1 - institutions, I2 – infrastructure, I3 - ICT. I4-macroeconomic stability, I5-healthcare, I6-skills, I7-product markets, I8-labor market.

Table 4 gives an overview of the most important problems of the domestic economy in relation to the competitiveness indicators. These indicators are in accordance with the Global Competitiveness Report 2018.

Table 4. Important problems of the domestic economy in relation to competitiveness indicators in 2018

#	Analyzed indicator in context of depth	World rank
1.	Sophistication of customers	127
2.	Ability to rely on professional management	122
3.	Relationship towards entrepreneurship	119
4.	Protection of private property	115
5.	State regulation efficiency	113
6.	Legal system efficiency	108
7.	Reporting system adequacy	108
8.	Independent Judiciary	107
9.	Market dominance level	106
10.	Protection of Intellectual Property	100
11.	Cooperation between employers and employees	100

Source: http://reports.weforum.org/global-competitiveness-report-2018/competitiveness-rankings/ [12]

It is evident from Table 4, that when it comes to competitiveness indicators, some of the rankings are professionalism of management, attitude towards entrepreneurship, sophistication of customers, efficiency of state administration, protection of private property etc. Factors such as intellectual property protection, private property protection, employer and employee relations, market dominance, professional management, entrepreneurship etc., are essential for a good functioning modern economy. Why is this important? Well, China and India have fostered entrepreneurial behavior, and managed to develop and nurture positive attitudes towards entrepreneurship. This approach provided the necessary basis for achieving competitiveness on a global scale. Countries such as China, South Korea, Japan, Taiwan, Singapore and others, that developed entrepreneurial climates in society, had an incentive for the development of entrepreneurship overall on a national level. It is false to assume that there are entrepreneurial or non-entrepreneurial countries, but rather there are entrepreneurial and non-entrepreneurial economies. Problems in the form of low entrepreneurial behavior, weak customer relationships, inadequate management, problems regarding private property, are significant and challenging to solve. This is because these problems were built over long periods of time. Competitiveness indicators (2018) that affect business in Serbia, are presented in Table 5.

Table 5. Top ranking factors that affect business in the Republic of Serbia in relation to competitiveness indicators in 2018

#	Analyzed indicator in context of depth	World rank
1.	Electrification rate	1 (several countries)
2.	Annual inflation rate	1 (several countries)
3.	Insolvency control network	14
4.	Severance pay costs	17
5.	Railway network development	19
6.	Capital banks regulation	20
7.	Time needed to start a new business	25
8.	Import in relation to GDP	31
9.	Education	39
10.	Road network connection	43

Source: http://reports.weforum.org/global-competitiveness-report-2018/competitiveness-rankings/ [12]

The reason behind low competitiveness of products and services that come from Serbia include low level of coverage of imports by export of products that are technologically intensive. The majority of products exported by Serbia are low in technology and have no technological content or quality that are competitive on the international market [13]. This leads to low income from technology exports. Further, because of this, Serbia lags behind other countries when it comes to applied technologies. However, there is room for improvement as among the best ranked factors that affect the business of Serbia are those that can influence the development of entrepreneurial behavior and achieving competitiveness.

4 Research and Results

In order to adequately address the issue of competitiveness of domestic enterprises in Serbia, a hypothesis is introduced accompanied by supporting data. In this research paper it was noted that some of the main contributors to competitiveness according to the World Economic Forum are:

- Electrification rate
- Annual inflation rate
- Insolvency control network
- Severance pay costs
- Railway network development
- Capital banks regulation
- Time needed to start a new business
- Import in relation to GDP
- Education
- Road network connection [12].

Furthermore, taking into consideration other studies, contributors to competitiveness of domestic enterprises are the following:

- standardization of business quality (SBQ) through quality management systems,
- innovation (INN),
- productivity (PRO),
- education – knowledge and skills (EDU).

Based on the thoroughly analyzed literature in this domain the following hypothesis is proposed:

H: Higher rates of business quality standardization, innovation, productivity and education in domestic enterprises positively reflect on the competitiveness of Serbia on a global scale.

Next, the following research questions are addressed through which the proposed hypothesis is analyzed/tested:

1. Does standardization of business quality positively affect the competitiveness of enterprises?
   It was found that quality management systems contribute and positively affect process innovation and product innovation which further positively affects competitive advantage of the enterprise [14]. Similarly, this was described in the research of Campos-Soria, García, and Ropero García, where service quality was linked to increased competitiveness [15]. In addition, positive impact of total quality management on competitiveness in metal industries was noted in the findings of Dametew, Kitaw, and Ebinger [16]. Further, there is a large body of literature that supports these findings. It is evident, that quality management systems and overall standardization of business quality has a positive effect on competitiveness.
2. Can innovation increase the competitive ability of an enterprise?
   Certainly. One of the best routes for an enterprise to achieve higher competitiveness is through innovation [17]. Even in the early research of Clark and Guy it was discussed that innovation and new technologies are crucial for developing competitiveness [18]. Innovative products and services have the potential to pierce markets and to obtain a stable market position [19]. It safe to propose that innovation can overall increase the competitive ability of enterprises [20, 21].
3. In what degree does productivity play a role in achieving competitiveness of enterprises?
   Increase in productivity positively affects product and service, consequently increasing competitiveness on the market [22]. It is important to add that it is not enough to lower costs, but organic productivity has to be increased in order to achieve long-term competitiveness [23]. As it was mentioned earlier in this present paper, increasing productivity inevitably lowers production costs which opens doors to lower and competitive prices.
4. How important is education (knowledge and skills of employees) in business and how does it affect business performance and competitiveness?
   Human capital positively affects the value creation process in the enterprise which further positively affects business performance and competitiveness [24]. Further, the research of Mendes and Machado noted that employee skills are positively

related to manufacturing flexibility, new product development, and to overall business performance [25]. Developing employee skills and introducing training and learning courses for employees have a positive effect on the enterprise's competitive ability [26]. Based on these findings, it is evident that employee skills and education has its role in achieving competitiveness on the market.

5. Can an increase in competitive ability of domestic enterprises affect the competitiveness of Serbia?
   It was argued that enterprises within a country are the core of the competitiveness of that country [27]. Certainly, there is a link between national competitiveness and the competitive ability of enterprises [28]. Based on these research findings, and numerous other studies conducted in this domain, it is evident that the more competitive are the enterprises in a country, the more competitive the country. Therefore, it is proposed that increase in competitive ability of domestic enterprises reflects positively on the national competitiveness of Serbia.

According to the research questions and the answers provided, the proposed hypothesis can't be rejected. Now, in addition to these findings, the competitiveness ranks of Serbia from 2009–2010 to 2018 according to the report of the World Economic Forum, are presented on Fig. 1.

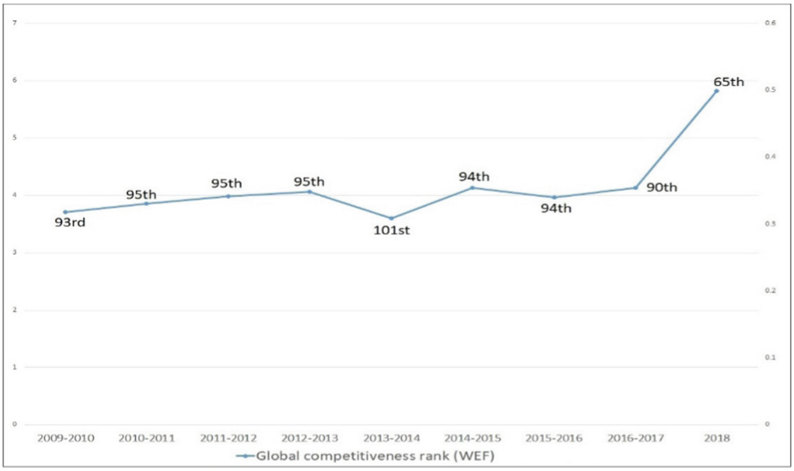

Fig. 1. Global competitiveness rank of Serbia from 2009–2010 to 2018

Takin into consideration the vast room for improvement, future projections can be positive. On Fig. 2, the projected future trends of national competitiveness are addressed. Standardization of business quality, innovation, productivity, and education – knowledge and skills are taken into consideration. It is important to note that the proposed future trend of global competitiveness of Serbia is based on previous studies, and analyzed data. On Fig. 2, there are four (A, B, C, D) scenarios depicted.

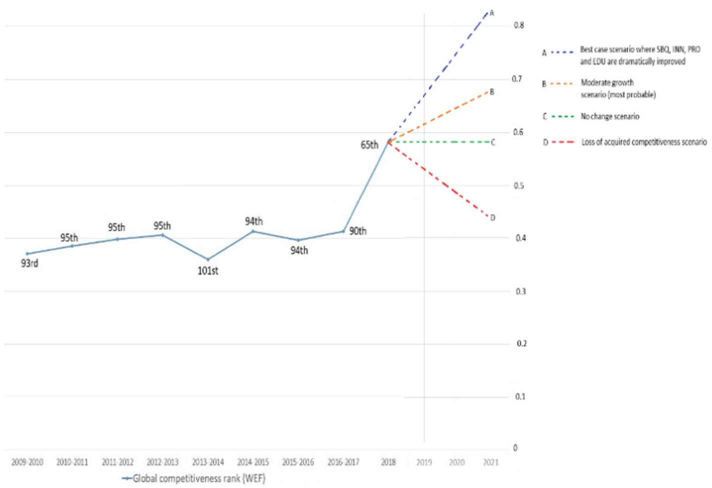

Fig. 2. Future trends of competitiveness of Serbia

Based on Fig. 2, there are several main development routes when it comes to competitiveness of Serbia. Scenario A is the best possible trend, but with low probability. This would mean that all quality, innovation, productivity and education are dramatically improved. Further, scenario B is also a positive trend, however with slightly lower improvement of rank, and little higher probability. Scenario C is the result of no changes or small changes that keep the rank slightly above or beneath the current (65^{th}) place. Scenario D, is pessimistic view on future competitiveness trends and it may be the result of no change or abandoning current levels of productivity, innovation, quality and education. In the next section, suggestion and guidelines for achieving competitiveness are discussed.

5 Suggestions and Guidelines for Achieving Competitiveness

Suggestions and guidelines for improving the competitive ability of domestic enterprises and the overall competitiveness of the domestic economy are the following:

- Improvement of organization and infrastructure,
- Improving and revitalizing the technological equipment of domestic enterprises,
- Improving and changing the behavior of leaders and managers,
- Improving product and service quality,
- Increasing productivity,
- Thriving towards sustainable manufacturing,
- Application of modern management methods and techniques
- Application of modern marketing techniques,
- Integrating innovations and into products and services,
- Defining long-term plans for achieving competitiveness.

Commitment to high technology and technological equipment is almost and imperative for the development of domestic economy. Domestic enterprises have to focus on business-oriented technological advancement and technological unification. These are important as they present necessary requirements of Industry 4.0. Products and services have to have a higher level of technological content, which would further be export-oriented. ICT and its application certainly can contribute to the development of competitiveness, however, domestic enterprises should base their business activity on products that are based on the manufacturing industry. This approach would open doors to the development of all the newly industrialized countries in the world.

Now, going back to ICT. Services in this domain are welcome, however the focus should be put later down the development road. Improving the technological base is a necessity for all domestic companies. Improving the IT base of business certainly has a positive impact on the improvement of productivity and of overall business performance. Enterprises and organizations of the future must be focused on innovation and to be flexible on any market. If an enterprise wants to be successful it has to simultaneously and continuously expand, innovate, and improve. Here, acquisition of new knowledge has to be taken into consideration as this would and will improve productivity, and increase competitiveness. This further means that domestic enterprises shouldn't focus only on the innovation of products and services, but also on the innovation on the business as whole as well. This innovation has to include the management system and the organizational structure. In addition, regardless of size and activity, domestic enterprises should focus on entrepreneurial activities as this will increase competitiveness in the long-term. This includes the use of state-of-the-art management tools and techniques. To ensure survival on the global market, domestic enterprises have to conduct business planning based predictions and adopting the concept of change.

Furthermore, enterprises who have adequate productivity have more room to continuously improve business quality. It has already been noted that quality and competitiveness are positively correlated. Why is quality improvement important? It is known that improving quality lowers business costs, reduces mistakes, delays, scrap, raw materials, and overall positively affect the management and business resources. Additionally, reduced operating costs, increases productivity. With lower costs and better productivity there is more room for a flexible price policy where good quality products and services are sold at competitive prices. Optimizing in this domain contributes to a stable market position. Application of international management standards would improve competitiveness and productivity in domestic enterprise. Managers should focus on consumers and competitors. Problems arise when managers and executives are focused on internal factors of the business. Through the years, managers of domestic enterprises in Serbia were not focused enough on consumers nor competitors. In modern business, focus on one's organization is not bad, but it is essentially surpassed. Local managers have to focus on developing relationships with all stakeholders in the environment. In addition, business managers have to think about the relationships among the consumers and other businesses.

Furthermore, on a global scale in the context of Industry 4.0, enterprises have to find the most efficient way to apply adequate technologies which will help them achieve increased productivity, increased quality of products and services, and increased competitive ability. Another important factor for achieving competitiveness is knowledge. Enterprises have to nurture and cultivate their employees' knowledge and skills. The main idea here is that knowledge and knowledge society are not the results of one individual, but the results of collective work of individuals who create, share and multiply knowledge as a resource [29]. Therefore, enterprises should focus on their employee's specialized knowledge and skills with the goal to apply that knowledge in business. Domestic enterprises suffer from the lack of competitiveness which is the result of low productivity, inadequate application of the quality management sector and the lack of application of knowledge and employee's skills.

Even though the competitiveness of the domestic economy is improving by each year, there are still problems in the domain of applied innovations, and productivity. These further affect product and service quality. Domestic enterprises have to realize that without continuous and good quality products services, there is no chance of achieving, maintaining and developing competitiveness. Managers of domestic enterprises have to implement and apply modern management and marketing techniques including knowledge-based management systems, marketing relations and standardization of business quality. In the era of the fourth industrial revolution (Industry 4.0), domestic enterprises have to act in accordance with the changes that this revolution brings, as competitiveness can only be obtained through adapting to these changes.

Finally, there is a misunderstanding of marketing in countries in transition [30]. The misunderstanding manifests itself as the personalization of marketing by the CEO or one of the managers. It is necessary to avoid fast modern techniques of marketing.

Kotler et al. clearly noted that marketing is not the result of careful planning and organization and the use of modern techniques, but rather, marketing is a generator of company growth [31].

6 Conclusion

Globalization has brought dynamic changes to the market. SMEs face a large set of challenges when it comes to achieving and maintaining competitive ability. Even more difficulties are present for new businesses. A modern, lean and sustainable approach has to be taken into consideration by domestic enterprises in order to increase "survival" rates on the market. Enterprises have to be agile when it comes to changes on the market and not only that, but they also have to predict these changes and to act accordingly. In addition, enterprises have to approach technology management in a more innovative way.

The results of this research indicate that the proposed hypothesis "*H: Higher rates of business quality standardization, innovation, productivity and education in domestic enterprises positively reflect on the competitiveness of Serbia on a global scale.*" is failed to be rejected. The analyzed data and the addressed research questions support this.

Further, it can be concluded that Serbia has a big potential when it comes to achieving competitiveness, however, issues in the domain of entrepreneurship, product and service quality, innovation, productivity and education should be addressed and taken into consideration in the long-term.

For future research, an Industry 4.0 manufacturing model could be analyzed. In addition, scalability of Industry 4.0 technologies in the context of globalization should be addressed. Finally, a meta-analysis of studies in this domain could be conducted in order to determine and create projection of future trends when it comes to domestic enterprises, the domestic economy and competitiveness on a global scale.

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Urban Manufacturing of Sustainable Customer-Oriented Products

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Abstract. Personalization and sustainability are becoming driving forces to achieve a leading role in a fast-changing market. Therefore, manufacturers need to become more agile and flexible, introduce personalized products and customer-oriented services, measure and capitalize environmental intangibles. To answer to those requirements, this paper addresses the key elements characterizing the urban manufacturing concept, thought as an innovative production scenario leveraging closeness to customer, customization and sustainability. Such a framework is based on innovative technologies enabling collaborative short value chains and responsive production in constrained environments, for customer-oriented products and services. The main aspects, discussed in this paper, defining the proposed production paradigm are: (1) Product customization and digitalization; (2) Sustainability; (3) Flexible and short supply chain; (4) Responsive production systems; (5) Design to manufacturing in one step; (6) Industrial symbiosis; (7) open innovation. Two application cases in the furniture and footwear sectors are discussed, highlighting experienced benefits, open challenges and future research directions.

Keywords: Urban manufacturing · Mini-factories · Customer-oriented products · Responsive factories · Collaborative value chains · Sustainability

1 Introduction

Nowadays, customers demand more and more personalised products and services. At the same time, there has been a strong drive towards awareness of how products impact on the environment. To cope with this constrains, manufacturers have to (1) become more agile and flexible, in response to the fast rate in which market trends change, developing collaborative value chains and responsive manufacturing infrastructures that can produce higher variations in smaller quantities [8, 9], (2) introduce personalized products and customer oriented services whose added value can trigger market acceptance [11, 12], (3) measure and capitalize environmental intangibles (such as environmental pollution, local sourcing, waste and energy consumption) [2, 11].

As an answer to the aforementioned requirements, and to achieve a leading role in the fast-changing market, this paper addresses the key elements characterizing the urban

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manufacturing concept, thought as an innovative production scenario leveraging closeness to customer, customization and sustainability as main drivers. Such a framework is based on innovative technologies enabling collaborative value chains [8] and responsive production plants [9] for customer-oriented products and services [11, 12].

This paper first addresses the main features of the proposed innovative urban production framework in Sect. 2. Then, two industrial application cases are discussed with reference to the furniture and footwear sectors in Sects. 3 and 4 respectively. In Sect. 5, an analysis of the two the application cases is performed highlighting the experienced benefits and the open challenges. Finally, some concluding remarks as well as future research directions are outlined in Sect. 6.

2 Key Elements of the Proposed Urban Production Framework

An urban manufacturing system is defined as a production system located in an urban environment that is actively utilizing the unique characteristics of the surroundings towards value creation for the customer [1]. Further to that, we explore the idea of urban manufacturing through mini-factories (Fig. 1), where the reduced dimension is cornerstone to place the factory directly where the customer is used to live and go shopping, revolutionizing the way products are designed, produced and sold. The urban mini-factory is meant to embody the concept of "close to the customer" in terms of features offered, place of fabrication, time to deliver and sourcing of materials. The main aspects defining the framework of the proposed production paradigm are outlined in the following points:

1. **Product customization and digitalization.** Customers are integrated into value creation by defining and configuring an individual solution, concretizing needs and desires into concrete product specifications (and later driving manufacturing). As far as production in mini-factories is concerned, the digitalization of the products and of the customization processes is a key element because of two main reasons: first, the concept of personalization itself, coupled with space constraints, basically limits the capability to experience physical products down to zero. Digitization turns a non-existent physical product into a digital customer experience to create competitive difference and drive engagement. Second, the digital customization process is an action that concretizes the personalization potential into a single customized product, with well-defined specifications ready to be seamlessly transformed into manufacturing operations [2].
2. **Sustainability.** The label of "sustainable" is a bottom line requirement: as a matter of fact, sustainability has become a common basic goal for many national and international organizations and a driver for customers' choices. Indeed, being sustainable is a picklock for accessing most demanding customers. However, in spite of the nearly universal recognition, people still struggle with the full understanding of the concept. The urban mini-factory must propose practical indexes to build-up an effective assessment model, to reflect in real time the impact of customer choices during his shopping experience. This evaluation represents a

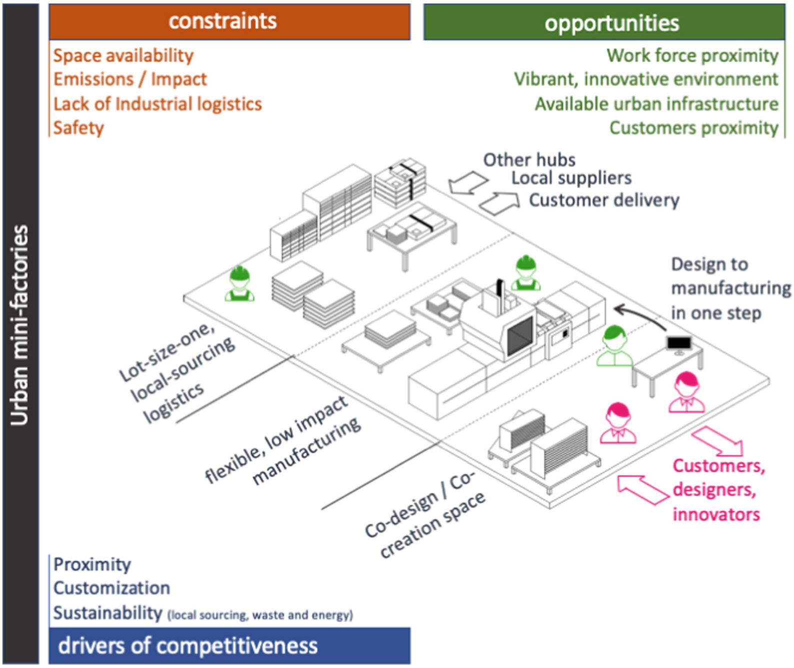

Fig. 1. The urban mini-factory framework: drivers, constraints and opportunities.

quantitative measurement of environmental, and possibly also economic and social performances: the use of concrete figures and quantitative evaluations transforms the well-recognized, but sometimes vague concept, of sustainability into a powerful tool that customer can understand and apply to guide their choices, further highlighting the attractiveness of the urban manufacturing paradigm [3].

3. **Flexible and short supply chain**. Even if an urban factory, by being situated close to the workforce, potential customers and suppliers, can take advantage of the urban infrastructure, logistical challenges are still commonly seen as one of the most demanding obstacles to urban production, particularly when considering the needed on demand and just in time supply chain features [4]. On the other hand, this notwithstanding, short and local (like "farm to table" concept) distribution channels could be an essential driving force towards value creation for the customer. Therefore innovative collaborative value chains are a major driver to enable the proposed concept [8, 11].
4. **Responsive production systems: low impact; safe; flexible.** To enable urban production, it is necessary to adapt standard manufacturing technologies to urban requirements, in terms of emissions, high flexibility to match customization requirements (the manufacturing system will need to ensure the execution of all the fundamental processes required, measured against the space available), and safety [5]. In particular reconfigurable [9] and highly automated production systems [10]

are needed to properly and effectively respond to the customers expectations, thus requiring novel machines and control solutions.

5. **Design to manufacturing in one step.** Tools and post-processing technologies, able to remove any software exchange and machine programming complexity, are needed to empower quick and highly automatized manufacturing of personalized goods. Once the product is configured, the design needs to be processed and transformed into machine-ready language on one side, and enterprise resource planning data on the other (to trigger the supply chain) [6]. To achieve such objectives advanced CAD-CAM as well as MES tools have to be introduced, supporting innovative post-processing and scheduling methods [8].
6. **Industrial symbiosis.** The socio-economical-technical constraints rooted in the urban manufacturing concept will call for a new set of a wide-ranging interaction among companies, also participating in diverse and collaborative value chains, in order to optimize the use of energy and other critical resources, such as water, materials (both raw and recycled), residues, etc. The beneficial reuse of flows (water, waste, by-products, energy, recycled materials, etc.) results in a more resource-efficient production at network level, and in fewer adverse environmental impacts: this is of the uttermost importance taking into account the urban environment in which the mini-factories operate [7, 12].
7. **Open innovation.** Potentially, an urban manufacturing system actively utilizes the urban society and the knowledge and skills of the citizens. This has the prospective to radically change the traditional logics, currently in place to design and manufacture products, towards an increased open-oriented approach for customers and value chain actors, to collectively develop and make personalized products and services, integrating digital-led innovative features and exploiting a dynamic and dispersed production ecosystem. The potential of the collaborative and networked innovation resulting from a high level of diversity can be exploited, for the benefit of the consumer, as well as for the benefit of the industry.

3 Application Case in the Furniture Sector: The CTC Project

The Close To the Customer (CTC) mini-factory is a production scenario exploiting closeness to customer, customization and sustainability in order to strengthen the competitive position of manufacturers in the furniture market. The idea of CTC is to move the factory directly behind a glass panel in the shopping mall (Fig. 2), making closeness to the customer and purchasing experience at the centre of the whole value proposition [13].

The CTC mini-factory finds its ideal location in a shopping mall where both the sales area and the production area are located next to each other and are accessible by people visiting the mall. The CTC mini-factory scenario begins with a customer entering the CTC shop and customizing the furniture he/she is interested into, using a user-friendly configurator. The design of furniture is driven by a parametric portfolio of products that has been predefined by CTC designers coherently with the functional constraints of the mini-factory. Once the furniture project (a single piece of furniture or

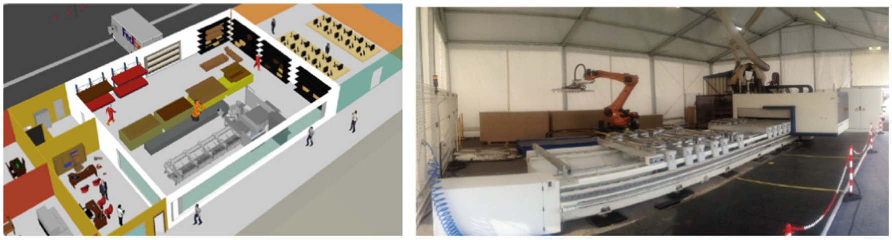

Fig. 2. The CTC urban manufacturing concept: scenario and real machining system.

a complete room) is finalized and the customer is satisfied with the offer, an order is generated and sent to the CTC-factory. Machine instructions are automatically created to command the behaviour of the mini-factory. A real-time update of production data allows the customer to monitor the processing status of his/her order other than to increase the efficiency of the production system itself. A high level of integration of informative systems is one of the main features the CTC-system. In fact, a smooth flow of information from the idea generation to the production allows a lean fulfilment of orders in short times.

Product Customization and Digitalization

CTC manufactures personalized furniture that can be configured in terms of colour, material, dimensions and shape. A dedicated basic design tool enables to define, starting from scratch, the parametric products compatible with CTC production system requirements and constraints. The tool is meant to support designers during the creation of the stable solution space characterizing the CTC products' portfolio. As output, the software develops a parametric product library that will be used, in the CTC configurator, as starting point for the creation of personalised product designs. By simply feeding the customization requirements through a tablet-based user interface, the design can be thus adapted, automatically updating price and specific sustainability impact of the configured product at each iteration.

Sustainability

CTC deliveries a green label, based on the concept of product footprint and the related life cycle analysis, used to give the customers the means to understand the impact their products and customization variants have on a set of sustainability indexes [14, 15]. In order to obtain this information, an assessment engine was built to retrieve the data related to material of the components, operations performed and environmental indicators of the material suppliers, and transform them in product related impact data. The assessment is meant to enrich the report sent to CTC customers after product configuration and prior to product delivery in order to increment the value-added proposition perceived by CTC consumers. The customer can thus know the environmental performances related to the configured product and, varying its configuration, can determine the best product both from the esthetical, technical, economic and environmental point of view.

Flexible and Short Supply Chain

In order to cope with product customisation needs, CTC requires an high level of flexibility in the upstream supply chain, enabling to achieve the required level of service that the business model propose (one week delivery). To meet this requirement, it is of primary importance that the CTC Mini-factory panel suppliers are distributed locally, which means at a distance around 20 km. This is intended to enable delivery of panels each 2 days, thus limiting the number of panels to be stored in the mini-factory near to zero, and enabling to maintain a greater variety in the type of materials and colours to be offered.

Responsive Production System: Low Impact; Safe; Flexible

The production of furniture within the CTC production system is carried out by an innovative manufacturing cell designed to withstand customized products manufacturing according with requirements of high automation, flexibility and safety [16]. The machining centre is able to ensure the execution of all the fundamental processes required to work wooden laminated panels: nesting, boring, routing and edge-banding, all in a single machine [17]. The process of furniture realization is fully automated thanks to the integration in the system of an anthropomorphic robot able to pick raw panels from stacks nearby the working centre and to position them on the machine worktable. The developed manufacturing cell is able to withstand customized product manufacturing requirements by providing (i) a high degree of flexibility for batch size 1 production; (ii) high degree of automation thanks to inclusion, in a single system, of all the functions (nesting, boring, routing, edge-banding) required for panel based furniture manufacturing; (iii) integration of simplified and optimized machine interfaces and safety equipment supporting machine supervision by means of a single worker; (iv) optimized dust extraction capabilities supporting near-zero production of wooden dust for installation in a not industrial context. Eventually, a reduced foot print area is obtained thanks to a compact lay-out able to include machinery, loading/unloading system, tools and edges warehouses and panels' stacks in 120 square meters.

Design to Manufacturing in One Step

The CTC scenario puts in place all the constitutive elements of a streamlined design to manufacturing procedure, enabling the transition from the digital avatar of the product to the real one, in a fully automated fashion [18]. Once a configuration is completed, the configurator translates the "design language" in machine readable language by means of a post-processor. The post-processor, developed in tight collaboration with the developers of the CTC production system, generates the scripting files required to re-tune the manufacturing system according with the customized characteristics of each product and to guide the manufacturing operations. For instance, the post-processor guides the nesting operation, intended to enable the minimization of the scrap rate and understand the raw material to be communicated to the ERP for raw materials order. Through the connection with the production system supervisor, the overall manufacturing time required to bore, mill, cut and edge-band all sheets is eventually calculated and used to evaluate the precise delivery date to be returned to the customer. The connection with a dedicated scheduler enables to generate and store the tasks required to manufacture the defined furniture. Considering the estimated raw material arrival date and the expected manufacturing time, the scheduler is able to define a production queue, thus empowering the expected manufacturing date that is eventually delivered to the customer.

Open Innovation

The nature of a business relying on digital designs opens-up several opportunities in terms of distribution and openness of the design community [19]. In CTC, the involvement of an open community of designers residing in a location potentially remote with respect to the CTC mini-factory, is considered a value adding element enabling to increase the number of design product to be offered and supporting the granularity of design styles. In a franchising-based scenario, as one of those conceived in CTC, the product portfolio will be kept updated, with new releases determined by the setup of the franchiser, validating and industrializing the proposals coming from the open community of designers.

4 Application Case in the Footwear Sector: The ADDFactor Project

In the footwear sector, consumers demand for personalised, comfortable, safe-healthy, affordable and sustainable products is growing. This is a traditional pillar of value-added manufacturing, targeting products recognized and considered as a reference all around the world [20]. To meet these demands, ADDFactor (ADvanced Digital technologies and virtual engineering for mini-Factories) proposes a "Mini-factories"

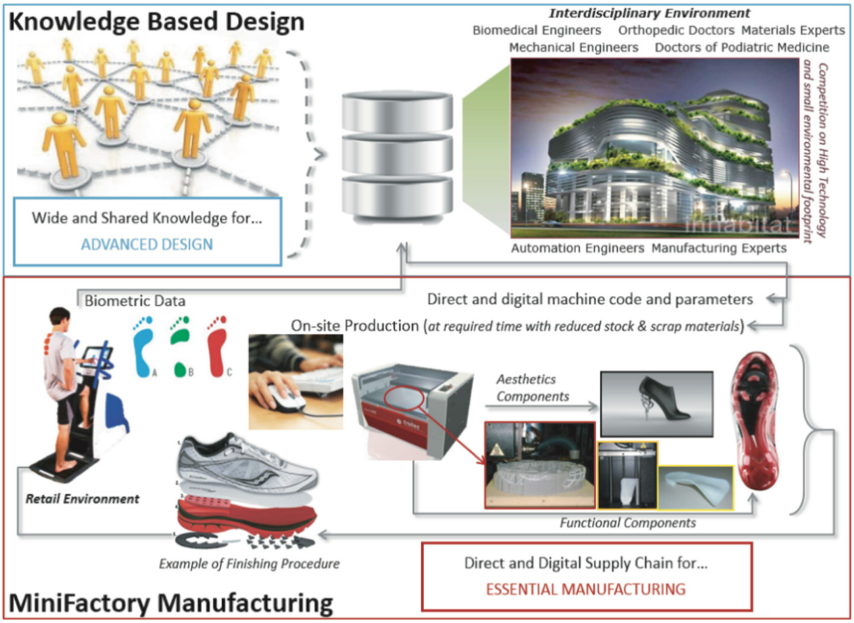

Fig. 3. The ADDFactor urban manufacturing concept.

concept, which is conceived to be an innovative solution for most of the actors involved in the whole supply chain: the link between retailers and the manufacturing technologies is supported by a new production framework concept, which is based on central knowledge-based design and local distributed manufacturing in mini-factories (Fig. 3).

This concept is applied focusing on need-driven products, where the functional personalisation along with the aesthetic customization become important assets to claim a direct relationship with the users of those goods. ADDFactor manages the complexity of the design phase thanks to a direct connection with the retailer, that provides "biometric data" of the customers as tacit requirements and "aesthetics tests" as explicit demands, being both fundamental for an effective individual personalization.

ADDFactor provides all the technologies needed to manage two typologies of data: the acquired *biometric data* as input for designing custom solutions and the *technological parameters* as output of design phase, necessary to drive the machines (in retails or near environments) to fabricate advanced products. In the retail, final users may personalize the aesthetics of products and the collected requests are then sent and automatically linked to the acquired data necessary to manufacture locally the products through an easy-friendly configurator.

ADDFactor provides manufacturing solutions which are placed at retail environment. At the end, the retails have all the acquisitions technologies necessary to collect the data, fabricate the complete product (such as foot orthotics), finalize a custom solution with the production of personalized element (such as heels, plateau and insoles) assembling them on standard products.

Product Customization and Digitalization

ADDFactor develops customized shoe's components (functional, bio-medical and safety-wellness related aspects), so as to guarantee comfortable, performing, safe and healthy products for different application (orthopaedic, sport and leisure and fashion) and different consumers, mainly biometric customization with aesthetic possibilities. In the retail, advanced shoes design configurators empower the final user to access and personalize the product, targeting necessary information gathering related to:

a. **insole based solutions:** the customer can select the desired upper part of the shoe from a set of available parts and the colour of the sole. The geometry of the sole changes according to the individual biometric data.
b. **fashion shoes:** in this case the customer can mainly customize aspects like the heel shape (geometry of the heel), the texture and the colour. Moreover, the customer can select the desired upper part of the shoe from a set of available parts.

ADDFactor products, accompanied by the biometric characterisation of user, are fully digitalized in order to support: (i) basic design of customizable products by means of ad-hoc created CAD applications and configurators; (ii) musculoskeletal analysis (iii) adaptive and auto-configurable local flexible production.

In order to support the biometric characterization of the customer, ADDFactor provides low-cost, precise, robust and easy to use scanning devices (such as 3D scanner, pressure distribution sensors device and inverse kinematics detectors) which allow the treatment of an important amount of biometric data and eventual relative product preferences. Those scanning technologies overtake the limits represented by the available technologies in application for commercial usage in local stores and detect biomechanical aspects of customers in order to drive the design phases of final products.

Responsive Production System: Low Impact; Safe and Flexible
As it is obvious to know, all the techniques such as vacuum forming, machining and hand-finishing produce orthoses that are not reproducible and difficult to verify or control for quality and functionality [21], they should leave the way to some other techniques able to use that complex data and confer major functionalities to the final product at reduced cost.

ADDFactor is mainly focused on subtractive and additive techniques which represent the most important rapid, flexible and low-impact manufacturing technologies. While the first one uses a conventional technique to remove the excess material, producing waste materials, the second one is a non-conventional production based on layer by layer manufacturing. In this case, the process which starts easily and directly from the digital file (treated and converted in standard format), allow an "essential" manufacturing through a faster and more repeatable procedure. Whereas the additive machine is more focused on rigid-semi-rigid materials and it is able to produce with a reduced volume of waste materials, the NC machines are more recommended to manufacture flexible materials which are obtained by conventional chemical procedures which guarantee the requested thermal and mechanical properties. The main effort of the additive manufacturing is mainly focused on developing dedicated and optimized solutions for flexible manufacturing of target products [22, 23].

In the milling machines operation, the complexity of shape, such as the bottom of the foot, is converted into three-dimensional trajectories in the working volume which are anytime calculated by CAM software and post-processed for the machine controls. The milling tool which follows "alone" the instructions going around in the 3D volume, is replaced by a dedicated layout of multiple tools which receive direct data to be implemented being auto-configurable and guaranteeing an ultra-fast milling operation which is finalized by one or two passages of the product under the multi-tools. This machine is mainly used for producing accommodative insoles, but the evolution proposed by ADDFactor allows a repeatable and industrial way to produce anytime personalized shape. The improved speed and easy-friendly con-figuration makes the approach suitable to provide insoles to the mass market along with normal shoes which already let customers to insert external and personal insoles.

All the ADDFactor machines considers the environmental aspects, in terms of ecologic and reusable materials (bio-degradable materials for sole, reusable and recyclable materials such as thermoplastics for extrusion-based machines). Moreover, the extrusion-based process neither uses toxic polymers nor causes smoke or fumes during the deposition. The fabrication is per-formed safely, allowing the installation of machinery and systems in office environments without health risks.

Design to Manufacturing in One Step
The biometric characterisation of the customer, accompanied by customer's personalization choices, drives the manufacturing process, thanks to CAD-to-Printer capability provided by the ADDFactor framework.

The motion and forces detected by the acquisition devices can be translated to understand the joint reaction forces and other data in order to develop foot personalized orthoses for better functional performance and comfort. The complex foot model interprets and simulates the input data being able to process dynamic external forces in order to define the optimal product specifications.

The data interpretation and simulation are performed by the ADDFactor design tools, provided for the engineering of the products, resulting in the creation of complex internal structures (meso-structures) and profile within the functionalised product, to be realized via rapid/additive manufacturing.

Management of the resulting complex structured product is then carried out at production level: data on product internal structure are handled and post processed so as to create a direct self-contained digital part program, comprehensive of all needed information to be manufactured at retail level, by means of ADDFactor production technologies.

Open Innovation

ADDFactor supports an open design community enabling the creation of new parts of products (for example new heels for fashion shoes or new textures for sole and insoles) compatible with the ADDFactor production framework. The involvement of an open community of designers represents a big opportunity for the ADDFactor framework because it enables to increase the number of design parts to be offered and proposed to the final user. This community can be widely spread, based on a single repository and accessible to each ADDFactor mini-factory instance obtaining, as final result, a value-added service.

5 Experienced Benefits and Open Challenges

Through both the presented application cases, the following major benefits have been experienced.

- **Customers involvement and satisfaction:** CTC underwent validation through the implementation of the mini-factory in a real the shopping mall. Customers involved in the demo activity have been able to experience the whole CTC concept, from configuration to manufacturing and delivery of customized product. In particular, more than 50 real customers have been involved in the configuration and manufacturing of customized furniture. The general satisfaction of the customers involved in the CTC process has been very high, with a particular mention about the flexibility of products' configuration. AddFactor shoes have been extensively tested with semi-professional runners, that evaluated through questionnaires the following aspects: comfort, weight, flexibility, medio-lateral stability, fitting. The customized shoes achieved good overall performances (including the perception of the customization process), this notwithstanding some critical issues that have been noted in the upper-tongue flexibility and sole edge rigidity.
- **Reduction of value chain and production times and cost***s* have been experienced in both projects. As an example, within the CTC validation activity, the average delivery time was 2.23 Days, throughput was 0.5 orders per hour (development of

customized cabinets), and inventory level (measuring the number of days the factory can produce without replenishment) was 4 days. Nowadays, the average delivery time for customized furniture, manufactured within standard value chains, is today around 3 weeks.
- **Increase of sustainability performance:** the green label is designed to communicate to the customers the sustainability of the overall production processes and the impact of his customization choices as far as the considered products, i.e. furniture and footwear products, are concerned. As an example, in the CTC project the LCA analysis was based on a comparison with a piece of furniture, produced with wood not coming from a certified supply chain. CTC products showed a general reduction of production related impacts on a set of 5 impact indicators, with an average reduction of 150% of CO2 emissions in the demonstrated scenario configurations.
- **Open innovation of products and processes** have been developed and assessed in the mentioned application cases of the proposed urban manufacturing framework. In the AddFactor project open innovation of products has been enabled through the design and manufacturing of customized shoes components, by means of different production technologies and solutions. In the CTC project, a set of industrial design students have been also involved in new furniture design for CTC products. The students proposed creative ideas that were included into the catalogue, offering, on the one hand, visibility to young designers, and, on the other hand, additional personalization options to the CTC customers (that also provided feedbacks). This approach has the potential to unleash creativity of designer towards co-creation of new pieces of furniture: this potential hardly finds today its way through the rigid structures of the furniture industry that is often based on a closed innovation approach. Thus, the project allowed democratizing the access to production resources in the furniture sector, towards increased capability to discover talents.

In order to fully implement the proposed urban manufacturing framework some major innovation challenges have to be tackled in the near future. In particular the main elements to be addressed are shortly addressed thereunder.

- **Open product co-design methods and tools** have to be developed, based on innovative and modular product development methodologies as well as on collaborative digital solutions.
- **Advanced post-processors** to shorten the design to manufacturing time and minimize human intervention are of major relevance in order to support on demand production of personalized products, specifically to properly integrated novel advanced CAD features with advanced CAM tools for CNC based flexible machines.
- **Reconfigurable, low impact and safe machines** are of crucial importance, with specific focus on their capacity to effectively produce a larger variety of products and/or products components.
- **Responsive and clean factories** integrating agile automation and real time scheduling capacities are needed to cope with the requirements of the proposed urban manufacturing framework, and to properly respond to the customers expectations.

- **Reactive and integrated value chains** are mandatory to guarantee the just in time and on demand production capacities needed to fully implement the proposed and discussed urban manufacturing framework.

Real time and effective LCA tools have to be further developed so as to support the sustainability oriented customer involvement in the product and process co-design.

6 Conclusion

Urban manufacturing is an innovative concept that leverages the production of sustainable customized products, manufactured and sold directly within the urban environment. This is meant as a strategic business model to support manufacturers in innovating products and services value chains. This paper addresses the main aspects defining the framework of this production paradigm and presents two application cases in the furniture and footwear sector, pointing out their benefits.

The implementation activities carried out in the two use-cases, briefly described above, showed how the urban manufacturing concept can be actually instantiated in a real urban context, involving customers that have been able to experience the whole concept by configuring, see manufactured and receiving their customized products. The quantitative and qualitative results obtained during those instantiations are promising and pave the way for further research: customers involved in the experience strongly supported the freedom of personalization, the sustainability aspects, and the short delivery times, demonstrating the actual feasibility at larger scale.

Future work will concern methods and tools for customers involvement through co-design instruments, flexible and clean machining centers for urban production, digital solutions for personalized production operations and planning, just in time and on demand value chains management solutions, novel sustainability assessment tools.

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Zero Defect Manufacturing Strategies and Platform for Smart Factories of Industry 4.0

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Abstract. Within the context of market globalisation, the quality of products has become a key factor for success in manufacturing industry. The growing unpredictability of demand necessitates continuous adjustments in production targets. Addressing customer needs and customer satisfaction are the most important factors for successful businesses. Being consistent in meeting their needs, the existing manufacturing systems have to be adaptable while maximising the quality of their products. Guided by this challenge, in this paper we provide a holistic framework and ad-hoc strategies applicable both to new and existing manufacturing lines to achieve zero-defects in manufacturing via a novel ZDM platform that integrates state of the art ICT technologies, AI models and inspection tools which elevate manufacturing plants to a superior level of competitiveness and sustainability. The proposed approach and results in this article are based on the development and implementation in a large collaborative EU-funded H2020 research project entitled Z - Fact0r, i.e. Zero-defect manufacturing strategies towards on-line production management for European factories.

Keywords: Industry 4.0 · Zero - defect manufacturing · Big data · Smart factories · Sustainable manufacturing · Industrial production

1 Introduction

Nowadays, the efficiency and sustainability of the manufacturing processes of high-tech products depend on the introduction of Advanced Manufacturing Technologies in the production processes [1]. In particular, the development of metrology solutions for zero defect applications is considered as a robust technology able to provide a vast competitive advantage to manufacturing companies [2]. This trend is perfectly identified by "European Factories of the Future Research Association" (EFFRA) in the "Multi-Annual Roadmap for Factories of the Future" for 2014–2020 under the framework of the penetration of flexible and smart manufacturing technologies in the field of control and monitoring of the quality of manufacturing products [3].

Manufacturing enterprises are pushed to take "local" actions: thinking globally but acting and staying economically compatible within the local (regional and national) context. In order to achieve high precision manufacturing of complex products, there

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has to be a fundamental rethink on how to increase the accuracy of machines and improved controls [4]. The improvement should not only concern the individual machines as isolated islands but encompass the totality of production process as a system of interrelated elements that seek to maximise efficiency, productivity, customer satisfaction; whilst at the same time eliminate waste and excess inventory.

To meet the requirements mentioned above and aligned with the Industry 4.0 key objectives toward eco-factories of the future [5, 6], this study provides a holistic framework and a comprehensive set of integrated strategies encompassing the whole manufacturing line for addressing the issue of zero defect manufacturing in smart factories of industry 4.0. Doing so, the research aims at providing an answer as to what could be the proper strategies and associated technologies to effectively minimize product defects in manufacturing systems. A large collaborative EU-funded H2020 research project entitled Z - Fact0r [7] has been the main driver of the described approach and is designed for its validation. The project consortium is formed by 12 organisations across Europe including industrial pilot plants, academic institutions and technology providing companies.

To this end, novel strategies are designed in this research to be deployed at the field. The implementation of Z-strategies solutions leads to the achievement of zero defects in a multi-stage production line. The zero defect management system proposed in this study will be demonstrated in three use cases, covering different industry types (i.e. electronics, and hard metal), proving its universal applicability and the achievement of zero-defects in multi-stage productions of various types.

2 Strategies for Zero Defect Manufacturing

The innovative synergies between online data gathering systems, real-time simulation models, data-based models and the knowledge management system form the main strategies which eliminate the generation and propagation of defects. On that regard, the proposed solution comprises the introduction of five (5) multi-stage production-based strategies targeting (i) the early detection of the defect (Z - DETECT), (ii) the prediction of the defect generation (Z - PREDICT), (iii) the prevention of defect generation by recalibrating the production line (multi-stage), as well as defect propagation in later stages of the production (Z - PREVENT), (iv) the reworking/remanufacturing of the product, if this is possible, using additive and subtractive manufacturing techniques (Z - REPAIR) and (v) the management of the aforementioned strategies through event modelling, KPI (key performance indicators) monitoring and real-time decision support (Z- MANAGE). Accordingly, the focus is on part, machine and process level to monitor the status of the manufacturing process in real time, and new strategies based on real data are defined to detect and prevent the generation of errors and defects. In case an error occurs, instead of wasting the part, corrective actions are suggested based on correlations and decision support mechanism. Also manufacturing equipment, part and process status measurement analysis are adapted to provide the means for process validation. Each of the developed strategies are triggered based on detecting and assessing the impact of system level events that cause lower quality, generate defects, and increase the costs. The holistic approach utilizes all the acquired data from which a prediction is made with confidence levels above 95%. Figure 1 highlights synergies and interactions between the five Z - Fact0r strategies which are further described below:

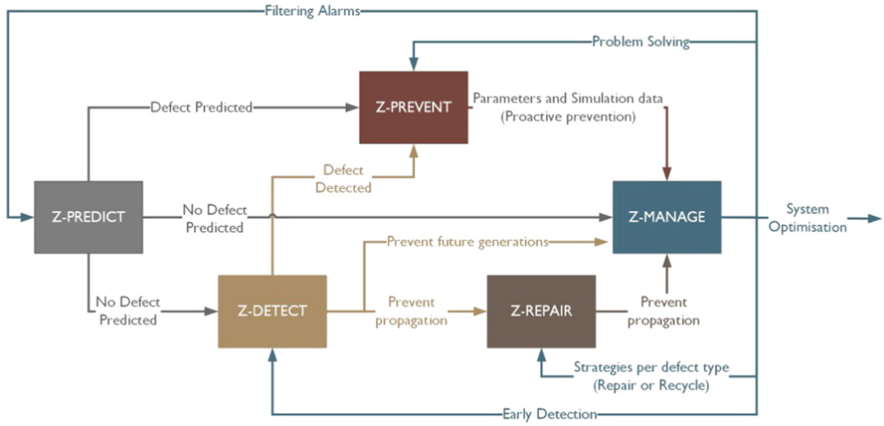

Fig. 1. Synergies and interactions between the five Z – Strategies

Z - PREDICT: The events detected from the physical layer of the system are engineered into high value data that will stipulate new and more accurate process models. Such an unbiased systems behaviour monitoring and analysis provides the basis for enriching the existing knowledge of the system (experience) learning new patterns, raising attention towards behaviour that cause operational and functional discrepancies (e.g. alarms) and the general trends in the shop-floor. The more the data pool is being increased the more precise (repeatability) and accurate the predictions will be. The estimations for the future states involve the whole production line, e.g. machine status after x number of operations and/or quality of the products for given set of parameters. The system can thus predict with high confidence the expected quality and customer satisfaction, allowing modifications to the parameters before the production of the products. In addition, it can operate in the reverse mode, i.e. insert a Customer Satisfaction Goal and control the parameters accordingly to achieve this target. The ability of the proposed zero defect management system to optimize the manufacturing processes according to certain/target quality levels and/or customer satisfaction is the key innovation to fulfil the industrial requirements.

Z - PREVENT: The prevention of defects strategy is based on the quality control and the inspection tools realized across the shop floor for condition monitoring of machinery and respective produced quality. The Z - PREDICT is predecessor of Z-PREVENT. The initial estimation of the future states and expected outcomes are taken into account and based on the simulation and modelling of the parameters. For each predicted defect, the responsible parameters are identified and flagged. The system adapts these parameters based on an initial estimation, which after the simulation are corrected recursively. The result of this process is to avoid the generation of defects based on each recorded event (defect, no-defect, low quality, high-quality) both from previous and current states. The system will demonstrate reduced false alarms by combining the future predictions.

Z - DETECT: This strategy is invoked when a defect is being generated after the adaptation of the parameters. In such a scenario, an alarm is being triggered to flag the parameters that resulted in a defect. By mapping the true reasons, the system is able to avoid having more generated defects by weighting the system model. Apart from the inspection of the product (from which the defect is being observed), the strategy involves more actions and processes to deal both with the generation of the detected defect, and its propagation to the next stages. Depending on the state that the defect was generated, the system will adapt its parameters to the previous successful state and plan to send the defected product either to downstream or upstream stage. The final decision on the actions is based on the Z - MANAGE strategy.

Z - REPAIR: Once a "repairable" defect is detected, a proper and customized repairing action must be deployed with the minimum time and effort, assuring the best productivity and production flow. In fact, a major challenge for an effective ZD manufacturing is related with the capability to automatically repair the occurred defects without perturbing the overall production flow. The proposed zero defect management system is based on a model-based, supervisory control solution that is able to interpret the inter-stage quality control measurements together with the monitoring of the process itself, in order to identify the defect sources and generate a proper and customized repairing action. Additive manufacturing in the form of inkjet or paste printing of various materials (metal, ceramic, and polymer resins) can successfully be used to fill a missing spot or correct a damaged part. Upon detection of the defected area, the printing head can deliver the patch material in solution or paste form. In the case of inkjet printing, defects as small as 20 μm can be patched. Post printing treatment of the delivered material include solvent evaporation (e.g. in the case of polymer patches), UV curing (e.g. in the case of epoxy resins) and low temperature laser sintering in the case of metal or ceramic nanoparticles, thermal curable resins or paste where a local reflow process is required.

Z - MANAGE: The overall supervision and optimization of the system is achieved after the execution of Z - MANAGE strategy. The defects are processed with Decision support system (DSS) tools and are interfaced with Manufacturing Execution Systems (MES). False positives and false negatives are clustered after the Z - DETECT strategy, which results into a good filtering of these false alarms. To achieve this, the previous acquired knowledge and incidents are also processed to fine tune the system's operation. Additionally, the production is optimized by better scheduling, taking into account the environmental impact of each process. The optimized scheduling and adaptability of the manufacturing improves the overall flexibility, placing a premium on the production rates, satisfying the demand, while preserving increased machinery availability. Since, the Knowledge Management system tunes the whole production according to certain quality levels and customer satisfaction, it is highly anticipated that the overall performance of the system suffices the increased needs of the customers. The strategy involves also the decision making in the event of a defect. The defect should be analysed via the Inspection system, from which the defect can be classified and categorized on its severity. In case of “repairable” defects the system decides for the following; (i) rework on spot, (ii) removal from the production line for further inspection and rework. If the defect is classified as “non-repairable” then the system decides whether the product will be (a) forwarded to upstream stages, or (b) considered as total failure where it will be recycled.

3 Proposed Zero Defect Management System

An efficient and effective zero defect management system should deal with the current trends for customisation and demand for zero defect manufacturing by introducing a holistic approach to not only achieve zero-defects but also maximise quality and performance. To do so, we employ five (5) strategies, namely Z - PREDICT, Z - PREVENT, Z - DETECT, Z - REPAIR and Z - MANAGE, all of which can be applied in the existing manufacturing plants with minimum interventions. Each of the strategies, as the name suggests, serves a different role which act synergistically with the others. The methodology relies on two inspection systems - one on the Work-Station level and one on the product level, as well as one online data gathering system and one online Defect Management system. In addition to the above, a Knowledge Management system provides intelligence and robustness to switch into the right strategy dynamically through the use of the three sub - systems. Figure 2 illustrates all the processes to achieve zero defect manufacturing from the four sub-systems and the output commands of each strategy.

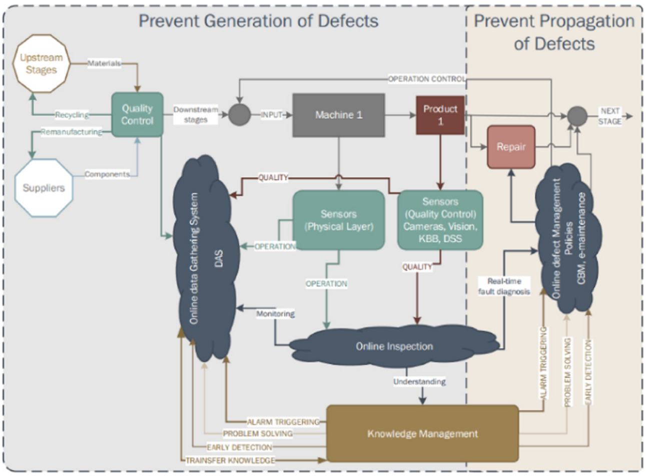

Fig. 2. Zero defect manufacturing system

Deployed Sub-systems

Work-Station Level: A series of sensors and actuators take readings for both the intrinsic and extrinsic machine's key performance parameters. The intrinsic parameters represent each factor that affects the work-station's behaviour on system level, such as structural health, degradation of components, energy consumption, production rate, temperature, etc. The extrinsic parameters involve factors that do affect the machine's performance but are not in the system level such as ambient conditions, temperature, humidity, operator's or system's inputs, etc. For each of the deployed use-cases there should be a different set of intrinsic and extrinsic parameters.

Product Level: Optical and visual sensors (lasers & cameras) monitor the quality of each product, according to the requirements for each use-case, based on the specific requirements of the parts from the use cases, it should be decided for each of the processes the areas to be inspected and the time available for such inspections. This frames the % of parts that are measured in each batch. The goal is to ensure that each product conforms to the pre-defined upper and lower acceptable quality limits. To this end, the repeatability is a critical indicator which is monitored using statistics. The goal of this approach is to categorise the products in quality classes, such as class A, class B, etc. All of the produced results are stored according to the quality inspection based on the requested quality, expected quality, and actual quality. The actions should then be aligned with the ISO 9001:2015 aiming at continual improvement to meet customer requirements and the industrial stakeholders.

Data Gathering: The data produced throughout the process along with the Inspection of the production line (Work- station & Quality) are logged into servers with time indexes. Wireless or cable transmission of data are achieved through a local area network. In order to avoid conflict and loss of data, each of the generated information is stored in the hard drives following a defined filing structure and naming system throughout all the stages.

Knowledge Management: This system receives input from all the rest acting as the "brain" of the zero defect management approach. The goal of this system is to provide feedback for all the processes executed in the production line. This system comprises an event modelling algorithm to identify the parameters from the overall production line which affect the Overall Performance Indicators (OPI) such as customer satisfaction, product quality, energy consumption, inventory control, and environmental impact. The decision support systems (DSS) and data management algorithms allow the evaluation of each performance and response to defects keeping historical data. The goal of this system is to optimise the overall manufacturing and the involved processes. To do so, the output of the knowledge management system is to provide alarms which will be filtered after the inherent learning process. Additionally, from the previous acquired knowledge early detection of defects are allowed with increased confidence levels. As a result, the proposed system is able to solve the problems arising in the production to maximise performance signalling strategies for handling the possible defects.

4 Zero Defect Manufacturing Platform Based on Z - Strategies

Manufacturing processes have to be environmental friendly and safe and deliver high quality products adapted to customer requirements, whilst minimising costs. The increasing interest in sustainable production places a premium on reducing material waste, re-works, rejects and stocks and has led to a demand for the development of zero-defect strategies at system level.

On that vein, the current trend in multi-stage manufacturing is towards more complex, distributed and faster evolving manufacturing facilities. To develop a zero-defect strategy to cope with increasing competition and sustainability related issues, plants should be designed and managed using best practices from emerging key enabling technologies. To that end, it is required to integrate a plethora of novel ICT technologies, state of the art algorithms and models, to support context awareness, inference conclusions, trend and root cause analysis, etc. to support online inspection, monitoring, and overall defect lifecycle management, towards zero-defect process operation and enhanced output quality. The final aim is to achieve production system configurations that profitably exploit the quality/productivity trade-off at system level whilst reducing complexity.

For that purpose, aligned with the Z - Strategies and the proposed zero defect management system concept explained earlier, a set of technologies and overall system architecture have been identified as a part of the proposed approach, following the method and procedures developed and proposed by May et al. [8].

The first high-level description to lead to the definition of the zero defect manufacturing platform consisted in identifying and classifying all components that can be called as the tools' landscape and logical architecture, i.e. conceptual view. Figure 3 presents this landscape by proposing a compact representation of the involved tools.

Based on the proposed approach and defined conceptual view of the system, in Z - Fact0r a novel zero defect manufacturing platform will be developed and demonstrated in three pilot plans proving its universal applicability for the achievement of zero defects in manufacturing. Therefore, the zero defect manufacturing platform will:

- Identify incoming defects and assure the best quality and the maximum production throughput;
- Reduce rejects and re-works by (a) identifying defects in parts caused by faulty machines, (b) by encompassing models and tools to support strategies for Predicting, Preventing, Detecting and Managing defects;
- Introduce autonomous diagnosis capabilities, including root cause analysis, (realized by the ES-DSS) aligned with both the production context (infrastructure, equipment) and the product (quality specifications and actual status);
- Integrate sensorial network with novel self-adjustment mechanisms to leverage semantic interconnection of sensors and online inspection tools, to manage, not only distributed data gathering from the shop floor, but also inter-stage communication and flow of production processes.

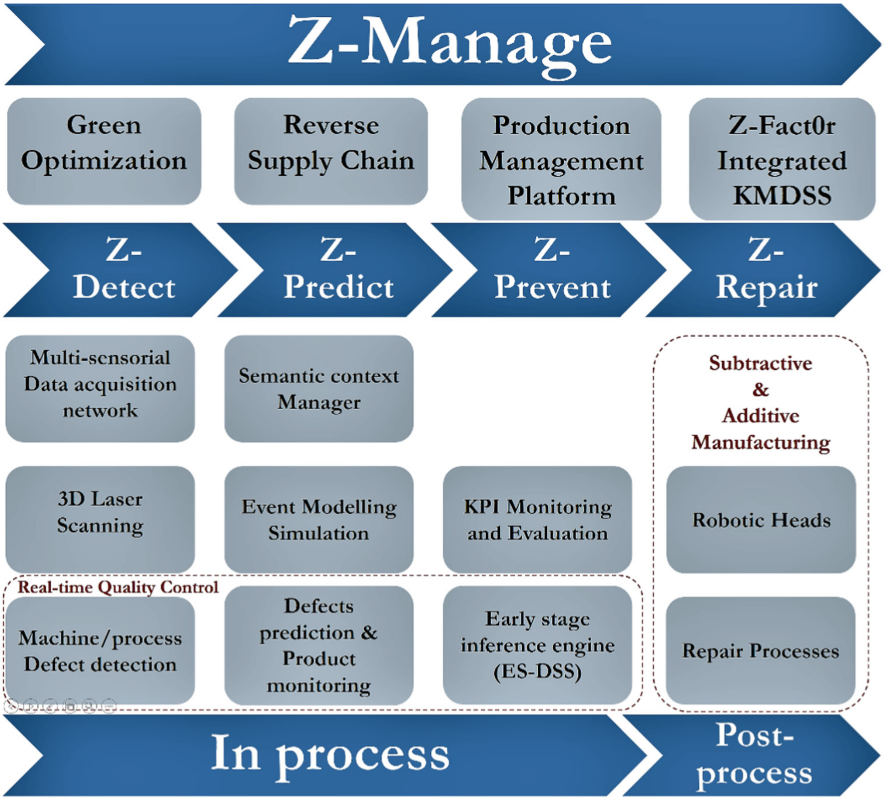

Fig. 3. Z - Fact0r tools' landscape

Following the development of the conceptual view, the required components have been highlighted in a preliminary architectural view, identifying services and dependencies within the Z - Fact0r platform. Later, new components were added in order to cover all the required functionalities of the resulting predictive maintenance platform.

Z - Fact0r functional viewpoint thus contains all the functions that the system should perform as well as the responsibilities and interfaces of the functional elements and the relationship between them. These functions are described using UML diagrams. Figure 4 shows the component diagram view of the overall Z - Fact0r architecture.

To sum up, the main components, their functionality, and their interactions are described in the functional view. Accordingly, the main components for Z - Fact0r architecture are:

- HMI & Sensor Network, which includes sensors, actuators, HMIs for humans to provide input to machines and thus the overall system, cameras, network infrastructure, legacy systems, etc.
- Shop-floor components which comprise semantic context manager, data acquisition and processing including 3D laser scanning, and Z - Fact0r repository.

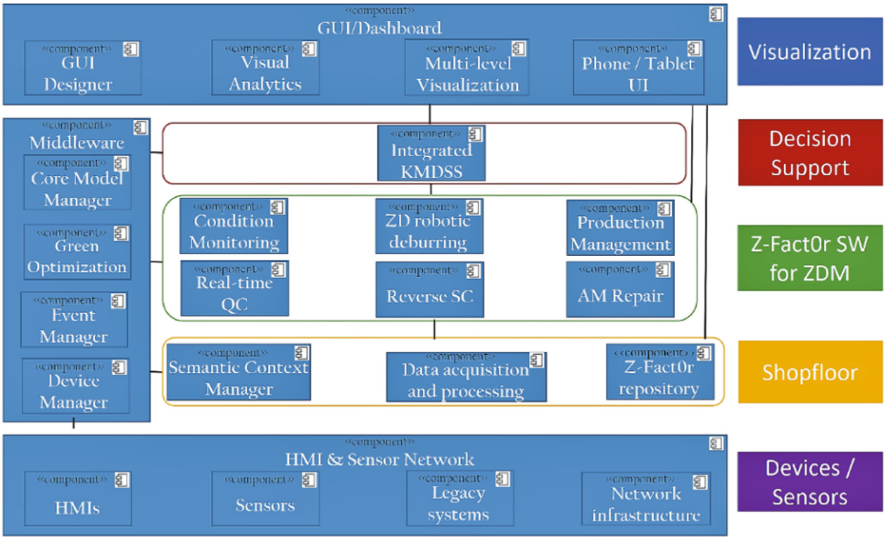

Fig. 4. Z - Fact0r system architecture

- Middleware including device manager, event manager, green optimizer, and core model manager.
- Z - Fact0r software modules for zero-defect management in manufacturing, which builds the service layer and includes Z - Fact0r specific tools such as real-time quality control, production management, reverse supply chain, zero-defect robotic deburring, and additive/subtractive manufacturing repair.
- Decision Support System (DSS) component, which will supervise and provide feedback for all the processes executed in the production line, evaluating performance parameters and responding to defects, keeping historical data.
- Besides, to facilitate the implementation of the five strategies, Z - Fact0r consortium has considered a policy to support a “reverse supply-chain” in the context of a multi-stage supply-chain attached to a multi-stage production. As a result, the defected products/parts detected in downstream stages (produced during a stage, or provided from suppliers in a particular stage) could be returned to upstream stages (internal or external supply-chain tiers) for remanufacturing or recycling.
- Finally, a visualization layer has been foreseen, which includes GUI/Dashboard designer, Visual Analytics Module, multi-level visualization component, and phone/tablet UI, etc.

In general, the idea of Z - Fact0r complete solution comes from the knowledge on the blackboard’s architectural pattern that provides a computational framework for the design and implementation of systems that need to integrate large and diverse specialized components. This Z - Fact0r blackboard architectural pattern provides the essential communication elements (middleware) for sharing information among components. In this context, novel correlation of machine behaviour with the process performance and the produced quality provide a vital feedback to the control loop in manufacturing systems. Z - PREDICT strategy gives estimations for the future states involving the whole production line, e.g. machine status after x number of operations and/or quality of the products for given set of parameters. The system can then predict with high confidence the expected quality as well as the customer satisfaction. The simulation is able to insert desired values and to predict the outcomes, making the zero defect management system a ‘tailor-made’ instrument. Z - PREVENT strategy tunes the system based on historical, current, and future (predicted) data to fine-tune the system to preserve the quality levels inside the acceptable limits. Z - DETECT strategy is triggered in the event of a defect. The logged data both for machine and product level avoids the generation of future defects. In addition, based on the inspection data the system deals with the defects to stop its propagation. Z - REPAIR strategy allows reworking to take place optimally, reducing the direct rework costs, making the outputs acceptable based on the quality standards. Last, the Z - MANAGE strategy acts as the brain of the whole system, receiving all the data and analysing them. The result is filtered alarms, early detection of defects, solutions to generated problems, strategies for repairing (rework or recycling) which all lead to system optimization and zero defects manufacturing.

5 Conclusion

In this paper, we provided a holistic framework and ad-hoc strategies applicable both to new and existing manufacturing lines to achieve zero-defects manufacturing via a novel ZDM platform that integrates state of the art ICT technologies, AI models and inspection facilities which elevate manufacturing plants to a superior level of competitiveness and sustainability.

Addressing the changing Customer needs and achieving customer satisfaction in the current factories is a great challenge, which when met it’s translated to business success. The proposed ZDM system proposed in this study considers these external factors as Key parameters integrating them in the processing, allowing re-tuning of the manufacturing line in order to meet the desired targets at all times. The holistic framework envisages to consider all the multi-stage manufacturing line as a living organism (as a whole) identifying which parameter causes diversion from the initial targets and lead to defects and/or reduced sales. Hence, the ultimate goal of Z-Fact0r is to become a standard for all the factories of the future in order to achieve zero defects, minimised costs, increased quality and customer satisfaction, while being environmental friendly. Therefore, Z-Fact0r comprises a complete monitoring solution for every manufacturing process as a sustainable and viable system.

Future work will focus on implementing and validating the proposed approach on several use cases in different industries, demonstrating its ability to support major actors of the manufacturing sector to take advantage of the digital transformation.

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Additive Manufacturing: New Trends in the 4th Industrial Revolution

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Abstract. Among the enabling technologies of the fourth industrial revolution, additive manufacturing (AM) is considered as a key factor for the success of the new production paradigm.

In this paper, the role of the AM technologies in the new scenery will be pointed out, focusing the attention on those factors enacting its success and its widespread diffusion among the most important companies of the main industrial sectors. These factors are mainly attributable to new materials of every kind, from polymers to metals passing from the composites, as well as, new processes, which open the possibility to reach new markets. The most relevant innovations will be reported, especially those related to the industrial implementation of AM. The issues related to the metrology of the additive manufacturing products and the sustainability of these manufacturing processes will be also described highlighting the main criticalities.

Keywords: Additive manufacturing · 3D printing · Industry 4.0 · AM processes · Materials · Additive repairing · Metrology · Sustainability

1 Introduction to the New Concept of Additive Manufacturing

According to its definition, Industry 4.0 involves a set of technological advances having a high impact in the current industrial landscape [1], leading to a strong integration of the industrial manufacturing with digital technologies.

The involvement of the additive manufacturing as an enabling factor of the Industry 4.0, changed the role of these technologies within the production scenery. In the Factory 4.0 ecosystem, AM plays an important role inside the Advanced Manufacturing Systems (Fig. 1) [2].

Most of companies are already adopting AM techniques for the development of prototypes, or for producing customized components. The costs of additive manufacturing decreased during the last years and, contemporary, speed and precision grew up. In practical words, this allows the design and the fabrication of more complex, stronger, lightweight geometries and, consequently, the application of additive manufacturing to higher quantities of products.

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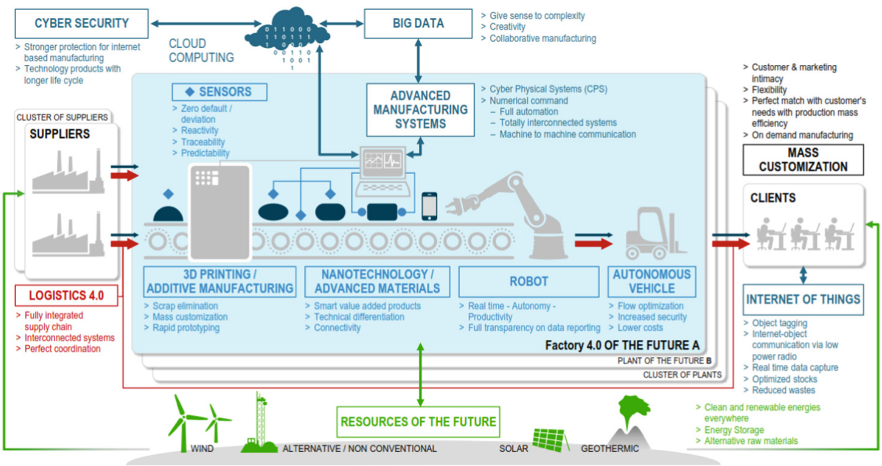

Fig. 1. The factory 4.0 ecosystem – a set of technologies about to interconnect and disrupt plant operations [2]. Source: https://www.rolandberger.com/ [2]

On the other hand, it is widely accepted the fact that AM is more suitable to high value low volume products. Thus, the role of AM in the fourth industrial revolution is not about replacing conventional mass manufacturing of large parts, which can exploit the large-scale economies, but it is rather a matter of making shapes and products, which are not either possible or cost-effective to manufacture through conventional manufacturing techniques. More interesting is the mass customization of low volume components, which can reach scale economies.

The concurrent development of hardware, software [3] and the intense research for adopting new materials, from polymers, metals to ceramics and composites has been key of success of AM technologies, so that multi-material components [4] become possible, broadening the application fields [5, 6]. Currently, the aerospace, the automotive, the biomedical and digital architectural design are the industrial sectors with the greatest interests towards AM processes. These industrial sectors are, indeed, particularly inclined to customization of products, as well as, the direct fabrication of functional end-use products, which are other fundamental driving forces and trends of AM processes. These are the real promises of AM, which have been enthusiastically welcomed by some of the world's biggest manufacturers, such as Airbus, Boeing, GE, Ford and Siemens. Aerospace companies are already using additive manufacturing to apply new designs that reduce aircraft weight, lowering their expenses for raw materials such as titanium alloys. Recently, the American giant GE acquired the european additive manufacturing companies, Concept Laser GmbH and the Arcam AB, for 1.5$ billions to create a new business unit and print aircrafts and other components [7]. Another application in the aerospace field is about the repairing of damaged parts, conducted through additive processes, which has many advantages in terms of time needed, materials and costs. Moreover, from a logistic and economic point of view, high-performance, decentralized additive manufacturing systems will reduce transport distances and stock on hand.

According to the Wolhers Report 2018, the growth of AM industry in 2017 was about the 21% and the total estimate of $7.336 billion excludes internal investments of both, large and small companies. Great investments are registered for R&D (Research and Development) [8]. The growth in metal AM sales was exponential (about 875%) in the past five years, whose, the 220% of growth, considering just the past two years. According to this research, there are now 135 companies around the globe producing industrial AM systems [9].

Another important datum is related to the origin of the machines sold in 2017: out of 202 machines, 82 were not produced by the leading companies [10].

2 The Latest Innovation About Additive Manufacturing

One of the greatest advantages of the AM techniques is the large variety of materials available. They are mainly grouped as polymers, metals, ceramics and composites materials in different states: liquid, filament or paste, powder and solid sheets [11].

According to the ISO/ASTM classification [12], the latest technologies available were investigated with the industrial cases.

2.1 Vat Photopolymerization

The leading company of the Vat Photopolymerization processes is the 3D Systems, although there are several newly developed technologies.

Among others, the CLIP (Continuous Liquid Interface) [13–16] process emerged as one of the most promising technology and it was developed by the **Carbon 3D** company [17] placed in the US. The Carbon 3D slogan says: *"Stop prototyping. Start producing"* and it represent exactly the expectation about the AM during the fourth industrial revolution. The CLIP technology (Fig. 2), uses digital light projection, oxygen permeable optics, and programmable liquid resins to produce parts. Instead of printing a layer-by-layer object, which leads to extremely slow speed, this technique uses light together with oxygen as an inhibiting agent, creating a solid and clean structure at surprising speeds.

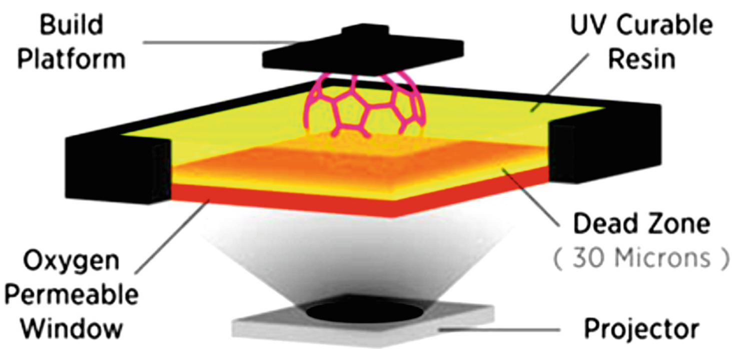

Fig. 2. Image of continuous liquid interface production (CLIP) process. Source: https://www.carbon3d.com/ [17]

A CLIP device is similar to a DLP device without a tiltable vat and instead with a UV and a special membrane similar to contact lenses, permeable to oxygen and transparent to UV [18].

Oxygen concentration at the bottom of the vat is thus sufficiently high to create a "dead zone" where radical polymerization does not occur. By regulating the flow of oxygen, through the membrane, dead zones are created, which cannot be cured by the UV light. The software adjusts the process, with a constant control of the chemical reactions, the heat distribution and the build-up stress, following the shape and size of the object, which then grows and emerges from the polymer liquid in a continuous and incredibly precise way. The main advantage of this technique is linked to the printing time, which is between 25 and 100 times lower than the main competitors. The mechanical properties, resolution, and surface finish are comparable with injection-moulded products. Looking at the needs of customers like BMW Group and General Electric, *Speedcell,* defined as a production unit, is a direct response: "For our customers, this means that their product development cycles no longer need to include the antiquated stages of the production process that include design, prototyping, tools, and therefore production. Now products can be designed and built on a platform that is also production, eliminating prototyping and intermediate parts such as the production of special tools" [17]. The *Speedcell* includes two brand new hardware components, a part washer, allowing optimal cleaning and simplified finishing of the parts and the new M2 3D Printer, with 189 mm × 118 mm × 326 mm of working volume. The materials are polymers: polyurethane for medical use, elastomeric polyurethane [19], epoxy, rigid polyurethane, flexi polyurethane.

Among the Carbon 3D industrial applications, the Adidas case has become one of the most representative of the potential of this technology, with the Adidas Futurecraft 3D, exploiting the capability of this technology to produce very complex lattice structure. Generally, the midsole has different lattice structures in the heel and forefoot, to account for different cushioning needs while running.

Another example of an ultra-rapid 3D printer exploiting the SLA principle is the **NewPro 3D**, whose technology is named ILI (Intelligent Liquid Interface) [20]. This main advance consists of a transparent wettable membrane between the photo-curing resin and the light source, chemically designed to enable faster movement between cured layers.

Very recently, the Michigan University developed a new SLA technology up to 100× faster than conventional printing approaches [21]. This method solidifies the liquid resin using different light wavelengths, to control where the resin hardens and where it stays fluid. The key of success lies in the chemistry of the resin. In conventional systems, there is only one reaction. A photoactivator hardens the resin wherever light hits it. In the Michigan system, there is also a photoinhibitor, which responds to a different wavelength of light. Rather than barely controlling solidification in a 2D plane, as current vat-printing techniques do, the new 3D printer can harden the resin at any 3D place near the illumination window. The Michigan University team has sent three patent applications to protect the multiple inventive aspects of the approach, and they are going to launch a start-up company.

2.2 Binder Jetting

Material jetting technologies are also improving their characteristics. Among others, HP developed the JET Fusion for the 3D printing of PA and the realization of full coloured functional parts. The 3D print bar has 30,000 nozzles spraying 350 million drops per second [22]. Comparing the JET Fusion technology process with a powder based process like Selective Laser Sintering (SLS), it is much faster, see Fig. 3. The first printing material used was nylon but the roadmap includes metals, plastics, and ceramics. In particular, metals indeed implied in the HP Metal Jet for the production of high volumes of parts, even large parts, with a binder jetting build size of 430 × 320 × 200 mm and HP voxel-level 1200 × 1200 dpi of resolution [23].

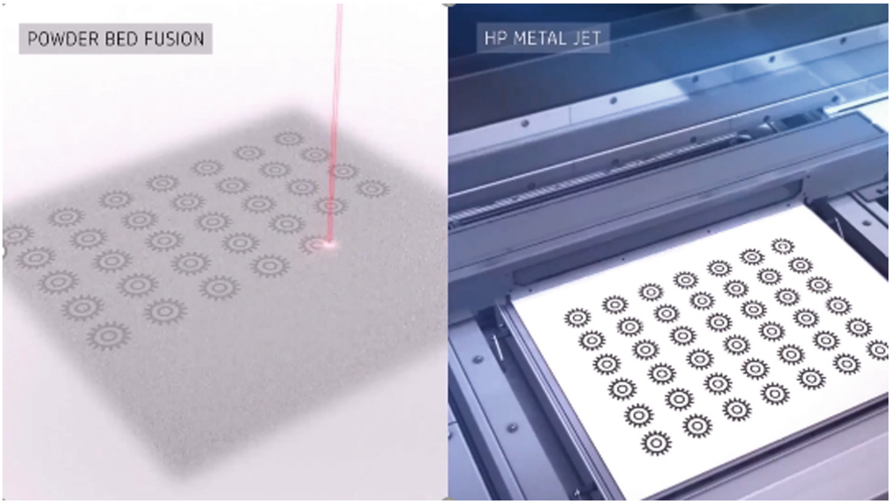

Fig. 3. Jet fusion vs powder based fusion. Source: https://www8.hp.com/us/en/printers/3d-printers.html

2.3 Powder-Bed-Fusion

Powder-based processes involves the use of polymers, composites, ceramics or metals. Selective Laser Sintering (SLS), Selective Laser Melting (SLM) are examples of *powder-bed fusion* processes. The leading company of powder-based processes is the German **EOS**. Among others, the EOS P500 for laser sintering of plastic parts, reduces cost-per-part by more than 30%, processes polymer materials at operating temperatures of up to 300 °C, enabling maximum material flexibility and putting this machine on the industrial scale. The EOS P 800 is the world's first laser sintering system for the AM of high-performance plastic products at the necessary high process temperatures (up to 385 °C), exploiting the HTLS principle (High-Temperature Laser Sintering). During the production process, the integrated Online Laser Power Control module (OLPC) continuously monitors laser performance, ensuring reproducible and optimized results on the components. The other version, EOS P 810, is mostly suitable for serial production of composite components.

Among the new processes, it is of great interest the new **High Speed Sintering** (HSS) [24], developed by the University of Loughborough in UK (UK patent No. 0317387.9). According to a study conducted in 2000, the SLS was considered able to produce small components up to 14,000 more economically than injection moulding [25], although, it was not implied as a high volume manufacturing technique. The most affecting cost item, indeed, is the machine cost, which is dictated by the cost of the equipment required for manufacture and the speed of production achieved. Differently from the SLS, the HSS process involves the sintering of 2D profiles of layers of powder without the need for a laser, but using an infrared source. The sintering can take place thanks to the addition of a secondary material to promote energy absorbance in the selected areas, such as carbon black. The material used is mostly nylon (Duraform Nylon 12) and the main advantage of this technology is the speed of the process, 10 to 100 faster than current industrial 3D printing processes and with the potential to produce up to 100,000 parts a day [26]. HSS is now able to compete on price and speed with high volume injection moulding, without the associated design limitations.

For the production of metal components using DLMS (Direct Metal Laser Sintering), EOS offers a comprehensive selection of metal powders ranging from aluminium, steel, as well as, titanium, nickel and cobalt chrome alloys. This allows the manufacturing of highly customized products. The new series M300 for metal additive manufacturing is a result of the cooperation with Siemens, including Siemens control and drive components from the Totally Integrated Automation (TIA) portfolio. The 3D systems launched the DMP Factory 500 Solution [27], comprising function-specific modules designed to maximize the efficiency. Each module within the factory solution is fully integrated with a Removable Print Module (RPM), for a controlled print environment, and designed to move between printer and powder modules without interrupting the production workflow. Powder Management Modules (PMMs) are designed to efficiently recycle the unused powder and to prepare the RPM for the next build. Besides, the EOS, new companies emerged on the market.

Among these, Renishaw [29] launched an ultra-high productivity multi-laser AM system, the RenAM 500Q, featuring four high-power 500 W lasers accessing the powder bed simultaneously, with a significant improvement in productivity and cost per part (Fig. 4).

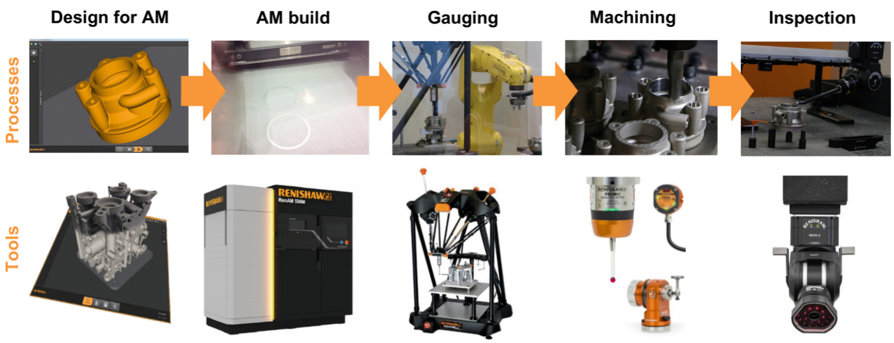

Fig. 4. Conventional machining vs additive manufacturing. Source: https://www.pma.org/apsc/assets/presentations/Skulan.pdf [28]

2.4 Material Extrusion

Stratasys is the leading company in FDM based techniques. Among the new machines, it can be mentioned the new series Carbon Fiber Edition, which prints with FDM Nylon 12 Carbon Fiber and Acrylonitrile Styrene Acrylate (ASA) [30].

The Metal X series machines, launched by the **Markforged** company, exploits the Atomic Diffusion Additive Manufacturing (ADAM) technology [31], which prints metal powder bound in a plastic matrix. ADAM is an end-to-end process based on powder captured in a plastic binder (which makes it safe to handle), which gives the part shape one layer at a time (Fig. 5). The sinterization takes place in a furnace, burning off the binder and solidifying the powder into the final fully-dense (99.7%) metal part. The materials adopted are 17-4 PH Stainless Steel (launch material), and other materials in beta testing, such as Tool Steel (H13, A2, D2), Titanium Ti6Al4 V, Inconel (IN) 625, Copper, Aluminum (6061, 7075). The turning point, which add further value on the Markforged products, is the comprehensive cloud-based fleet management solution called *Eiger*. There are thousands of Markforged printers producing parts all over the world, like a distributed farm. Among them, the 20% are used in operations to manufacture sample parts: about 6.5 k parts per month. Moreover, it is up to 10× less expensive than alternative metal additive manufacturing technologies and up to a 100× less than traditional fabrication technologies like machining or casting [32].

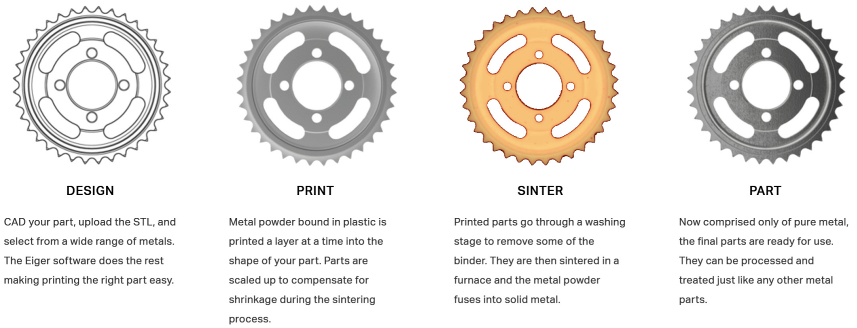

Fig. 5. Description of ADAM process steps. Source: https://markforged.com/metal-x/ [32]

Markforged company, generally, produces FFF machines for both, composites and metals. Among composites, the Onyx, is 40% stiffer than ABS and it can be printed on its own or reinforced with continuous fibers. Carbon fiber can also be printed and it is strong enough to replace aluminum at half the weight for end-use parts. Fiberglass is used to print parts that are an order of magnitude stiffer than typical 3D printed objects at a more affordable price [33]. Respect to the simple fiberglass, the HSHT fiberglass features a higher impact resistance and Heat Deflection Temperature (HDT). Kevlar, a low density and highly durable material, is also used. Besides metal powders bounded in a plastic matrix, Markforged produce also the FFF machines for *metal extrusion.* Materials for the extrusion are 17-4 PH Stainless Steel, widely used in the manufacturing, aerospace, petroleum, and medical industries (if heat treated, it has an ultimate tensile strength of 1250 MPa and a Rockwell Hardness of 36 HRC) and H13 Tool Steel, a material optimized for high temperature (if heat treated, it can reach a Rockwell hardness of 46–50 and an ultimate tensile strength of 1500 MPa) and wear applications (moulds, wear inserts) [33].

Another company dedicated to material extrusion is the Italian **Roboze** [35], specialized in 3D printing of PEEK. Patented mechatronic movements in x and y make Roboze 3D printers some of the most accurate FFF 3D printing systems, ensuring mechanical repeatability and high precision for production of small batches and on-demand products. The Roboze feature a Beltless System™ with 0.025 mm of mechanical accuracy. The ARGO 500 (Fig. 6), mounting the (High Viscosity Polymers) HVP extruder, designed and manufactured by Roboze, reaches temperatures up to 550 °C, which allows the extrusion of high viscosity polymers, such as Carbon PEEK, PEEK and ULTEM ™ AM9085F. The controlled printing environment played also an important role: it is thermostatic, dehumidified and capable of reaching 180 °C, to offset the deformation of thermoplastic materials, particularly those with large dimensions and to ensure perfect adhesion to the build plate. Argo 500 is equipped with a vacuum plate system that simplifies and speeds up the printing process. Considering all the machine models, Roboze CARBON PEEK adds extra thermal stability and rigidity to the simple PEEK.

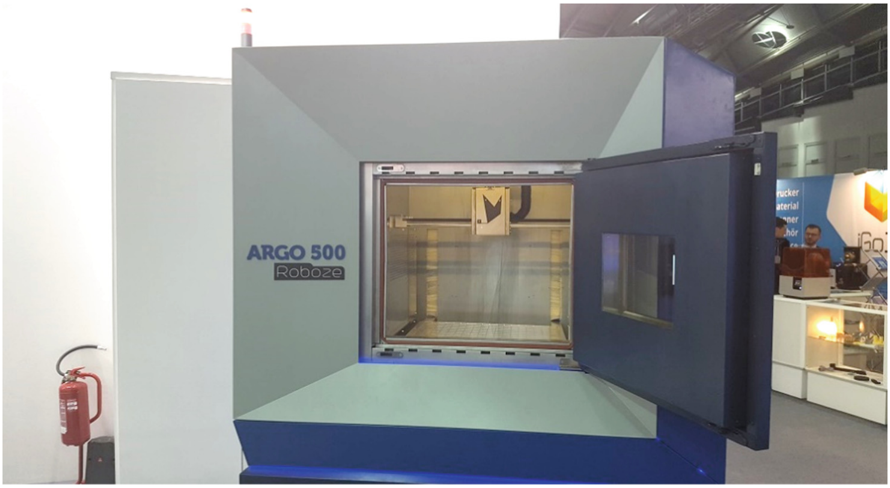

Fig. 6. ARGO500 produced by Roboze. Source: https://3dprint.com/194165/roboze-argo-500-3d-printer/ [34]

The addition of specially selected Carbon Fibers improve mechanical properties of the material and increase its HDT maintaining its properties even at a higher temperature. Moreover, the Carbon PA, Polyamide reinforced with 20% carbon fibers, represents an eco-friendly, safety solution (for its weight reduction and metal replacement). Functional-Nylon, ABS-ESD and other 3 advanced materials leads to the highest level of versatility. Applications of these machines are reported in [36–38].

A preliminary study was conducted in [39] for assessing the feasibility of realizing a low-cost AM system which is a hybrid between a fused filament fabrication 3D printer, derived from an open-source project, and a 2D commercial inkjet printer with the aim to obtain fully coloured AM parts. The very revolution of this printer is its capability of incorporate electronic components in the final product.

3 Additive Repairing of Aerospace Components

A very interesting application of AM is the repairing of damaged parts, arising from its integration with reverse engineering processes [40]. The additive repairing is defined as the set of additive technologies that allow to repair parts by adding material selectively in the damaged areas. The currently available manual repairing processes are time and labour intensive and produce inconsistent quality. The automation of such recovery processes of worn parts is of significant importance to meet the stringent quality requirements [41]. Ever more attention, indeed, is paid to the life cycle of the products, and it is preferable to repair damaged parts, especially when it is difficult or expensive to produce them, both from an economic and environmental point of view. The Life Cycle Assessment (LCA) on the energy and environmental impacts showed that, when the repair volume is 10% (1.56 kg), there is at least a 45% carbon footprint improvement and a 36% saving in total energy respect to replacing the part with a new one [42]. The repair of worn parts is of great interest for aerospace industries to extend the life cycle of aerospace parts [43]. In [42] Wilson et al. demonstrated the effectiveness of laser-direct deposition in repairing defective voids in two turbine airfoils based on a new semi-automated geometric algorithm. In [44] Xue et al. investigated the feasibility of repairing fretting damaged RR501 K fuel injectors using laser cladding of L-605 alloy powder. Although, it is of paramount importance for the success of the repairing process, the integration with reverse engineering, which consists of acquiring the 3D dimensions of the damaged area, in order to compare it with the original model, defining the deposition paths of the material where it is necessary and, finally, checking the success of deposition process. Based on the scanned repair model with different defects, a reverse engineering (RE)-based geometry reconstruction method was proposed and developed in [43] for the nominal geometry reconstruction of a worn blade. In [45] Heralić et al. developed and integrated with the robot control system a 3D scanning system for automatic in-process control of the deposition. 3D digitization systems are usually adopted to acquire a worn part's geometry in the format of polygonal mesh. Then identification and positioning of the part's damaged area can be achieved by comparing the nominal CAD model with the 3D model of the defective part surface [41]. Non-contact techniques, and particularly optical measuring techniques, are suitable for this kind of applications, because they have the unique capability of acquiring the 3D model of the entire damaged area in far shorter time than CMMs. The surface geometry of the worn part can be scanned and digitized into a set of point clouds by using various 3D optical scanning systems [41, 43–46].

In this context, in 2016, GE Avio and the Politecnico di Bari opened a facility in Bari, called Apulia Repair Development Centre for Additive Repairs, which is inside the repair research laboratory network of GE Avio, joining different expertise with the

Fig. 7. Cold spray developed by GE Avio. Source: https://www.ge.com/reports/secret-weapon-supersonic-blaster-rebuilds-jet-parts-flying-powder/ [47]

aim to develop innovative repairing procedures for aerospace engines based on the laser deposition and cold spray (reference lab for GE repair in the world - Fig. 7), involving components such as, the GE90, mounted on the Boeing 777 and the GEnx mounted on the 787 Dreamliner and the 747-8.

4 Metrology of AM Parts

The great advantages connected to the implementation of AM systems, e.g. the realization of complex and unconventional shapes, as well as the possibility to use different materials at the same time, pose some unsolved issues, which can be summarized in one thing: the need for quality assurance after production. The quality assurance encompasses the concept of dimensional metrology and material verification. Regarding the dimensional metrology, there are, currently, different approaches comprising *in-situ* [48], inside the building chamber, *ex-situ* and *offline*, to indicate the measurement outside the chamber. The metrology of AM parts is of paramount importance, when considering AM products as final products and not just prototypes. The possibility to ascertain the functional properties, shape and dimensional tolerances represents a *conditio-sine-qua-non* when answering the market request for reliable AM-built parts. Considering just the off-line techniques, contact-measuring systems, such as CMMs (Coordinate Measuring Machines), are not suitable for inspecting complex shapes and they are limited by the accessibility of some surfaces. Non-contact techniques are more suitable and they are divided into optical and x-ray based systems. Optical systems are widely used for complex geometries, such as free-form geometries with cooperative surface characteristics and they are potentially suitable for such verifications [49, 50]. Although, when measuring polymers, widely adopted in AM, there are issues related to the translucency of these materials and they have to be considered [51]. In [52] a photogrammetry-based technique was used as measuring tool for AM micro-fluidic devices with challenging surface texture (visible and tactile) characteristics. The measurement of polymers is successfully done by x-ray based computed tomography, thanks to the low density of such materials. Differently from CMMs, when adopting non-contact measuring systems, it is not easy to assign a geometrical tolerance (ISO 1101:2017), to a freeform shape and connect this to its function and manufacturability [53], since proper specifications systems, as defined in ISO 1101, has not been developed for complex freeform shapes. The poor surface finish represents a great limitation in dimensional verification when considering the form error and the measurement uncertainty is greatly affected by this component. Thus, post-processing operations are generally required [54–56]. Moreover, the material quality of AM parts must be inspected, especially when dealing with powder-based process of metals, e.g. in terms of undesirable grain characteristics and unexpected porosity, as well as internal features, such as internal channels. Considering the material quality check and the presence of internal feature, computed tomography (CT) results to be the most suitable non-destructive measuring technique [57], which allows simultaneously the dimensional verification of the external and internal shapes, as well as, the porosity and material's defects check. The CT scanning systems are also suitable for verifying assembled structures, which are easily realized by AM processes.

5 Sustainability

Sustainability of AM technologies represent a critical issue to be take into account if we wish the outcomes of this revolution to be long-lasting and affordable to our civilized societies. Additive manufacturing technologies, depending on the specific technology, are typically seen as "cleaner" and they allow to fulfill the "Reduce" sustainability principle either in terms of resource or pollution, as follows: allow the manufacturing processes to consume the exact amount of material commanded (contrary to conventional machining which produces waste material); reduce manufacturing efforts by simplifying assembly processes [58]; allow savings and opportunities in using new recycled materials [59]; use less energy intensive manufacturing processes; allow eliminate the use of harmful ancillary process enablers [60]; less harmful materials [61]; potential to completely eliminate supply chain operations associated with the production of new tooling [60], the same for spare parts [62]; allow savings in the supply chain, say due to production close to use places due to regional and delocalized characteristics (which may be sometime less efficient [63]; reduction in weight of transport-related products [60], reducing inventory wastes [62], reduction in quality problems due to product simplification [62], saving opportunities and new businesses in Maintenance, Repair and Overhaul [60]). Another sustainability principle addressed by additive manufacturing technologies is Redesign: they allow increase design freedom, with potential design-for-maintenance features to prolong life of products [62] (i.e., durability due to repairing, remanufacturing and reuse possibilities, also called "design for longevity" [63]), parts with superior energy consumption in service due to innovative functions embedded (e.g. cooling channels, gas flow paths [60], etc.).

Tipical sustainability assessment of AM consider many factors such as primary and secondary materials, product life-cycle [64, 65], quantification of environmental impact limited to the production setting, focusing on criteria related to the sustainability of manufacturing process, such as: standby and in-process energy consumption [kWh/kg] [65–68] which typically is proportional to machining time, the cooling-heating processes, the part geometry [65], the warm-up and cool-down procedures upon discretion of operator, that may also be dependent on job type (say process rate, process efficiency, productivity, etc.) [67]; material waste or scraps flows [kg]; emissions generated during production. The usage profile of the additive machines is critical to the assessment but rarely performed [65].

Other more interesting issues should also be added to the sustainability analysis of AM technologies, in a cradle-to-cradle perspective, such as: product supply chain issues such as transportation related measures (energy consumption [kWh], pollution [land usage, toxicity, climate change]); product usage impacts in terms of energy in-use energy consumed; product's end-of-life issues in terms of energy, recycling rates, disposal costs, pollutions; tooling supply chain [65]; machine tool life cycle [65]; manufacturing system reconfiguration, which may lead to better capital use [59]; societal impacts – positive: say, for instance, potentials of creating new businesses by creating value to customers adding services to products [62], or from opportunities from circular economy [63]; societal impacts – negative: health problems (say, potential toxicity, environmental hazards, and chemical degradability of solvents used for their removal still remains a topic [69]); counterintuitive negative effects may appear, such as disposable products use habits against traditional long-lasting products (say printable wheel chain, etc.).

According to the above, studies performed with an accurate profile shows that the common belief of "cleanness" of additive technologies, which one of the sustainability pillar, is not always assured *tout court* [65]. The same is for cost effectiveness (the other sustainability pillar), where AM technologies proved to be cost effective only for manufacturing small batches with continued centralized manufacturing [70]: with the increasing automation the distributed production based on AM may become cost effective in the next future. Another point is that it is not yet clear whether many applications of 3D printing exhibit an absence of scale economies resulting from the present indivisibility of manufacturing tooling [63].

New issues are emerging on sustainability of AM technologies, which can add new perspectives to the discussion about the sustainability of this manufacturing paradigm. The new idea of Design for Sustainable Additive Manufacturing [71], allowing to minimize the whole flux consumption (electricity, material and fluids) during manufacturing steps. Also, new opportunities of changing the way of working are appearing, provided AM allows end-users to have a feasible and more sustainable alternative when maintaining, repairing, overhauling or replacing components and spare parts [60].

6 Conclusions

From their beginning, AM technologies have greatly changed their role within the manufacturing scenery. The newly developed AM machines demonstrated their capabilities to enter the market not just for the fabrication of prototypes but for the manufacturing of final products. The main factor is related to the needs for highly customized products in many fields, such as biomedical, automotive and aerospace.

The AM process are becoming ever faster and the rising of new rapid technologies is in rapid increase. AM is an enabling technology for the Factory of Future I4.0 within the Digital Manufacturing paradigm. Another successful application regards the additive repairing of aerospace components. The high-volume production is also possible with some kinds of technologies. The industrial world is rapidly changing and the AM is going to remain one of the leading factor.

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A Hidden Markov Model Based Approach to Modeling and Monitoring of Processes with Imperfect Maintenance

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Abstract. Maintenance interventions are usually imperfect. In this paper, we propose a novel degradation model that addresses the uncertainty in maintenance effectiveness. The new model assumes system's degradation level at the end of any production run can be recovered to a random degree by the subsequent maintenance activity. Based on parametric uncertainty in the newly proposed model, a novel process monitoring method is proposed for providing condition indicator each time a new observation is retained from the monitored system. Using a large-scale semiconductor dataset, significant improvement in the log-likelihood was observed in the HMM assuming imperfect maintenance against the HMM assuming perfect maintenance. In addition, it is shown that the newly proposed monitoring method is capable of dramatically reducing false alarm ratios, compared to the conventional multivariate signature-based methods.

Keywords: Condition-Based Maintenance · Hidden Markov model · Process monitoring · Imperfect maintenance · Receiver operating characteristics

1 Introduction

Condition-Based Maintenance (CBM) aims at facilitating maintenance operations exactly where needed and exactly when needed, based on sensor readings that reflect the actual condition of the maintained assets [12]. However, sensor readings obtained from highly complex engineering systems, such as distributed fields (plasma) or systems of many interconnected subsystems (automotive engines) usually provide insufficient information about the underlying conditions due to the insufficiently detailed physical models or the insufficient number and character of sensors. Monitoring of such systems therefore hinges on the development of degradation models capable of handling partial information about the system condition within the available sensory data.

The intuitive relation between the sensor readings and the underlying machine condition can be modeled probabilistically, by associating probabilities of the various levels of system degradation with the observed signatures extracted from the sensor readings. The concept of hidden Markov models (HMMs) [15] can be efficiently used for this purpose, with its observable variables modeling the signatures extracted from the sensors mounted on the monitored machine, while its hidden states model the

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conditions of that machine. Such modeling approach was recently proposed by Cholette and Djurjdanovic [4] and Zhang et al. [22], and was successfully demonstrated in monitoring of a plasma-based deposition tool operating over multiple months in a major semiconductor-fabrication facility.

Despite the importance of these two studies, they implicitly assumed that after each maintenance action, the monitored system always returned to the state of being as-good-as-new upon completion of the maintenance intervention. However, maintenance actions are not perfect [14], and the post-maintenance condition depends on the effectiveness of that maintenance action. For example, chamber cleaning [10] is a type of periodical maintenance event commonly scheduled on semiconductor manufacturing tools to reestablish purity in the chamber environment. Such operation may leave residue on some surfaces inside the chamber and at the same time etch away some useful surfaces in that chamber. As a consequence, the tool condition after maintenance is a stochastic variable itself [21].

Monitoring of a system whose condition is modeled by hidden states of an HMM can be pursued in multiple ways once the parameters of the underlying HMM become available. One approach is to identify the most likely condition of the system via likelihoods of the newly arrived sensor data, given the HMMs modeling the degradation of the target system. This approach has been applied by Wang et al. [20] to diagnose historical wear patterns and detect deviations from the good-as-new tool. Alternatively, one can monitor the departure of the dynamics in the new data from the dynamics in the nominal HMM modeling the normal system behavior. Fox et al. [6] and Brown et al. [2] demonstrated the efficacy of this approach in detecting faults when HMM is used for modeling the behavior of a robot and an electric power plant, respectively. Recently, Cholette and Djurdjanovic [4] used the later approach to model the degradation of a semiconductor-manufacturing tool using regime-specific degradation HMMs. Zhang et al. [22] extended the previous work by enabling estimation of parametric uncertainties in estimation of the HMMs that model the system degradation, as well as by introducing a novel HMM based condition monitoring method that incorporates those parametric uncertainties in the degradation HMMs into the fault detection decision.

Recognition of the degradation state in a HMM based model of degradation is a well-known problem about using available observation sequences to identify the corresponding hidden HMM states. A traditional approach to identifying the hidden HMM states is the Viterbi algorithm [5], which finds the sequence of hidden states that maximizes the log-likelihood for a given observation sequence. This algorithm has been applied to detect a machine failure [17], and recognize degradation states of bearings [19] as well as the condition of a turbofan engine [7]. Even though entropy of the entire trajectory provided by the Viterbi algorithm was recently analyzed [9], uncertainty information of any individual state is not available through the Viterbi algorithm. On the other hand, estimation of the probability of the most recent state, or filtering, is another approach to the state recognition problem. This approach provides a full distribution of the current hidden states and has been utilized for recognizing degradation condition in machining (Heck and McClellan 1991) [8] and an antenna [16]. However, in both the approaches mentioned above, the HMM parameters are assumed to be perfectly known. without any parameter uncertainties in them. As Zhang et al. [22] have argued, the parametric uncertainty of degradation HMM is highly important for modeling and monitoring of engineering systems. Unfortunately, to the best of authors' knowledge, a method capable of recognizing degradation states in an engineering system whose condition is modeled by HMMs with uncertain parameters does not exist.

Despite all the advances in applying HMMs for condition monitoring, modeling the variability in degradation condition caused by the imperfection in maintenance effectiveness has not been addressed. Considering this gap, we extend the condition modeling via hidden states of regime-specific HMMs from condition modeling only in the operating regimes where degradation state worsens, to also modeling potentially imperfect maintenance operations as yet another operating regime where degradation state probabilistically recovers, as modeled using right-to-left HMMs. We also propose a new method for performance assessment based on the newly proposed degradation and maintenance HMM whose parameters and corresponding uncertainties are obtained via the Bayesian identification procedure described by Zhang et al. [22].

The remainder of this paper is organized as follows. In Sect. 2, the concept of HMMs is briefly discussed, after which a novel HMM based degradation modeling framework that incorporates models of imperfect maintenance operations is described. A novel fault detection method based on the understanding of parametric uncertainties of the degradation HMMs will be presented in Sect. 3. Section 4 will show results of degradation modeling and monitoring of an industrial semiconductor manufacturing process accomplished using the new HMM based degradation modeling and monitoring methods described in Sect. 3. Finally, Sect. 5 offers conclusions of this paper and outlines some possibilities for future research.

2 Hidden Markov Model

The Hidden Markov model is a doubly embedded stochastic process $\{X_t, Y_t\}_{t=0}^{\infty}$ with an unobservable Markov chain X_t and the observable process Y_t for which at each time t, the observable variables Y_t are probabilistically related to the hidden state at each time t. Assuming that the set of possible states for the hidden process X_t is $S = \{s_1, s_2, \ldots, s_N\}$ and the set of possible observable symbols is $O = \{o_1, o_2, \ldots, o_M\}$, the HMM can be described by a parameter triplet $\boldsymbol{\theta} = (\boldsymbol{v}, \mathbf{P}, \mathbf{Q})$, consisting of the initial state distribution $\boldsymbol{v} \in [0, 1]^N$, state transition probability matrix $\mathbf{P} \in [0, 1]^{N \times N}$ and emission probability matrix $\mathbf{Q} \in [0, 1]^{M \times N}$. The emission distributions, such as Gaussian distributions, can be conceptualized and parameterized, leading to a vector of state dependent means and variances substituting the emission matrix Q in the parameter triplet $\boldsymbol{\theta}$.

In many applications, physics of the process modeled using the HMM can lead to specific patterns in the state transition matrix. For example, if the hidden states $S = \{1, 2, 3\}$ represent condition of a monitored system, with state 1 denoting the excellent condition, state 2 denoting the OK condition and state 3 representing the bad condition, the state transition matrix P is constrained to be an upper triangular matrix, or $p_{ij} = 0, \ \forall i > j$, since without a maintenance operation, degradation state of the system can only deteriorate. Such "left-to-right" HMM structure has been utilized for degradation modeling in Cholette and Djurdjanovic [4] and Zhang et al. [22].

Recently, the standard HMM construct described above has been extended to regime-specific HMMs by incorporating time-varying dynamics and observation models, in order to account for variability in the degradation models caused by the potentially variable operating regimes of the monitored system [4, 22]. However, in those papers, each maintenance operation was assumed to be perfect, meaning that the condition after each maintenance was assumed to be as good as new with probability 1.

In order to model the potential imperfections of maintenance operations, in this paper, we will model the degradation state recovery caused by a maintenance intervention as yet another Markovian hidden state transition, only this time encoded by a left-to-right structure of the state transition matrix, denoting a stochastic and thus imperfect recovery. Suppose the operating regimes over time are denoted by a sequence z_t, t = 0, 1, 2, …, with each z_t having a known value from the set of possible operating regimes

$$R = \{r_1, r_2, \ldots r_L, \rho_1, \rho_2, \ldots, \rho_{L'}\} \tag{1}$$

where r's denote the production regimes (system condition degrading) and ρ's denote the maintenance regimes (improving the system condition). For each regime in the set R, let us allow different HMM dynamics and observation probabilities by introducing a regime-specific HMM concept, which, assuming N hidden states $\{s_1, s_2, \ldots, s_N\}$, can be described by parameters

$$\begin{aligned}\boldsymbol{\theta}^{(R)} = (&\boldsymbol{v}, \mathbf{P}^{(r_1)}, \mathbf{Q}^{(r_1)}, \mathbf{P}^{(r_2)}, \mathbf{Q}^{(r_2)}, \ldots, \mathbf{P}^{(r_L)}, \mathbf{Q}^{(r_L)}, \\ &\mathbf{P}^{(\rho_1)}, \mathbf{Q}^{(\rho_1)}, \mathbf{P}^{(\rho_2)}, \mathbf{Q}^{(\rho_2)}, \ldots, \mathbf{P}^{(\rho_{L'})}, \mathbf{Q}^{(\rho_{L'})})\end{aligned} \tag{2}$$

with initial state probability vector

$$\boldsymbol{v} = [v_1\, v_2 \cdots v_N]^T; \tag{3}$$

$$v_i = \Pr(X_0 = s_i),\ i = 1, 2, \ldots, N \tag{4}$$

regime-specific left-to-right state transition matrices $\mathbf{P}^{(r)}, r \in \{r_1, r_2, \ldots, r_L\}$

$$\mathbf{P}^{(\mathrm{r})} = [p_{i,j}^{(r)}]_{i,j=1,2,\ldots,N'}; \tag{5}$$

$$p_{i,j}^{(r)} = \Pr(X_{t+1} = s_j | X_t = s_i),\ \text{for}\ z_t = r \tag{6}$$

describing the maintenance related state transitions that degrade the system state (describing production regimes of the system[1]), "right-to-left" transition matrices $\mathbf{P}(\rho)$, $\rho \in \{\rho_1, \rho_2, \ldots, \rho_{L'}\}$

$$\mathbf{P}^{(\rho)} = [p_{i,j}^{(\rho)}]_{i,j=1,2,\ldots,N'}; \tag{7}$$

[1] These matrices satisfy $P_{ij}^{(r)} = 0$, for $1 \leq j < i \leq N, \forall r$.

$$p_{i,j}^{(\rho)} = \Pr(X_{t+1} = s_j | X_t = s_i), \text{ for } z_t = \rho \tag{8}$$

describing state transitions that recover the system state (describing maintenance regimes of the system[2]), regime-specific emission probability matrices $\boldsymbol{Q}^{(r)}$, $r \in \{r_1, r_2, \ldots, r_L, \rho_1, \rho_2, \ldots, \rho_{L'}\}$ satisfying

$$\mathbf{Q}^{(r)} = [q_{i,j}^{(r)}]_{\substack{i=1,2,\ldots,N' \\ j=1,2,\ldots,M}}; \tag{9}$$

$$q_{i,j}^{(r)} = \Pr(Y_t = o_j | X_t = s_i), \text{for } z_t = r \tag{10}$$

and the hidden states process X_t progressing according to probabilities

$$\begin{bmatrix} \Pr(X_t = s_1) \\ \Pr(X_t = s_2) \\ \vdots \\ \Pr(X_t = s_N) \end{bmatrix} = \boldsymbol{v}\left(\prod_{i=0}^{t} \mathbf{P}^{(z_i)}\right). \tag{11}$$

Let us note that (11) formalizes the well-known notion of the continuity of degradation, stipulating that the last state of degradation after one operating regime becomes the initial state of degradation for the next operating regime.

The HMM parameters $\boldsymbol{\theta}^{(R)}$ need to be identified from the available realizations of the observable variables (sensor readings), and Zhang et al. [22] described a Bayesian estimation based approach to identification of those parameters.

3 Condition Monitoring

The In 2014, the European Commission introduce a program of "renaissance" of the European industry [19, 21], based on digital technologies (cloud computing, big data analytics, new industrial internet applications, smart factories, robotics and 3D printing). This program provides a fundamental contribution to increasing European competitiveness through redefining business models for CPM and creating new products and services. Also, in 2012, when the EU defined industrial policy, it identified six priorities, where three of them are related to the Industry 4.0 model: advanced manufacturing (CPM), smart grid and digital infrastructure (industrial internet) [21]. In 2013, the EC formed a working group for advanced and clean manufacturing, and a year later the Strategic Policy Forum on Digital Entrepreneurship, with the aim of supporting the digital transformation of European industry. It also supports the development of national centers of excellence for digital production, as well as a range of activities related to education, communication standards, ICT and digital skills,

[2] These matrices satisfy $P_{ij}^{(\rho)} = 0$, for $1 \le i < j \le N, \forall \rho$.

digital economy, etc. [21] Within the Seventh Research Program - Horizon 2020, specific CPM research units have also been defined and supported.

Condition monitoring needs to be done for *each newly arrived observation* to facilitate on-line condition monitoring of the system without any delay. For a system whose degradation is modeled by HMMs, as proposed by Cholette and Djurdjanovic [4] and Zhang et al. [22], one approach to realize this is to use the well-known Viterbi algorithm [5] to determine the most likely sequence of states

$$\boldsymbol{x}_t^* = \underset{\boldsymbol{x}_t}{argmax}\, Pr(\boldsymbol{x}_t, \boldsymbol{y}_t | \boldsymbol{\theta}^{(R)}). \tag{12}$$

Nevertheless, as mentioned earlier, this method does not take into account the uncertainty of the model, nor does it offer information on the uncertainties regarding the most likely states $\boldsymbol{x}_t^*$.

As an alternative, let us estimate the probability of the current state x_t being the most degraded state given an observation sequence $\boldsymbol{y}_t$. Following Rabiner [15], it can be calculated by using forward probabilities $\alpha_t(i)$ defined by

$$\alpha_t(n) = \Pr(x_t = n, \boldsymbol{y}_t | \boldsymbol{\theta}^{(R)}) \tag{13}$$

followed by a normalization step

$$\bar{\alpha}_t(n) = \frac{\alpha_t(i)}{\sum_{i=1}^{n} \alpha_t(i)} = \Pr(x_t = n | \boldsymbol{y}_t, \boldsymbol{\theta}^{(R)}) \tag{14}$$

Since the Bayesian HMM estimation procedure introduced by Zhang et al. [22] and utilized in this paper yields a distribution of model parameters, rather than a point estimate of those parameters, one should monitor the probability of the worst state n, using the entire distribution of $\bar{\alpha}_t(n)$, rather than a single state probability estimate in (14). Namely, the estimate of the degradation model parameters $\boldsymbol{\Theta}^{(R)}$ from the Bayesian estimation procedure is a distribution and the distribution of $\bar{\alpha}_t(n)$ over the entire distribution $\boldsymbol{\Theta}^{(R)}$ can be considered. One possibility is to monitor the expected value for the distribution of $\bar{\alpha}_t(n)$

$$A_t = \int_{\Omega^{(R)}} \bar{\alpha}_t(n) \pi(\boldsymbol{\theta}^{(R)}) d\boldsymbol{\theta}^{(R)}. \tag{15}$$

$$\int_{\Omega^{(R)}} \Pr(x_t = n | \boldsymbol{y}_t,\, \boldsymbol{\theta}^{(R)}) \pi(\boldsymbol{\theta}^{(R)}) d\boldsymbol{\theta}^{(R)}. \tag{16}$$

which can be estimated as the average obtained through sampling in $\boldsymbol{\Theta}^{(R)}$, as described by Zhang et al. [22]. This is the method pursued in the rest of the paper.

4 Results and Discussion

4.1 Description of the PECVD Datasets

The dataset used in this study is collected from a PECVD tool used to deposit thin films of multiple thicknesses onto silicon wafers, with residual depositions in the tool chamber removed by periodic in-situ cleans [1], or so-called wet cleans [10], which take place less frequently and remove residual depositions caused by imperfections in the in-situ cleans. Figure 1 illustrates operation of a PECVD tool in terms of operating regime-specific HMMs of its degradation and maintenance operations. Namely, each sequence of observations consists of sensory signatures observed between two in situ cleans, with each in situ clean stochastically improving the system condition, while in between the in situ-cleans, the system degrades according to the operating regime-specific HMMs). Within each sequence, several film thicknesses could be deposited on the wafers (multiple subsequences of film depositions can be observed), with degradation processes being different for each of those film thicknesses[3]. In other words, different film thicknesses correspond to different operating regimes of this tool, and hence, a regime-specific (film thickness specific) HMM is needed to describe its degradation.

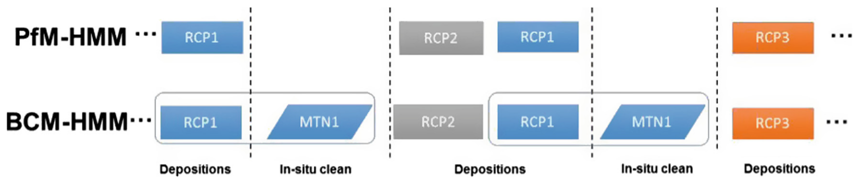

Fig. 1. Illustration of regime-specific HMM of system conditions assuming perfect maintenance (referred to as the Perfect Maintenance HMM or PfM-HMM) and regime - specific HMM assuming imperfect HMM (referred to as Backward Coupling Maintenance HMM or BCM-HMM). The terminology is adopted to emphasize the association of regimes between each in situ clean and the last deposition regime before that in-situ clean

Ideally, HMMs for modeling condition recoveries from maintenance operations could be identified from sensory signatures collected during those interventions, just like degradation models are identified from the corresponding sensory signatures. However, in spite of its unique size and granularity[4], this data set does not contain sensory signatures corresponding to the in-situ cleans and hence, an alternative approach was needed. Different regimes of deposition can leave different byproduct or residue levels on the chamber, and thus the effectiveness of each *in situ* clean depends to a large degree on the last deposition sequence executed prior to that *in situ* clean. On the other hand, condition of the PECVD tool at the start of each wafer sequence, i.e.,

[3] The parameters of the corresponding degradation HMMs are different for each film thick-ness.

[4] Signals from dozens of sensors were collected during more than 30,000 depositions, and all the signals were collected concurrently at 10 Hz.

just after the in-situ clean, reflects the condition to which the previous in-situ clean brought the tool. Therefore, the state-transition between the state just after processing the last pre-clean wafer and the state just before processing the first post-clean wafer reflects the maintenance (in-situ clean) activity and is assumed to follow an *in situ* clean regime that is associated with the last pre-clean deposition regime. As described in Sect. 2, all in-situ clean regimes are associated with right-to-left state transition matrices, illustrating recoveries of system conditions when those cleans take place. Eventually, the overall regime-specific HMM contains regimes for all deposition thicknesses, as well as in-situ clean regimes In this study, multiple sensory signals are collected over several months from a PECVD tool operating in a major 300-mm semiconductor-manufacturing facility. The tool was used to deposit four possible thicknesses of tetraethyl orthosilicate (TEOS) films onto silicon wafers. Automatic in situ cleans were triggered based on the total thickness of deposited films since the last in situ clean. Sampling rate of 10 Hz was used to concurrently acquire signals from the tool's RF circuitry, as well as temperatures, pressures, and flow rates from various parts of the tool. In total, the dataset consisted of signals corresponding to 2556 sequences of wafers, with each sequence containing signals from approximately 25 to 100 wafers that were processed between two consecutive in situ cleans.

Along with this massive dataset, the corresponding maintenance event logs and metrology data were also available and were used for validation of the monitoring results. Based on those logs, two periods of abnormal tool behavior were identified. Shortly after the first PM, the tool operation was stopped due to dramatically elevated particle counts on the wafers. The interval between the first PM and the last repair on the tool after that PM is treated as the first faulty period.

The second faulty period corresponds to a dramatic particle excursion event caused by Coulomb crystal formations [18] and correspond to the last 36 wafer sequences in the dataset. Consequently, all 2556 sequences of wafers were labeled as either normal or faulty, allowing evaluation of fault detection capabilities of the monitoring methods, which is to be discussed in the next section.

4.2 Data Processing and Process Modeling by Regime-Specific HMM

From the raw sensor readings collected during processing of each wafer, a set of 40 dynamic and statistical features was extracted, as described by Bleakie and Djurdjanovic [1].

These features were then discretized using a growing self-organizing map (SOM) [11] constructed on the training dataset. The training dataset consisted of the first 512 wafer sequences and was selected for training since both the maintenance and metrology logs indicated that during that period, the tool behaved normally.

A regime (film-thickness and in-situ clean) dependent HMM with 8 regimes (4 deposition thicknesses and 4 in-situ clean regimes), 4 hidden states, and 60 observation symbols (size of the SOM) was identified from the training set, along with the corresponding parameter uncertainties, using the Bayesian estimation procedure introduced by Zhang et al. [22]. This HMM will be referred to as Backward Coupling Maintenance HMM, or BCM-HMM for the rest of the paper. In contrast, the same amount of training data and the estimation method was used to train regime dependent degradation HMMs assuming perfect maintenance operations, resulting in 4 degradation HMM regimes with 4 states and 60 observation symbols. This method corresponds to the degradation model used by Zhang et al. [22] and will be referred to as the Perfect Maintenance HMM or PfM-HMM. The distribution of log-likelihoods yielded by these two models, as evaluated on the training set, is shown in Fig. 2 and some properties of the corresponding distributions are listed in Table 1. It is clear that the BCM-HMM outperforms the PfM-HMM significantly in terms of log-likelihood, which indicates that modeling of maintenance imperfections considerably improves the model of degradation dynamics within the PECVD process.

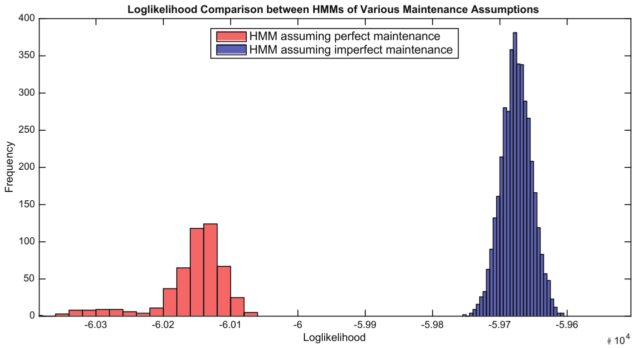

Fig. 2. Comparison of distribution of loglikelihood slopes based on the regime-specific HMM assuming perfect maintenance and regime - specific HMM assuming imperfect maintenance

Table 1. Improvement in log - likelihood based on the HMM with and without modeling of imperfect maintenance, using the same training dataset

Model	Mean of log-likelihood	Variance of log-likelihood	Sample size	Improvement in mean of loglikleihood
PfM-HMM	−60156.8	2805.83	500	NA
BCM-HMM	−59675.4	495.50	4000	0.8%

4.3 Improvement in Detection Performance for Sequence-Based Process Monitoring

Receiver operating characteristic (ROC) curves and the associated areas under the curves (AUC) are utilized to evaluate the monitoring performance of the newly proposed BCM-HMM-based method, the PfM-HMM-based method proposed by Zhang et al. [22], as well as the traditional PCA/T^2 based statistical process control monitoring method [13]. Figure 3 shows the ROC curves and the associated AUCs for the three methods. It is evident that the ROC curve yielded by the new method outperforms the other two monitoring methods for almost all potential control limits. Furthermore, AUC corresponding to the BCM-HMM-based monitoring method is 2.75% larger than that of the PfM-HMM-based method, and 27.23% larger than that of the PCA/T^2 based method.

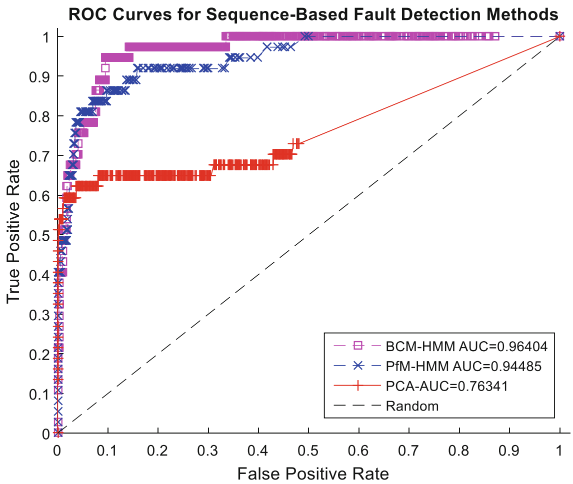

Fig. 3. ROC curves for detection of faulty sequences using the models of PCA/T^2, PfM-HMM/LS, and BCM-HMM/LS

4.4 Evaluation and Analysis of Wafer-Based Monitoring Methods

In this section, we assess the monitoring performance of the fault detection method based on the use of degradation HMMs that account for maintenance imperfections (BCM-HMM) and individual observations, as described in Sect. 4.3. This method, denoted as the BCM-HMM/filtering method, was evaluated on the aforementioned PECVD tool data and compared to several benchmark methods.

These methods include the traditional PCA/T^2 SPC method based on observations from each individual wafer, monitoring based on HMMs that do not account for maintenance imperfections and the newly proposed filtering that evaluates hidden state probabilities for any given sensory observation (labeled as the PfM-HMM/filtering method), monitoring based on the degradation HMMs that assume perfect maintenance operations, but using the mean log-likelihood slopes within a given observation sequence for monitoring, as suggested by Cholette and Djurdjanovic [4] and Zhang et al. [22] (labeled as the PfM-HMM/slope method), and finally, the method based on the newly proposed degradation HMMs that model maintenance imperfections, but using mean log-likelihood slopes of observation sequences (labeled as BCM-HMM/slope method). Figure 4 shows the results of this comparison and it is evident that the BCM-HMM/filtering monitoring method outperforms all the other approaches and for all false positive alarm rates. It is interesting to note that the PfM-HMM/filtering method has dramatically worse performance than the counterpart method that uses the BCM-HMM degradation model (or any other method for that matter). Such poor performance may be attributed to the fact that the accuracy of the probabilities of the hidden state sequence relies heavily on the accuracy of recognition of the initial condition for each sequence. Within the PfM-HMM degradation model, the initial conditions were always assumed to be as-good-as-new and that deteriorated the resulting monitoring performance based on state filtering. On the other hand, the PfM-HMM degradation model coupled with monitoring based on the mean log-likelihood slopes for any given sequence provides a slightly better (higher) AUC value than the BCM-HMM degradation model coupled with monitoring based on the mean log-likelihood slopes. This advantage can be attributed to the fact that the log-likelihood slopes in the degraded states become steeper when the initial wafer state is modeled as perfect, as opposed to being recognized as random, which is the case with the BCM-HMM degradation model.

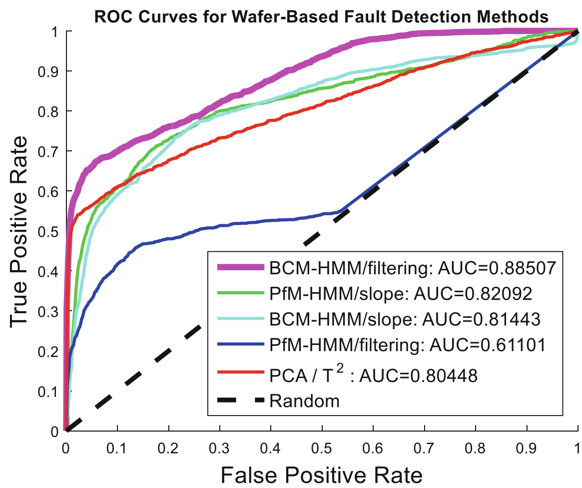

Fig. 4. ROC curves for detection of faulty wafers using the models of BCM - HMM/filtering, BCM - HMM/slope, PfM - HMM/filtering, PfM - HMM/slope, and PCA/T^2

5 Conclusion

This paper introduced a new method for modeling of degradation in complex systems using regime-specific HMMs that model imperfections in maintenance activities. Furthermore, a novel monitoring method based on the estimation of probabilities of hidden condition states using degradation HMMs with uncertain parameters was also proposed. Unlike HMM-based monitoring methods reported by Cholette and Djurdjanovic [4] and Zhang et al. [22], the newly proposed method enables on-line performance evaluation based on each individual observation symbol, rather than monitoring solely based on an entire sequence of observations.

Using a large-scale semiconductor manufacturing production dataset, it was demonstrated clearly that the newly proposed model yields significantly higher data likelihoods compared to the previously reported degradation models that assumed perfect maintenance operations, thus indicating better representation of the data where the new method is used. Furthermore, the newly proposed monitoring method based on the degradation HMMs that are aware of maintenance imperfections and fault detection based on estimating probabilities of hidden degradation states using uncertain HMMs of system degradation yielded significantly and consistently better performance compared to a set of benchmark methods.

Many extensions to the research presented in this paper are possible. The methodology seems to be obviously applicable to monitoring of plasma etch processes in semiconductor manufacturing, where the periodic yet imperfect chamber cleans take place after periods of production. Furthermore, other complex and insufficiently observable systems, such as Li-ion battery, or oil/gas extraction systems could be monitored using HMM-based models of degradation. In addition, sensory signatures collected during maintenance operations could be used to estimate maintenance-related HMMs of condition dynamics (condition recoveries), similarly to how degradation HMMs were estimated by Cholette and Djurdjanovic [4] and Zhang et al. [22]. Finally, let us note that ultimate benefits of the work presented in this paper would be realized once degradation information from multiple machines in a system gets collected, coordinated and utilized for cost-effective operational decision-making. In a recent thesis, Celen [3] proposed optimized operational decision-making for systems of machines whose degradations followed operating regime dependent HMMs such as those considered in this paper. Nevertheless, degradation HMMs by Celen [3] were assumed to be perfectly known and were not obtained from any realistic piece of equipment. Hence, full integration of the degradation modeling described in this paper and operational decision-making described by Celen [3] remains to be done in the future.

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Launching New Projects in Industry 4.0: Best Practices of Automotive Suppliers

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Abstract. The purpose of this paper is to present the meaning and benefits of new Industry 4.0 (I4.0) projects for organizations future and competitiveness. The background was scholarly literary research, best practice analysis and interviews with operation managers. Qualitative research ran from 2017 to 2018 in two automotive supplier organizations, but information results from the experience of other organizations managers with implemented I4.0 strategy were also used, particularly in the area of project management, and quality engineering and management. At this stage of research, it is about finding a suitable conceptual framework for deciding on the implementation of a new project.

Keywords: Industry 4.0 · Project management · New project · Risk management · Digital Management Control

1 Introduction

Starting a new production program requires individual approach and professional support of research and development (R&D), manufacturing, as well as other departments of the organization. This approach is especially important when it comes to Industry 4.0 projects.

Industry 4.0 (I4.0) is commonly referred to as the Fourth Industrial Revolution [1] and is representing mainly Cyber-physical systems, System integration, Internet of Things (IoT), Simulation, Additive manufacturing, Cloud computing, Cognitive computing, Augmented reality, Big data, Autonomous robot, Knowledge automation.

According to Professor Klaus Schwab, author of The Fourth Industrial Revolution "… in this fourth revolution, we are facing a range of new technologies that combine the physical, digital and biological worlds".

I4.0 aims to achieve a level of "smart factory" with cyber-physical systems capable of autonomously exchanging information, triggering actions and controlling each other independently [2].

This enables a significant improvement in processes related to research and development (R&D), materials utilization, engineering, manufacturing, performance and asset management, as well as supply chain management and overall product lifecycle. Intelligent materials and intelligent products are part of this industrial digital transformation.

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The digital revolution is radically changing the traditional processes of engineering. At present, digital models, virtual prototypes and a digital replica of physical assets are expanding more and more.

The point of view on quality engineering and management is also changing. According to the lecture of Willy Vandenbrande on the 60th EOQ 2016 conference in Helsinki: “Every engineer has to be a quality engineer!”, moreover, we also want to add that “Every manager has to be a quality manager!” This verbs implicitly means that all engineers and managers in organizations with the Industry 4.0 strategy have to know and be apple to apply new technologies supporting such oriented quality assurance (called as Quality 4.0).

The benefits of digitization are mainly in the possibilities to lean the organization [3], including simplified data management, greater possibilities of creating cheaper and more individualized solutions, automation of labor-intensive processes, or the introduction of measures that simplify these processes. The benefits of I4.0 can be seen in conventional manufacturing companies as well as in companies operating in the service sector.

A majority of I4.0 projects start as a result of operation managers trying to solve problems or improve their daily work on the shop floor [4].

2 Methodology and Research Problem

We know how new projects happen in a predictable world [5]. In a predictable environment, a team is created, the market is analyzed, a forecast is created, and a business plan is written. Resources are then collected, and the plan will be launched.

Increasing the unpredictability of the environment also increases the risk of decision-making. Therefore, the research question is how to start new projects in a less predictable environment, among which I4.0 certainly belongs. The problem is to find the best way or at least a good way to achieve it in an age in which dissemination of data and opinions does not allow for a decisive analysis. Remote events have an immediate, unexpected impact and economic uncertainty cause companies to be reluctant to make big decisions in such a risky environment.

It is also difficult to find a well-established theoretical framework in this area.

Our qualitative research was conducted through a literary survey and published short examples of best practice from scholarly sources and interviews with project managers in organizations with an I4.0 strategy.

The interview research questions are oriented on the methodology of the I4.0 new project launching in organizations that already have an implemented I4.0 strategy, and the research questions were oriented on the methodology.

3 Literature Review

The topic of I4.0 is relatively extensively described in the literature and is currently also discussed at conferences, discussion forums. This topic is also addressed by separate reports and organization studies, for example [6–8].

In the Emerald Insight database, the I4.0 theme appears from 2014 until now (19–01–2019), while the number of published articles and case studies by topic and keywords "Industry 4.0" is 2,915. Other related terms: "Project 4.0", "Lean 4.0", "Digital Management Control" that we searched for in this database are only rarely found.

Various evidence of the implementation of Industry 4.0 in organizations are globally growing [8]:

(a) The internet is used as a primary source of information and the most important means of communication;
(b) Creating and using virtual representations of the real world. Cybernetic systems that partly act autonomously and can make their choices are developing more and more.

Several authors [8, 10–12] investigated organizations, their risks and logical procedures used for projects related to new products and services. They are seeking new business models for situations where old methods of analysis, forecasting, modeling, planning, and allocation does not work.

Generalization can be found in an approach that defines acceptable loss and instead of looking for the perfect solution also allows a pretty good solution in terms of win-win strategy [8, 13] and/or min-max [14].

This approach allows different thinking and focuses more on modeling and simulating the future than on predicting it. This new logic assumes that every manager will do the same when confronted with the unknown because it is a precarious way to start new projects. Of the many exciting practices, we have chosen three, which can be summarized in simple steps.

According to an article of Jill Juska, published in Industry Week [8], it is essential to recognize early that the goal of new product development projects is to eliminate the difference in knowledge between when to start a new product project and when to implement it. According to Oosterwal [15], "the whole objective is to create reusable knowledge better, faster, more efficiently and the way to be able to get products developed faster," and the procedure can be summarized in three steps [8]:

(S1) Agile Development → (S2) Knowledge-based Development → (S3) Spiral Development.

According to the study in [6], six steps are required for success in Industry 4.0:

(S1) Map out the organization I4.0 strategy → (S2) Create initial pilot projects → (S3) Define the capabilities you need → (S4) Become a virtuoso in data analytics → (S5) Transform into a digital enterprise → (S6) Actively plan an ecosystem approach.

One of the theoretical frameworks is also a project approach based on the I4.0 strategy of Faurecia [16]:

(P1) Prerequisite anticipation → (P2) Scoping → (P3) Connectivity: Master data (P4) DMC implementation → (P5) Support → (P6) Full plant roll-out.

The following two chapters present the examples of best practices from the environment of Tier 1 supplier organizations.

4 Faurecia Best Practice Example

Since 2015, Faurecia has been involved in the strategic transformation of its operations into Industry 4.0 or the Internet of things. The emergence of new solutions such as robots for cooperation called "cobots", automated handling devices or "automated guided vehicles" (AGV) led in 2009 to a breakthrough in automation of assembly and handling in many plants. Implementation of Radio Frequency IDentification (RFID) barcodes or QR codes allows tracking components and finished parts in production areas from goods receipt to product pick-up and transportation. An example of best practice in launching a new project in I4.0 is the Faurecia story based on [16–18] and interviews with operation managers.

The digital transformation of Faurecia takes place since 2015 in the following phases:

- 2015: Explore & Design → Experiment and Learn → Prepare Rapid Scale-Up. The result was 200 digital use cases and 40 proofs of concept.
- 2016: Core solution design and pilots. Design of the digital core solutions on the scope of selected initiatives → Implementation of the solutions on pilot sites to adjust and validate the design before mass industrialization. The result was the first digital solutions catalog for operations such as Predictive maintenance, Digital Management Control, Collaborative robots, Product Life Cycle solution, Digital Learning Platform.
- 2017: Deployment industrialization. Industrialization based on large scale deployment of the solutions available in the catalog → Design of new digital solutions to enrich the catalog. The result: Massive deployment of digital solutions from the catalog all over the world.

Digital Management Control (DMC)
A step forward shop floor digitalization and Lean 4.0 is a procedure of Macro planning projects:

- P1: Pre-requisites and anticipation
  - Team mobilization and planning
  - CAR approval for Mii server and procurement
- P2: Scoping
  - Kick-off and site visit
  - Fit Gap analysis
  - Project scoping (SOW, blueprint)
- P3: Connectivity & Master Data preparation
  - Data preparation for the Mii test
  - Machine connectivity: cabling, PLC modification
  - Key user training
  - Translation if needed
  - Master data adaptation (routings, booking point)
- P4: DMC project implementation
  - Material reception (devices, cabling, etc.)
  - Mii NG installation, configuration, and basic test

  - Non-Regression test of the solution
  - End users training
  - Knowledge transfer (cutover plan)
- P5: Support
  - Post Go Live support
- P6: Full plant rollout

Deployment Industrialization: Attribute Data Entry System

Automation of specific logistics tasks and adapting process parameters by feedback information from each produced component or product was the internal strategic goal of the Košice plant in 2015.

In 2016, after the initiative of operational managers and proposing a pilot project, future users of the new attribute data entry system (ADES) defined their requirements for its features and functions. The Quality Function Deployment (QFD) application, in collaboration with the University and system vendor, has been designed and implemented by the ADES system for permanent operation of the plant.

Digital dashboards enable real-time sharing of information from pre-operational, operational and after - operational inspection and provide the opportunity for the immediate response of operating teams and in case of disagreement, drift or production line break can be immediately reacted (Fig. 1).

Fig. 1. Attribute data entry system

After training and through permanent use of the system by personnel, after a year of use, the number of nonconformities fell from 680 a month to 136. The implementation of digital management tools, along with "big data" to control manufacturing processes opens new prospects for optimizing the operating conditions of production lines and increasingly making better use of industrial assets.

Currently, within the stages of Deployment Industrialization, several plants have implemented this system.

At present, Faurecia focuses on seamless data generation and communication, including data on the quality of manufacturing and production processes to increase efficiency and productivity while increasing visibility and control of production processes through global cloud solutions. To that end, Faurecia chose IBM [19], which has built a global cloud-based solution to collect, manage, and analyze data from every manufacturing facility in the entire company. Using cloud capabilities and analytics, poor quality can be significantly reduced, and efficiency and performance increased [20].

4.1 Automotive Supplier of Casting Components Best Practice

The organization focus on its digital transformation and the Industry 4.0 concept has been spreading during the last year in all the plants. Different Industry 4.0 projects and solutions were implemented. Some of them realized in the plant in Slovakia are presented.

4.2 Big Data Project

The organization implemented the Noris complex information system for automatic capturing, storage and analysis of large amounts of data from all relevant manufacturing devices (produced parts, cycle times, availability of machines, breakdowns, employee identification, ect.). The system provides information from the production, which are accessible and communicated in real time via smartphones app, tablets, e-mails notifications, SQL report generation. It also provides a hierarchical system of access rights and all data protection. Big data supports the improvement of manufacturing processes (increasing effectivity and productivity, improving the capability of processes and quality of outputs). The implementation of the Noris system eliminated the paperwork and mistakes connected with manual data collection and entering to the database. The system enables prediction and pattern recognition of coming breakdowns based on the knowledge database and actual parameters. It also helped to optimize maintenance cycles and decrease maintenance costs.

Product tracking in production is ensured by QR code which enables the communication with the machine and the machine get the information if the part shall be operated, where it shall be operated, ect.

4.3 Using Simulation and Virtual Reality in the Project of the New Production Hall Construction

The organization cooperated with CEIT (Central European Institute of Technology) to solve the project of construction of the new production hall concretely to create the parametric digital model for testing the parameters of future production to uncover all the bottlenecks before own realization of the project. The goal was to optimize the production layout and logistic system. Teams set draft available using 3D visualization. In digital environment except for the static aspects such as layout arrangement of production facilities also dynamic aspects like cycle times, logistic flow, machine and employee capacity utilization and even profitability were presented on the base of simulations. Layouts and logistics systems were created interactively and further analyzed and improved. There were used more than 40 simulated variants of production (see Fig. 2). The solutions were verified in virtual reality, which enabled to visualize the production environment and helped to identify shortcomings of the project which could have occurred in the future and improve the project before its realization.

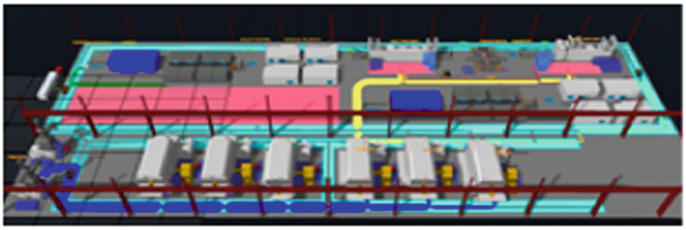

Fig. 2. One of the production hall layout variants

The solution provided information for the right decision making. Such experiments in a real environment would be costly.

5 Conceptual Framework

The paper presents the first phase of research on the new project launch in I4.0. Three models of logical procedures are presented in the design of new projects. Best practices are taken from organizations presenting Tier 1 suppliers in the automotive industry and are described as more detailed.

We created the general conceptual framework for the new project launch decision making and project risk management on the base of previous research realized in the organizations with the I4.0 strategy:

Research problem in the I4.0 new project launch decision making and project risk management → Inductive synthesis of relevant concepts from various sources → Quantitative and qualitative analysis → Application of conceptual framework to I4.0 new project launch.

6 Conclusion

For most manufacturers, Industry 4.0 is just a dream, but, at presented organizations producing components for the automotive industry, it is a reality [17, 20].

The paper presents the first phase of research on the new project launch in I4.0. Three simplified models of logical procedures are presented in the design of new projects. Best practices are taken from organizations presenting Tier 1 suppliers in the automotive industry and are described more detailed.

- Using simulation and virtual reality is the starting point of the I4.0 new project launch decision making and project risk management.
- Digital enterprise project is set to transform working practices in virtually every aspect of both organizations.

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RETRACTED CHAPTER: The Use of Neutron Scattering in the Advancement of Additive Manufacturing

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Abstract. Additive manufacturing is a transformative approach to industrial production that enables the creation of lighter, stronger parts and systems while bringing digital flexibility and efficiency to manufacturing operations [1]. Despite the constant progress in the field, there are still a lot of challenges that must be addressed. In the case of metal components, residual stress caused by the unique thermal cycle in AM is the critical issue since the steep stress gradients can generate distortion and increased fragility, which can lead to serious deterioration of the end-use parts [2]. The present study tries to prove that neutron diffraction is one of the most versatile and powerful analysis tools for internal stress, as it allows the determination of the complete 3D stress tensor on real sized components, even in-situ or in-operando conditions. The stress field in an aluminum additive manufactured support is mapped out under load, by determining 3 orthogonal components.

Keywords: Additive manufacturing · Neutron diffraction · Analysis

1 Introduction

Neutron strain analysis is the ultimate method for materials science and engineering. It is one of the most versatile and powerful analysis tools for various industries developing metal and ceramic products, particularly in aerospace and transport sectors. It allows the determination of the complete 3D stress tensor on real sized components, even in-situ or in-operando conditions. Besides precision, important quality factors are reliability and reproducibility of the results, thus independent of the neutron strain-scanning instrument at different facilities [3, 4].

The residual stress characterization of the support was done by neutron diffraction using ILL's SALSA instrument (a stress-strain analyzer for large scale engineering applications).

Measuring the residual stress using diffraction relies on the correlation between deformation and the variation of the diffraction angle. External or internal forces change the distance between crystallographic planes leading to a shift in the diffraction angle. This correlation is mathematically expressed by Bragg's law:

$2d \cdot \sin(\theta) = n\lambda$, where:

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- d is the distance between 2 planes belonging to the same family of crystallographic planes
- θ is the diffraction angle
- n is the order of diffraction
- λ is the wavelength of the incoming radiation (in this case the associated de Broglie wavelength) (Fig. 1).

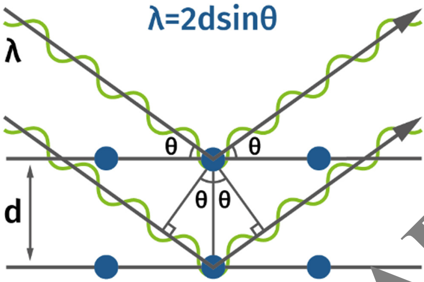

Fig. 1. Bragg diffraction. Source: www.stresstech.com

Bragg diffraction occurs when electromagnetic radiation or subatomic particle waves with wavelength comparable to atomic spacing incident upon a crystalline sample, are scattered in a specular fashion by the atoms in the system, and undergo constructive interference in accordance to Bragg's law. For a crystalline solid, the waves are scattered from lattice planes separated by the interplanar distance, d. Where the scattered waves interfere constructively, they remain in phase since the path length of each wave is equal to an integer multiple of the wavelength (n). The path difference between two waves undergoing constructive interference is given by 2dsinθ, where θ is the scattering angle.

When the material is under stress, the distance between planes changes leading to a change in the diffraction angle. Because of material anisotropy the new distance between planes is no longer a constant, but rather a distance distribution, thus the diffraction peaks tend to broaden. This can be seen in the mapping of the detected neutrons [5] (Fig. 2).

The angle is obtained through fitting of the experimental data (in our case with the Pseudo - Voigt function). With this value, the strain can be calculated:

$$\varepsilon = \frac{d - d_0}{d_0} = \frac{sin(\theta_0)}{sin(\theta)} - 1 \tag{1}$$

where:

- ε is the strain
- d is the distance between the planes
- θ is the corresponding diffraction angle
- d_0 is the reference value
- θ_0 is the corresponding reference diffraction angle.

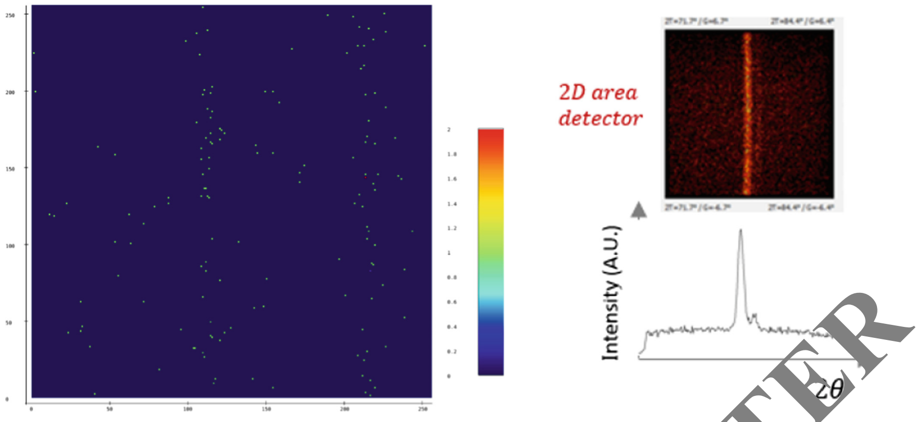

Fig. 2. Neutron peaks in 2D detector area

The reference value is chosen from a sample considered stress-free. This makes the result relative and gives the method a measure of subjectivity.

This strain is calculated for three orthogonal components to obtain the complete characterization of the sample. The stress can then be obtained, using 2 material constants, Young's modulus E_{hkl} and Poisson's ratio ν_{hkl}:

$$\sigma_{xx} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{xx} + \nu_{hkl}\left(\varepsilon_{yy}+\varepsilon_{zz}\right)\right] \quad (2)$$

$$\sigma_{yy} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{yy} + \nu_{hkl}(\varepsilon_{zz}+\varepsilon_{xx})\right] \quad (3)$$

$$\sigma_{zz} = \frac{E_{hkl}}{(1+\nu_{hkl})(1-2\nu_{hkl})}\left[(1-\nu_{hkl})\varepsilon_{zz} + \nu_{hkl}\left(\varepsilon_{xx}+\varepsilon_{yy}\right)\right] \quad (4)$$

The stress can now be plotted to obtain the 3 stress maps. To predict the yielding of materials under complex loading the equivalent von Mises stress, also known as the equivalent tensile stress, is used:

$$\sigma_v = \sqrt{\begin{array}{c}\frac{1}{2}\Big[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 \\ + (\sigma_{33}-\sigma_{11})^2\Big] + 3\left(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2\right)\end{array}} \quad (5)$$

2 Experimental Set - Up and Procedure

In Fig. 3, the set up describes the fixed position of the measuring point is shown (gauge volume, GV: red point). Because of this, it is necessary to move the sample in order to be able to map the whole region of interest (ROI). For each position, the Bragg-diffraction peak is recorded at a fixed 2θ position of the detector. The position of the peak is a precise measure of the lattice spacing of the crystallites within the GV that also allows phase-specific studies as for composites. Then, stresses can be determined from the peak shift relative to a reference unstrained condition. The strain component direction is defined by the scattering vector q which is bisecting the angle between the primary and diffracted beam. Hence, the sample would need to be oriented as many times (angle configurations) as strain components are needed to be measured. The Al-311 reflex was tracked for all regions of interest at a monochromatic wavelength of 1.6211 Å (then with a $2\theta = 82°$ for the detector positioning) since it is the most suited for extrapolation to macroscopic behaviour following the ISO guidelines [3]. A detailed schema of the neutron diffraction set up is given in Fig. 3.

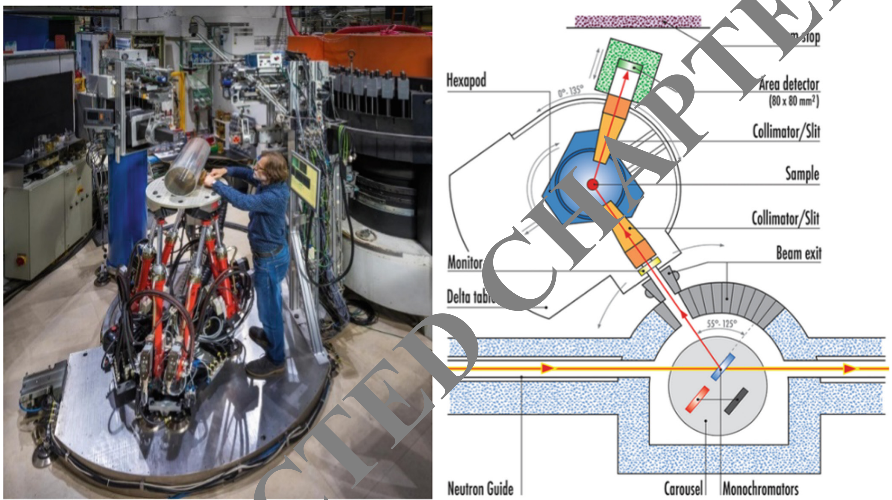

Fig. 3. [6] SALSA beam line. Left: real scale picture and right scheme of principal components (q is the diffraction vector i.e. strain component measured at a time)

The instrument's monochromatic beam has a fixed wavelength of 1.62 Å. The calibration and alignment of the instrument has two parts: collimators positioning (both for primary incoming beam and the secondary towards detector) and single crystal measurement to correct the detector pixel 2θ position. The sample is aligned using a camera assisted metrological system and the hexapod table. The region of interest (Fig. 4) in the sample is chosen based on the initial simulation and is 10 × 5 × 2 mm. The origin is chosen in the centre of the sample.

The instrument angular positioning for the different strain components of the sample is shown in Table 1. Based on the geometry of the support area, those were the LONGITUDINAL component (Fig. 5), the NORMAL component (Fig. 5) and the TRANSVERSAL component. Note that the measurement of 3 strain components is mandatory in order to calculate the absolute stresses on. The MAPPING STRATEGY (Fig. 6) was specifically created to have a 3D overview of the stress in the analysed sample.

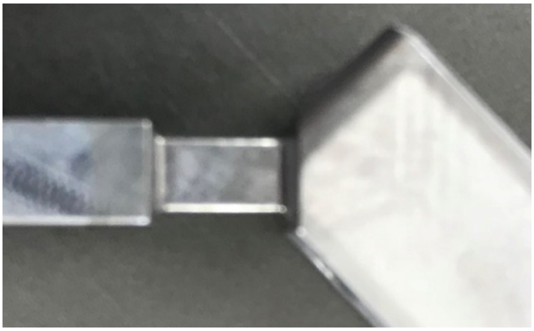

Fig. 4. Area of interest dimensions

Table 1. Angular parameters (all in°) for the 3 strain components measured

Strain component	2θ (detector)	Omega (hexapod)	Psi (rotation table)
Longitudinal	83	−138.5	0
Transverse	83	−138.5	[illegible]
Normal	83	−48.5	90

Programming the automatic scan for the three components is done in the NOMAD software – ILL. Measuring the sample is starting from the origin observed in Fig. 7.

(1) Tool description and calibration. *Brief description of the main SALSA components*

(a) Beam collimation system

The neutron beam is delivered via a double focusing monochromator composed of 39 silicon variably bent crystals, each within 5 mm height, 170 mm long and 12 mm thick. Its total height is 209 mm, corresponding to the guide dimensions (30 × 200 mm). Thanks to phase space focusing, it takes advantage of the beam divergence provided by the neutron guide and supplies the high resolution needed for strain determination. Changing the horizontal curvature and/or the take-off angle allows the use of high-intensity or high-resolution configurations. The optimum neutron flux is at λ = 1.66 Å, which is ideal for a many typical of engineering materials.

Two options for beam size definition are available: computer controlled variable slit systems and radial focusing collimators. The primary and secondary slit systems allow beam size variations between 0.3 mm and 5 mm horizontally and up to 25 mm vertically. A range of collimators are available with foci as small as 0.6 mm (the one used in this study; FWHM) and a fixed distance to the gauge volume of 150 mm. Collimators are particularly useful for high spatial resolution measurements near interfaces, surfaces or in coatings, since they give lower surface aberrations.

The collimator has a transfer function that helps the flattening of the background.

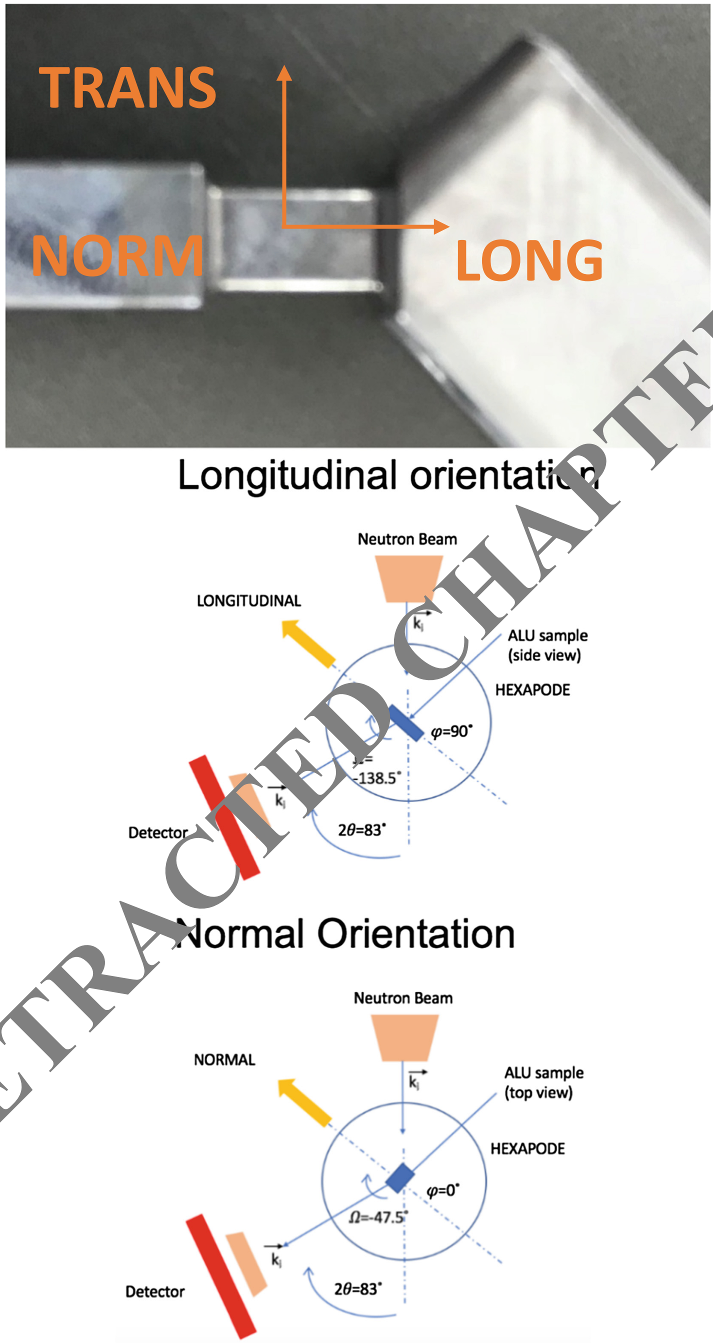

Fig. 5. LONGITUDINAL component setup and NORMAL component setup (note that TRANSVERSE is similar with a rotation 90 in psi)

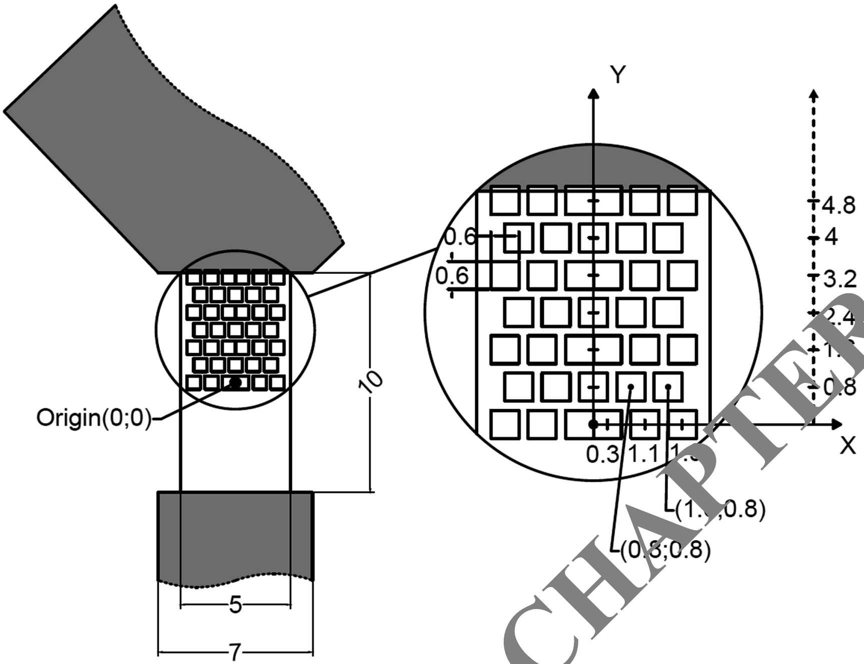

Fig. 6. Mapping strategy for the ROI.

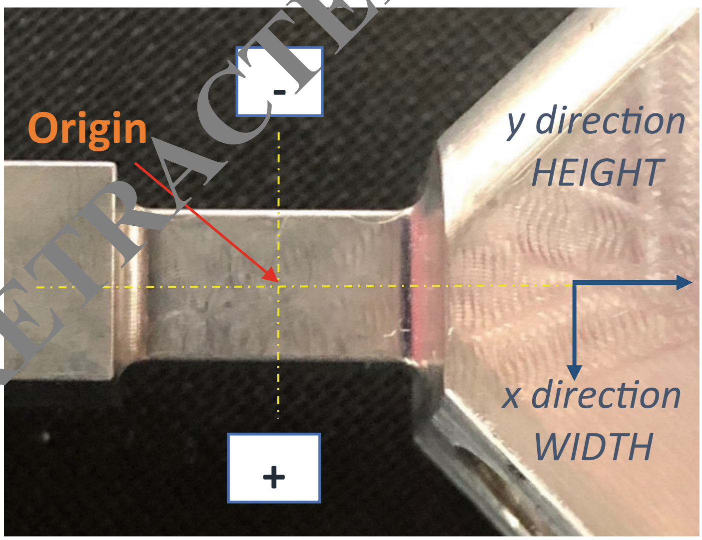

Fig. 7. Sample origin and system orientation. Note that (+) is the direction towards inner region of the support and (−) towards exterior

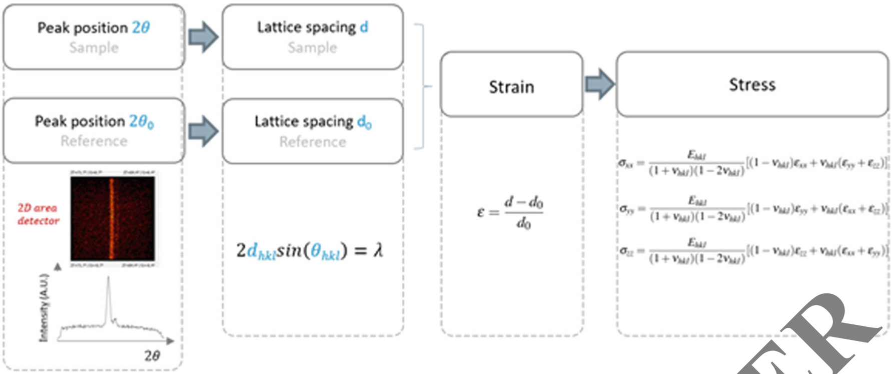

Fig. 8. Data treatment flow

Variable background can influence the peak positions obtained on the detector. It is accepted that, since there is no good statistics in the background, this should be minimized or removed.

(b) Detector
The detector relays to the detector encoder. The measurement is represented by an encoder position and a channel position. The data is stored in channel numbers in the detector.

(c) Rotating support table
Sample dimensions can vary from a few millimetres to over a meter. The sample stage is a 6-axis 'hexapod' which is able to support samples of over 500 kg and performs complicated spatial scans at high resolutions. A 360° rotation (omega) is available around a vertical axis through the "gauge volume".

(2) Set-up procedure for a sample with load
The sample was put under a load of 300 N using a bolt and a torque wrench

(3) Data treatment
The data is acquired through the NOMAD software designed, specifically, for the instrument. It is then read into the LAMP software for interpretation.
The integrated data is then fitted using the Pseudo-Voigt function, to obtain the diffraction angle and other statistics.
The fitted data is then imported into MATHCAD and analysed in the program created by ILL scientific staff. The reference value for θ_0 was obtained by taking the mean of the equilibrated values in the normal direction. The program computes the strain and stress fields and represents them as 2D maps.
Relevant points were extracted from the graphs and then plotted in Origin to highlight the stress distribution and gradients in the three components in the measured area. The equivalent von Mises stress was calculated for evaluation of the cracking possibility of the component under load.

3 Data Analysis and Discussion

Data treatment and analysis of the results by using LAMP (peak fit) and in-house MathCad routine (strain and stress). The data treatment workflow is presented in Fig. 8. The specific elastic diffraction constants to be used for the particular reflection Al-311 are E = 69.4 GPa and ν = 0.35 (Fig. 9).

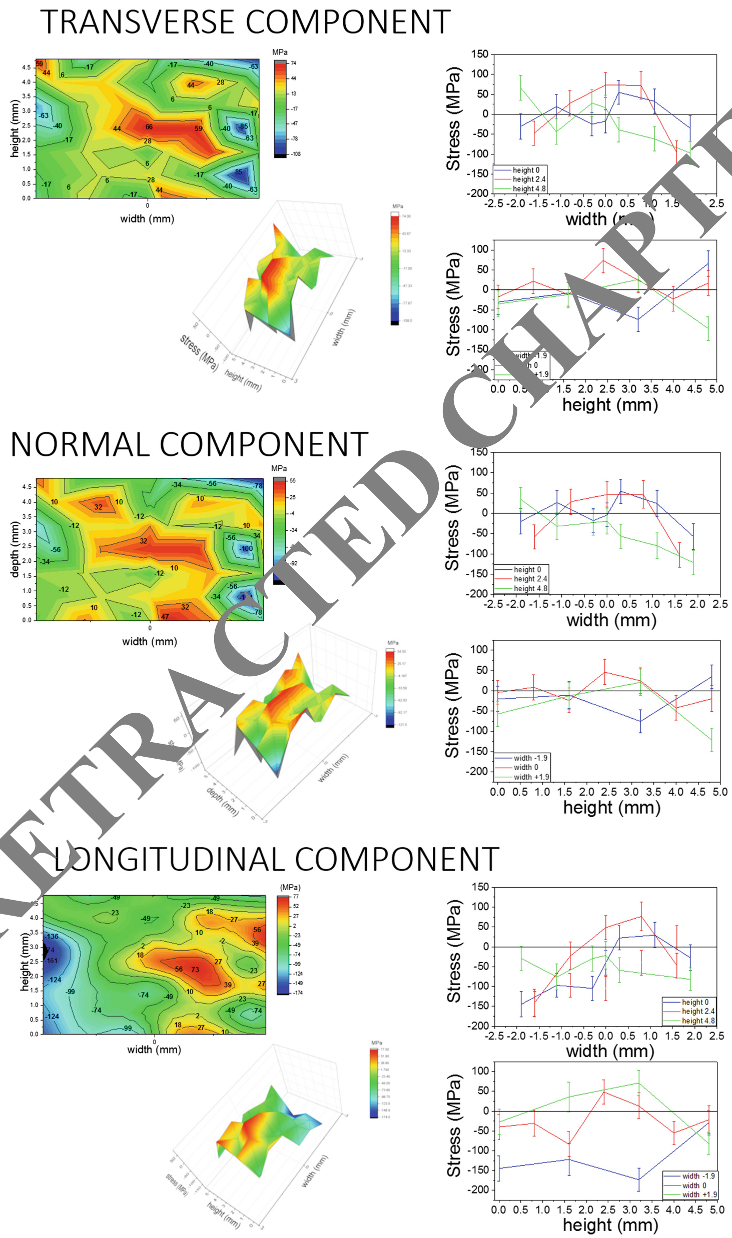

Fig. 9. Stress mapping and graphs of results

4 Conclusion

The results show low overall stress within the sample, with some incipient trends in the width from compressive to tensile stresses (maximum span of 100 MPa ± 30 MPa). Regarding the characterization method by neutron diffraction, it has been shown that even low strain gradients can be resolved within the bulk of a final structural component in in-situ conditions. This can be used for both quality control and further improvements of additive manufacturing techniques, thus proving the power of this technique.

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A Cloud-Based Process Planning System in Industry 4.0 Framework

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Abstract. When generating and optimizing process plans nowadays, new concepts and models which consider dynamic harmonization of all participants, systems and people involved in planning stages are applied. A number of systems and environments for distributed process planning that utilize various techniques of intelligent planning and collaborative technologies have been developed in the recent period. Today, a growing number of manufacturing companies adopt the principles of smart factory, also known as the Industry 4.0 concept with the focus on the effective integration of knowledge sources with a production process. This integration uses cloud manufacturing principles whose integral part is the cloud-based process planning. This paper will present such a system that utilizes cloud technology and services for defining process plans as well as expert heuristic knowledge for optimizing process plans and selecting the best solutions.

Keywords: Industry 4.0 · Cloud manufacturing · Distributed process planning · Knowledge sharing

1 Introduction

Industry 4.0 is aimed at creating smart factories where manufacturing technologies are upgraded and transformed by cyber-physical systems (CPS) [1, 2], the Internet of Things (IoT), and cloud computing [3]. Cloud computing represents a framework for the development of Cloud Manufacturing (CMfg) system or service which deploy and manage manufacturing information and sustainable management services for accessing and exploiting over the Internet. Cloud manufacturing represents an advanced production model that combines cloud computing, IoT, virtualization and service-oriented technologies. In this way, manufacturing resources are transformed into services which can be entirely shared and distributed. Industry 4.0 is widely considered as a key enabling technology for cloud manufacturing implementation. The advantages of cloud-based services in manufacturing use include:

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- Efficient resource utilisation and sharing,
- Rapid implementation,
- Frequent innovation,
- Cost savings,
- Scalability,
- Productivity gains,
- Quality and compliance, etc.

Cloud manufacturing integrates the continuous system for data management with the network of digital models, services and applications, including simulation and visualization. As shown in Fig. 1, the common services platform supports the service modules of machine availability monitoring [4], collaborative process planning [5, 6], adaptive setup planning [7], dynamic resource scheduling, process simulation and remote machining are built into the platform [4, 8, 9].

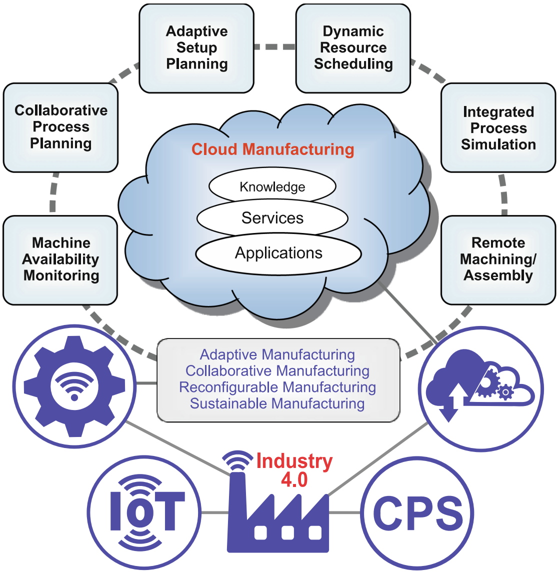

Fig. 1. A Cloud manufacturing platform in Industry 4.0 framework. (Adapted from [4, 8])

Within the cloud itself, products, processes and resources are modelled on the basis of real data. Planned products as well as their processes are being intensively verified and improved by using virtual models until they are fully developed. After all potential faults are removed, the models can be used in real manufacturing. The vision of the cloud-based concept focuses on the integration of available services and tools for planning and control of products at different levels of manufacturing and operational control within a factory. The cloud does not only contain datasets on models, processes and resources, but also the knowledge that is used in the process. As the knowledge within the cloud relates to different elements of manufacturing, it can represent a knowledge repository that includes explicit and implicit knowledge, procedural knowledge, rules, heuristics, expert analyses, decision support, etc. The knowledge has a dynamic character such as a production process - it is modified, complemented and corrected. Shaping knowledge in this environment is initiated by an intelligent system or a human. Industry 4.0 implies the implementation of Machine to Machine (M2M) communication which significantly reduces the direct involvement of a human in a manufacturing process. Given the tendency for cloud services to be autonomous and intelligent, in other words to represent smart objects, cloud-based manufacturing often utilizes multi-agent technologies and various methods of self-organization and coordination between agents [10–12] as well as function block-based methods [9, 13]. However, regardless of the use of intelligent services, it can be claimed that the influence of engineers and experts, i.e. people in process planning, is still very important [14], especially at the conceptual level. Expert heuristic knowledge is often impossible to fully simulate and represent with the help of existing artificial intelligence methods.

2 Cloud-Based Process Planning

Cloud-based process planning is a technology, in other words, discipline that provides a strategic approach for the development, implementation and optimization of all elements of a production process. That primarily involves the framework which combines digital product with digital processes and resources as well as the integration of a virtual model of manufacturing with a real physical model. Cloud-based process planning system should represent a set of distributed, flexible, open access and intelligent services for process planning in a collaborative environment and should help users to define process plans with required level of detail. These levels are known as meta, macro and micro process planning [15]. Meta or conceptual process planning is performed in order to determine manufacturing process and the machines that fit the shape, size, quality and cost requirements of the parts that are planned. Macro process planning is responsible for the specification of equipment, minimum number of process operations required for manufacturing a part, as well as the operation sequence. Micro process planning refers to the selection of tools, fixtures, generation of the tool paths in manufacturing process (e.g. machining process) and definition of other parameters related to the shop floor operations so that productivity, product quality and manufacturing cost remain optimal. Cloud-based process planning defines a framework that allows integration and coordination in the development of "smart products" and the exchange of information between entities which are parts of services, applications and experts. Collaborative connections are priority and with the development of new products, it is necessary to establish a collaborative process with both customers and suppliers within a common communication infrastructure [16]. In this scenario, defining process plans becomes one of the most important tasks.

3 Conceptual Model of the Cloud-Based Process Planning System

By analysing the necessary tasks of the modern collaborative environment for process planning within the Industry 4.0 and its main components, it leads to the conceptual model of the cloud-based system for process planning (Fig. 2).

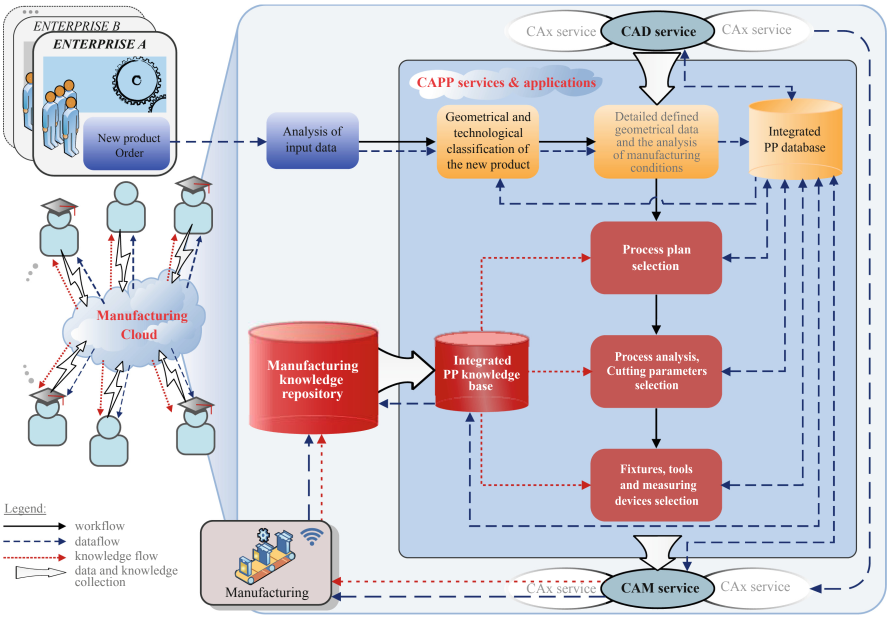

Fig. 2. Model of the cloud-based process planning system.

The core of this system is located in the manufacturing cloud and consists of various services and applications for process planning. Process planning system uses resources of the CAD service from the manufacturing cloud which results in the process plan as the basis for generating NC programs within the CAM service. Besides, different CAx services are simultaneously used in the development and analysis of product life cycle stages.

The module for generating process plans is not fully autonomous due to the reason that engineers and experts are also involved in the optimization of process plans [5, 6]. Human knowledge, experience and heuristics are used for evaluation and ranking of variants of process plans that are generated by CAPP services and applications. Parameters which represent equivalents of the quality of process plans are used for evaluation and multi-criteria ranking of process plans. Experts involved in the optimization are members of a virtual collaborative team and are enabled to work synchronously and asynchronously. Their common and final decision will be the best process plan for specific part family that will be used in manufacturing. Therefore, expert heuristic knowledge will become a part of a production knowledge repository within the manufacturing cloud, also known as the integrated process planning knowledge base (Fig. 3).

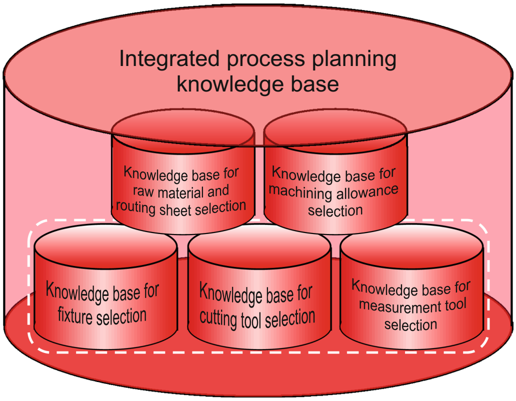

Fig. 3. Integrated process planning knowledge base.

The conceptual model shows the work, data and knowledge flows which represent links between services and applications. Using the dataflow diagram dataflows inside and outside the system can be graphically presented. This way shows the paths through which data groups flow as well as the elements between which the flow takes place. The elements of the graphical presentation of the dataflows consist of processes/services, data warehouses and objects. Figure 4 shows the main (context) dataflow diagram that is further decomposed so that each function, process or a service at one level is represented with a new dataflow diagram at the next level.

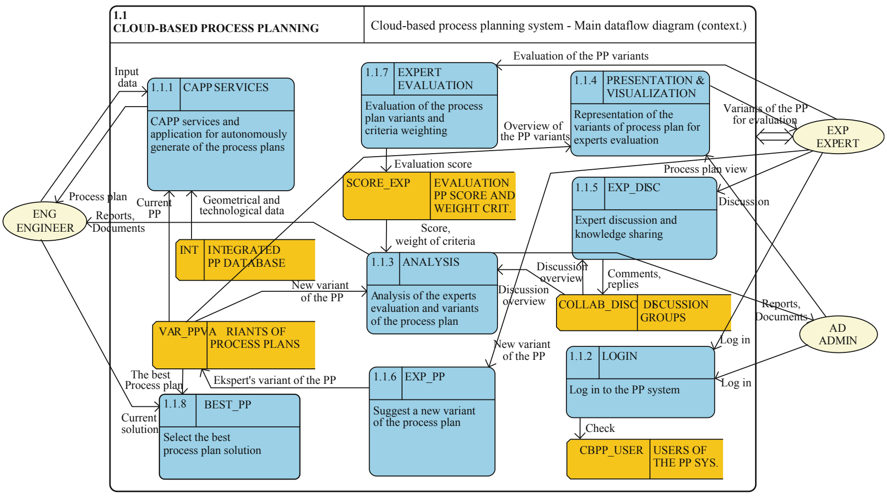

Fig. 4. Main dataflow diagram of the cloud-based process planning system.

All the data used by CAPP services in the cloud are stored in the integrated process planning database (Fig. 5). That is a set of logically divided sets of data for different stages of process planning and defining routing sheets.

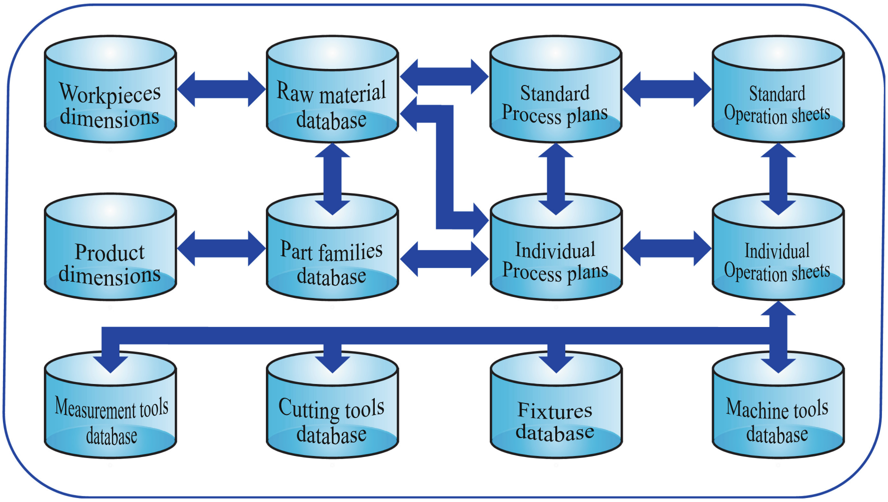

Fig. 5. Integrated process planning database.

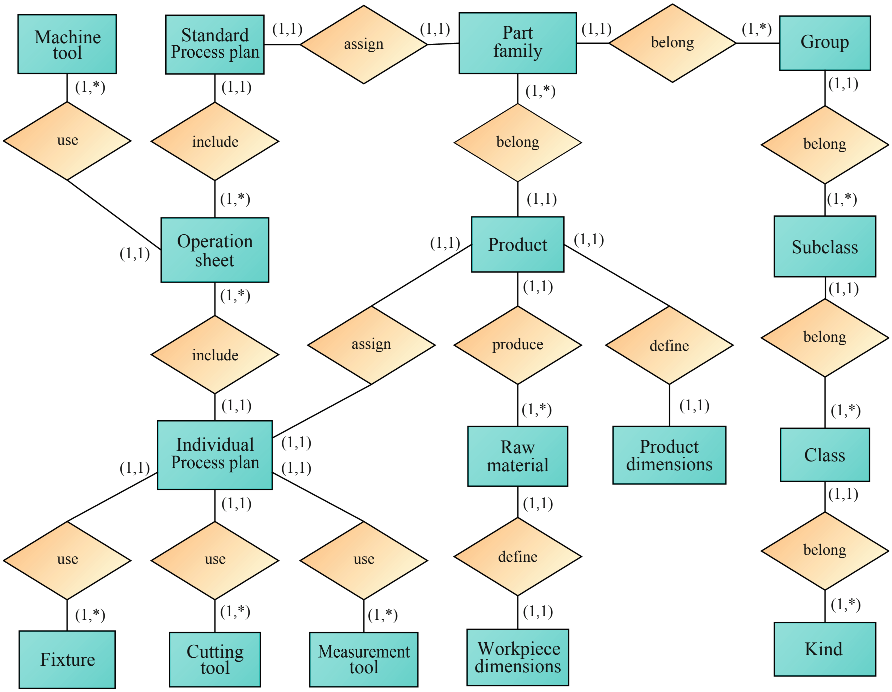

Fig. 6. Segment of the conceptual database schema.

Segment of the conceptual schema of the integrated database that includes entities and relations is shown in Fig. 6. This schema is a part of manufacturing data repository and defines only the entities related to process planning. However, the data repository within the cloud manufacturing structure includes much larger volume of data from all stages of product life cycle.

4 System Architecture and Verification

Figure 7 shows the global architecture of the Cloud-based collaborative system for process planning. Architecture includes a CAPP server, a collaborative server and a database server.

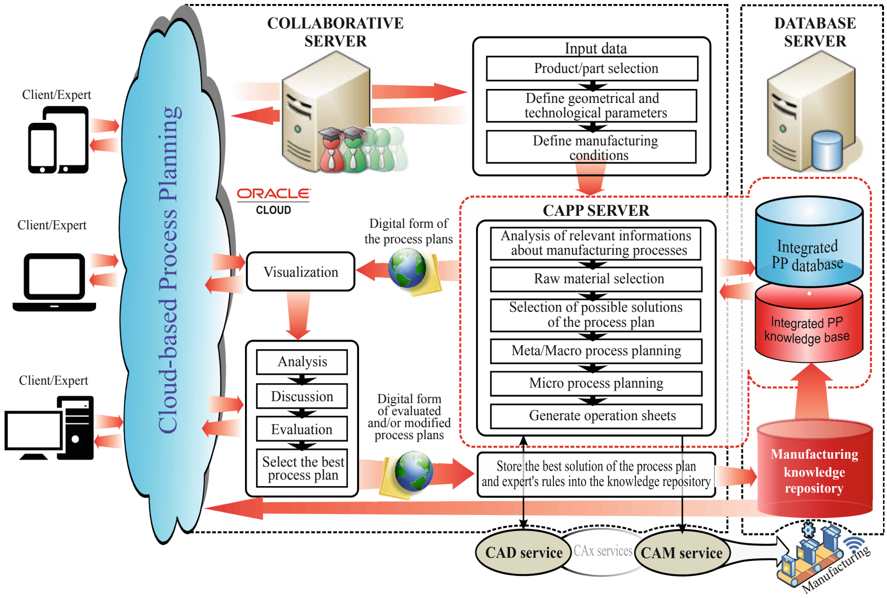

Fig. 7. Architecture of the cloud-based process planning system.

The use of a distributed CAPP server enables the automated generation of process plans on the basis of adequate input data. Functions of the CAPP server are based on the use of autonomous services and applications that are synchronized with the integrated knowledge base. Generated process plans are stored in the integrated database and the final evaluation is made by experts who in that way perform optimization of process plans.

Functions of the collaborative server are to exchange and share knowledge, offer users, primarily experts, insight into appropriate process plans as well as to process and store expert knowledge. With the help of the collaborative server, user requests are processed and forwarded to the database server. The task of these services is also a visualization as well as the realization of expert analysis, expert discussion and expert evaluation with the purpose of finding optimal process plan for observed conditions.

In order to address practical implementation of the proposed cloud-based collaborative system, the verification of the piston-cylinder assembly parts of the internal combustion engine was performed. The system involves the process plans for cylinder liners, ribbed cylinders and pistons. Previously, the part families manufactured within a real enterprise were defined in the system. By using the CAPP service, variants of process plans were generated at the meta and macro level. The expert team was formed and the proposed routing sheets were evaluated (Fig. 8).

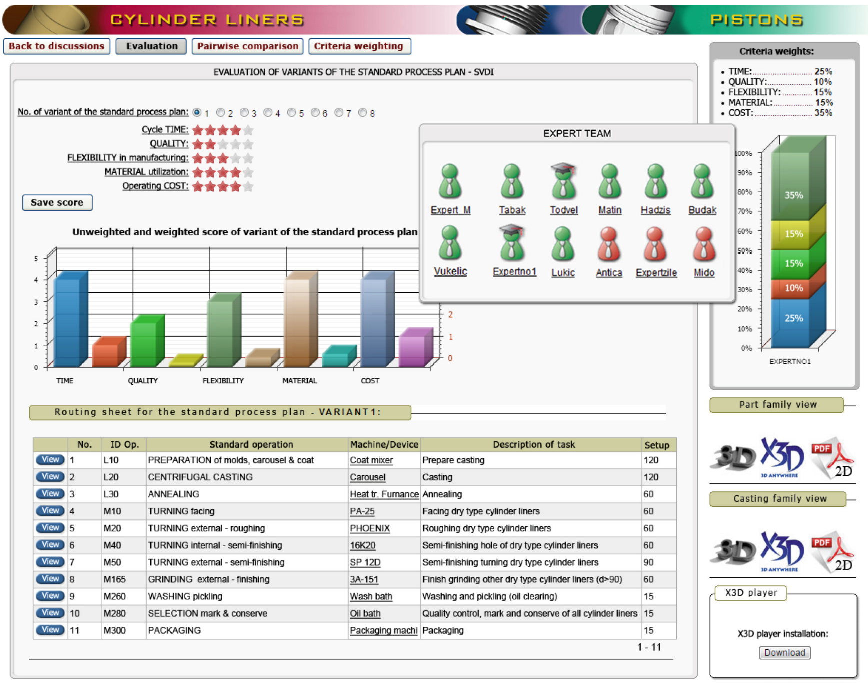

Fig. 8. Evaluation of the process plans routing sheet by the expert team.

Based on the evaluated criteria, the best solution was selected. This solution was further specified at the micro level where the focus was put on the definition of appropriate operation sheets (Fig. 9).

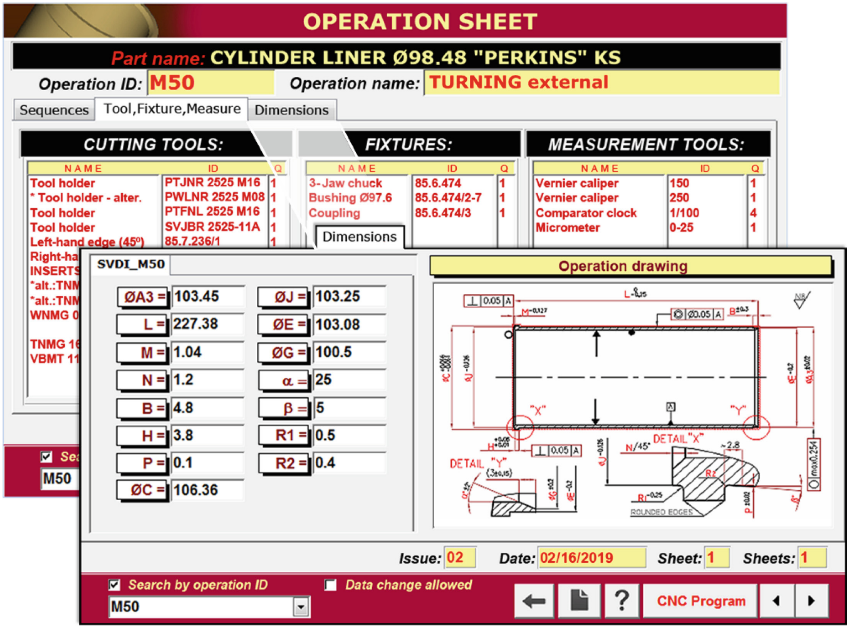

Fig. 9. A detailed operation sheet generated within the system.

5 Conclusion

Firstly, through the analysis of the given system, the significance of the use of cloud technologies in process planning and modern preparation of production were noticed. Thanks to novel technologies included in the Industry 4.0 framework, engineers and experts are able to create efficient virtual design environments that function globally within the manufacturing cloud.

The implementation of autonomous intelligent services enables the automated generation of process plans, but the influence of humans within the process planning at the conceptual level still remains very important. Therefore, the presented cloud-based system offers dislocated development teams and process planning experts to collaborate and exchange knowledge. Experts in a collaborative process can evaluate existing process plans, perform their modifications and suggest entirely new process plans. In addition, the system provides collection of expert heuristic knowledge within an appropriate manufacturing knowledge repository at the level of a distributed enterprise.

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Quality Education and Digitalization of the Economy

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Abstract. Education significantly affects the socio - economic sector of the national economy development. Currently, transformations and changes occurring in numerous spheres of human activity also imply the corresponding requirements for education quality and knowledge obtained while training specialists in various spheres of human activity. The digitalization of the economy makes both great demands and can provide great opportunities for the education system and educational organizations in respect of implementation of research competencies, intensive improvement of education quality, active strengthening of their positions and authority in the educational services markets. For effective implementation of digitalization of the economy and improving the quality of educational organizations activities in the innovation process, it is proposed to use a tool such as a three-level role-based management model - the "digital platform of an educational organization"; "digital competence centers"; "project working groups on improvement of education quality", built on the principles of ISO 9001: 2015 [1], and allowing constructively consolidate special competences while comprehensively solving the tasks of managing an educational organization and improving quality of education.

Keywords: Digital economics · Newest technologies and tools · Quality of education · Role - based management model · Digital platform

1 Introduction

In modern conditions, an important role in development of countries is played by digital economy, the main factor of which is information and knowledge, as well as the ways to access them. Digital economy is not a separate industry, but a virtual environment that complements our reality [2]. Today, digital economy has unconditional advantages over material commodity money exchange such as speed of goods delivery or almost instant delivery of services. Another advantage of digital economy is lower price. For example, an e-book is usually 25–55% cheaper than a printed version. One of the key advantages of digital economy over material exchanges is that electronic goods are practically inexhaustible and they can be found in electronic form while material goods are almost always limited in quantity and it is more difficult to get an access to them [3].

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The main material in modern conditions of digital economy development is human capital. It is a resource that allows not only ensuring development of the economy and improving the quality of life, but also serves as a basis for improving the state's competitiveness in the world economic system and its participation in all social and economic processes. It also determines the country's influence and reputation in the international space.

In the classical sense, "digital economy" is regarded as an activity, in which the key factors (means) of production are digital data and their use. They can significantly increase efficiency/productivity in various types of economic activity. Also, "digital economy" refers to the kind of economy that uses digital technologies and services [4]. Another definition reveals digital economy as "internet-based economic activity, including a system of economic property relations based on software and computing (digital) technologies for material, spiritual and virtual goods to meet human wants" [5].

At the same time, development of digital economy does not mean elimination or replacement of real economy. Digital economy itself does not produce material goods (food, clothing, equipment, motor fuel, etc.) but creates conditions for more efficient production of these goods, predetermines progress in all spheres of the national economy [6].

2 Education

The development of higher education underlies the accumulation of human and social capital and training of qualified personnel for successful development of digital economy. Modern education should be adapted to new realities of the society's strategic development. The new challenge is digital economy. It can be fulfilled with the help of innovative processes intensification, formation and accumulation of human and intellectual capital and formation of appropriate models and tools for management and development of educational organizations.

Researchers at various scientific schools show that currently, many traditional national education systems are in crisis and need to be adapted to changing conditions and development trends. Modern trends in the development of various national markets for educational services and the state of educational systems are characterized by many contradictions, such as:

- need to increase the volume and quality of education in accordance to the growth of digital economy. It is necessarily to be done to meet the specific needs of national economies in respect of innovative development and formation of a knowledge - based economy;
- limited governmental budgets and expenditures in the sphere of education, while having a reduction in social expenditures;
- need to preserve and increase education expenditures in objective conditions while optimizing public social expenditures, including education expenditures or looking for partners to ensure a stable level of investment in the education system, which can be achieved at the expense of private investors and households.

This situation indicates that the management systems of educational organizations require changes and adaptation in accordance with the trends that occur in the digitalization of the economy.

Modern conditions for the society's development characterize the processes affecting the macro-environment of the educational system operation in general, and educational organizations, in particular. Turbulence in the economic space, digitalization of economies, development of technology, demographic crisis, formation of a knowledge – based economy are the main trends in the development of macro-environment that have a great influence on the educational system. Under these conditions, the educational system is not only a social need, a condition for development and the most dynamically developing sector of the economy, it is also a criterion for the effective development of digital economy, which is based on improving the quality of education, efficiency of education based on adapting the educational system to modern development conditions.

3 Quality of Education

The tasks of improving the quality of education in conditions of industrial revolution accompanied by the digitization of the economy require new approaches, new solutions and tools. Such modern approaches to improving the organization of educational organizations performance include the toolbox, which consists of combining these approaches with the requirements of international and national standards, governmental policies, strategies and programs, and also has a real prospect for the further development of education.

A modern organization of higher education (hereinafter - the university) is a complex system, which involves not only training of highly qualified specialists but teachers' professional development, scientific and research activities and a number of other areas. It is impossible to manage the university in the direction of improving the educational services quality in the conditions of digital economy development without coordinating interests as well as interacting with all stakeholders and combining organizational, labor, information and financial resources of the state, business, scientific and educational organizations.

In terms of digitalization universities with basic, branch, information, administrative, scientific and research structural units (institutes, departments, laboratories, academic chairs) in their arsenal, have great opportunities to be diversely developed while participating in solving the urgent problems set for the industry. Intensity of this process can be enhanced by close connection of the educational organization with various scientific, industrial and educational spheres. In its turn, this contributes to improving the quality of higher education, carrying out scientific research, involving high-tech IT companies in the innovation process and introducing the latest technologies and tools into production.

4 Tools

Figure 7 In modern conditions, it is impossible to achieve high quality results without high-tech tools. A comprehensive indicator of activity quality depends largely on the level of information and digital technologies. It is the education that shares a bulk of the burden regarding development of new programs, competencies and methods of personnel training for new formation economy. Having a solid scientific base, resources and pedagogical practices higher education institutions will become the driving force in education [7].

According to the ISO 9000-2015 standard, quality is considered as "the degree of compliance of the object's integral features functionality with the requirements [1] reflected in the regulation documents in the field of education. Including goals, objectives and strategic development directions some active actions of educational organizations are predetermined by these documents. On the one hand, such documents impose strict requirements on educational institutions: For example, they can make changes in the way the universities are certified; the determine the way the definition is introduced in the educational program; determine the way the teaching staff can attend courses for their professional development in educational organizations. On the other hand, in order to adapt the educational process to a digital information environment, they can also provide financial support (grant support for staff and organizations in the field of education, prospective lines of development, new courses, student start-ups, postgraduate and master schools, as well as setting up venture funds with universities, business and state on partnership basis.

Formation of efficient digital role-based management model in an educational organization can be an effective tool for further digitalization development of the economy. It confirms that educational organizations tend to meet their commitments to high quality activities, processes and results.

Taking into account challenging opportunities of successfully solved tasks, as well as the risks accompanying this process, in these conditions the university needs to find the most optimal organizational solution to implement the development requirements to improve education quality in the "digital environment". Otherwise, the organizational structure of universities, which is poorly focused on the integrated development of digital technologies, can be a serious obstacle to overcome for further development. The best way to solve the problem of adaptation may be deepening and expanding the practice of role-based management model used in project activities to improve activities of the university and its quality of education.

It should be emphasized that the role model that is focused on the principles of ISO 9001-2015 standard helps to increase the interest of top management (implementation of the "leadership" principle) to involve talented scientists, post graduate students, specialists, teachers and applicants with creative potential, high competencies and business activity into the creative process of team work (implementation of the " interaction of workers" principle). Without fundamental changes in the organizational structure and possibly in some cases in the personnel schedule, the role model is able to create an effective mechanism for adapting the educational organization to the digital innovation environment (implementation of the "improvement" principle).

The three-level digital role model can be considered in the following way: at the strategic level, the University's Digital Platform (UDP) is established, the key task of which is to analyze the university's capabilities and needs of the digital economy in order to select the most prospective areas of development and establish Digital Competence Centers (DCC) on the basis of specialized departments. For this reason it is necessary to distribute the responsibility and allocate the resources with the purpose to solve current issues of the digital economy effectively (the principle of "decision-making based on facts").

At the same time the working body of strategic management of digitalization processes (UDP) should be in charge of forming a policy of digitalization, setting goals, approving plans, managing portfolio of projects, coordinating interaction of Digital Competence Centers (DCC) with internal and external participants of digitalization processes, coordinating financial activities from various sources, monitoring and lending methodological support to DCC at a consolidated level.

At the tactical level each DCC, focusing on its tasks solving profile, provides for the regulation of digital transformation processes, implements the management of individual projects in certain areas based on the process approach (implementation of the "process approach" principle), develops plans for specific activities, accompanies projects, initiates research, supports startups, organizes and manages project working groups. For this purpose, profile specialists from other departments of the university may be involved in the DCC on mutually beneficial basis.

The DCC, which have been previously formed, operate to solve specific project tasks at the operational level. Some project working groups are involved in solving specific project tasks while implementing the digitalization process, which has been launched. The structure of the project working groups (PWG) may include employees and students of the university, specialists of IT companies, representatives of partner enterprises. This partnership envisages close relationship with high-tech companies and industrial enterprises to enhance joint and business productive activities (implementation of the "relationship Management" principle).

It is not advisable to predict the quantity and quality of Digital Competence Centers, especially the quantity and quality of the Project Working Groups before making a decision on formation of the University's Digital Platform. The most prospective are the following centers of digital competence of the university:

1. Software Center may participate in the creation, testing and implementation of collective software development technologies for the implementation of digital economy technologies and infrastructure for capturing information on the occurrence of change and termination of rights to intellectual property results.
2. Center for Paperless Technologies can solve the problems of reducing paper media, effective document management. It also can develop proactive requirements for the form, content and size of regulatory documents, systematize and regulate them, as a rule, before digitizing a chaotic regulatory framework.
3. Center for the systematization of information systems can solve the architectural problems of information space of the scientific, educational and industrial environment. The threat of local IS inconsistencies (white spots in the information space, duplication of the same functions by different IP, contradictions in the user

interface) as well as the presence of IS with unproductively low demand. The number of these IS increases with the expansion of the information space, which shows that this process needs managing.

4. Center for the Digitalization of Curricula can digitize the normative bases of the components of educational programs including standards and government requirements, digitize educational material in such a way that it can be effectively reproduced with the latest multimedia computer tools.
5. Center for the Digitalization of Production Processes can introduce its developments and the latest information technologies into the production sphere. One can find an extensive field of practical implementation of plans for the digitalization of educational organizations (implementation of the principle “consumer orientation”).
6. Center for the Digitalization of Management Processes may resist ineffective traditional practice. Formalization (digitalization) of management processes will allow forming a transparent control environment in terms of the effectiveness of the entire corporate system of the organization.
7. Digital Project Office can support projects and start-ups for talented employees and students, scale pilot projects and the best practices. The main point of the project office can be the 4P information system (innovative proposal, pilot project, practical application, with free access to projects at productive stages and taking into account each participant’s contribution).
8. Center for the Advancement of Digital Qualifications can be the beginning of postgraduate and master schools. It can conduct teaching staff training courses for their professional development and certify production workers and students, form personalized educational programs on the subject of the digital economy.
9. Center of Communication with the Production can provide significant support to industry production structures in the process of plunging them in the information environment. It will ensure the creation of targeted digital sites which will bring together the interests of IT companies and industrial enterprises and will encourage development of digital technologies in production.
10. IT Contact Center for Companies can use its unique industry based competencies and close links with production structures to participate actively in collective and multilateral development of digital economy projects in order to transfer research results to application stage. However, other companies specializing in the field of information technology do not have such opportunities.
11. Contact Center with Foreign Partners may maintain business relations with foreign partners for development and application of digital technologies. It also allows creating effective partnerships and consortia with foreign centers and companies to transfer technology and knowledge. The list of Digital Competence Centers can vary widely and they also can be changed by university management depending on the basic and potential capabilities.

5 Conclusion

The development and use of the three-level digital role-based management model for an educational organization will allow one to benefit to a full extent from this format of organizing internal and external interactions in the field of information technologies. At the same time the model proposed will ensure active participation of the university in solving its own problems and issues regarding improvement of education quality and contribute to development of common system of economy digitalization. The conducted system of actions will directly affect the image, quality and economic stability of the educational organization.

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Correction to: Nano - Precision Systems for Overlay in Advanced Lithography Processes

P. Ajay and S. V. Sreenivasan

Correction to:
Chapter "Nano - Precision Systems for Overlay in Advanced Lithography Processes" in: L. Monostori et al. (Eds.): ***Proceedings of the 4th International Conference on the Industry 4.0 Model for Advanced Manufacturing*****, LNME,**
https://doi.org/10.1007/978-3-030-18180-2_1

The original version of this chapter starting on page 1 was revised. The incorrect legends of the figures 2, 3, 4, 5, 6 and 7 have been corrected.

The updated version of this chapter can be found at
https://doi.org/10.1007/978-3-030-18180-2_1

L. Monostori et al. (Eds.): AMP 2019, LNME, p. C1, 2019.
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Retraction Note to: The Use of Neutron Scattering in the Advancement of Additive Manufacturing

Ioan M. Ghiţiu, Cosmin M. Jalbă, Mădălina E. Florescu, and Alexandru Măgureanu

Retraction Note to:
Chapter "The Use of Neutron Scattering in the Advancement of Additive Manufacturing" in: L. Monostori et al. (Eds.): Proceedings of the 4th International Conference on the Industry 4.0 Model for Advanced Manufacturing, LNME, https://doi.org/10.1007/978-3-030-18180-2_15

The Editors have retracted this chapter. After publication, the authors were notified that they did not have ownership of the presented data. Additionally, the necessary consent and permissions were not obtained for Fig. 3 prior to publication.

Authors Ioan M. Ghiţiu, Cosmin M. Jalbă and Alexandru Măgureanu agree to this retraction. The publisher has not been able to obtain a current email address for author Mădălina E. Florescu.

The retracted version of this chapter can be found at https://doi.org/10.1007/978-3-030-18180-2_15

L. Monostori et al. (Eds.): AMP 2019, LNME, p. C2, 2022.
https://doi.org/10.1007/978-3-030-18180-2_19

Appendix 1

L. Monostori et al. (Eds.): AMP 2019, LNME, pp. 219–226, 2019.
https://doi.org/10.1007/978-3-030-18180-2

USA – EU – Far East - Serbia

4th Conference on the Industry 4.0 Model for Advanced Manufacturing

INDUSTRY 4.0 and Internet of Things for Manufacturing

3rd – 6th June, 2019, Belgrade, SERBIA

www.mefics.org

Main topic: **INDUSTRY 4.0 AND INTERNET OF THINGS FOR MANUFACTURING**

Objective: White paper on main topic !

After great success of three Conferences: USA-EU-Japan-Serbia Manufacturing Summit, Belgrade, **2016**, with main topic - Advanced Manufacturing Program – INDUSTRY 4.0 model for Serbia, of **2017** – New Conference with advanced topic – Smart and Intelligent Products, at last year **2018**, on topic – Industry 4.0 for SMEs .

The main objective of this conference will be to bring together leading world experts to discuss the challenges and opportunities of the new Industry 4.0 model of manufacturing. Our hope is that such an even will assist in the development and growth of new innovative manufacturing industries in Serbia, producing smart products with intelligent characteristics, and relying on modern, new manufacturing processes and systems.

Conference will be hosted by the Faculty of Mechanical Engineering of the University of Belgrade. Belgrade is the capital city of Serbia, located at the scenic confluence of two major European rivers, with a uniquely remarkable and turbulent history, and a vibrant cultural and entertainment scene. University of Belgrade has a long tradition of academic excellence, where great minds from Nikola Tesla to Milutin Milankovic held lectures or were faculty. Its engineering still remains exceptionally respected in Europe, with its alumni scattered in top universities around the globe. Faculty of Mechanical Engineering in Belgrade is the largest such school in south-eastern Europe and one of the largest in Europe. Exciting lab tours and ample networking opportunities with faculty and students from this school will be organized for conference attendees.

Invited papers/best practices and experiences presentation by world-wide and national experts.

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4th Conference on the Industry 4.0 Model for Advanced Manufacturing

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Relevant people who will include policy makers, company managers, as well as representatives of industrial associations and academia, discussed possible concrete policy measures and actions that could be launched in the coming period – 2020/2030, to leverage national efforts in this area to speed up the modernization of the Serbian industry, based on new generation of products – smart products.

Main topics of interest for this conference include, but are not limited to:

- Industry 4.0 model framework
- Design of smart and Intelligent products
- Innovative design and development of intelligent products
- Internet of Thinks for Manufacturing
- Big data challenges, data integrity, accuracy and authenticity
- Cloud Computing, cloud-based products, Cloud Manufacturing
- Cyber-Phisical Manufactruring
- Manufacturing automation in the Industry 4.0 model
- Manufacturing systems and enterprise models for Industry 4.0
- Advanced Manufacturing
- Engineering education for Industry 4.0
- What we can to do ?
- Roadmap for AM based on I4.0 model in Serbia.

Conference Organisation 2019:

Conference chair: Prof. Dr. Yoram Koren, The University of Michigan, Ann Arbor, Michigan, USA.

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4th Conference on the Industry 4.0 Model for Advanced Manufacturing

INDUSTRY 4.0 and Internet of Things for Manufacturing

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Conference co-chairs:

1. **Prof. Dr. Dragan Djurdjanovic**, Department of Mechanical Engineering, University of Texas, Austin, TX, USA.
2. **Prof. Dr. Vidosav Majstorovic**, Belgrade University, Faculty of Mechanical Engineering, Belgrade, Sebia;
3. **Prof. Dr. Jack Hu**, The University of Michigan, Ann Arbor, Michigan, USA. – for North America region;
4. **Prof. Dr. Jozsef Vancza**, (Chair of the CIRP STC-O), SZTAKI, TU Budapest, Budapest, Hungary – for EU region;
5. **Prof. Dr. Yashiro Takaya**, Osaka University, Osaka, Japan - for Far East region.

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4th Conference on the Industry 4.0 Model for Advanced Manufacturing

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4th Conference on the Industry 4.0 Model for Advanced Manufacturing

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3rd – 6th June, 2019, Belgrade, SERBIA

www.mefics.org

Panelists: ***Please see list of invited Speakers for AMP I4.0 2019 (www.mefics.org).***

Representative from Serbia (invited):

1. Prime Minister
2. Minister of Economy and Minister of Education, Science and Tehnological Development
3. President of Chamber of Commerce and Industry of Serbia / Belgrade
4. General Managers of top 20 Factories from Serbia and Software Companies
5. Representative from Belgrade, Novi Sad, Kragujevac and Nis University
6. Others (nacional/international relevant institutions-organizations from Serbia who are involved in main Workshop topic)

Draft Agenda of Conference:

Day 1: Lecturing and learning from the best examples in the world. Take global lessons.

Day 2: Case studies of HIGH TECH ADVANCED manufacturing in Serbia.

Day 3: Panel and presenting to government officials (hopefully 30-60 minutes with the prime minister).

Only invited papers by the leading world experts will be offered at the conference. Authors of all papers will also be invited to convert their papers into book chapters that will be **published by Springer** in a book based on this conference.

USA – EU – Far East - Serbia

4th Conference on the Industry 4.0 Model for Advanced Manufacturing

INDUSTRY 4.0 and Internet of Things for Manufacturing

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For full paper deadline according Springer template – 15th December 2018. For more information, please contact Prof. Dr. V. Majstorovic – vidosav.majstorovic@sbb.rs

Welcome on AM Program Conference, June 2019, Belgrade.

Proposed by

Prof. Dr. Y. Koren
Prof. Dr. D. Djurdjanovic
Prof. Dr. V. Majstorovic
Prof. Dr. R. Mitrovic

Avg. 2018, Belgrade.

Appendix 2

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Science Technology Park Belgrade

U.S. COMMERCIAL SERVICE
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The 3rd International Conference on the Industry 4.0 model for Advanced Manufacturing – AMP 2018

June 5th – 7th 2018, Belgrade, Serbia

DETAILED PROGRAM

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https://doi.org/10.1007/978-3-030-18180-2

The 3rd International Conference on the Industry 4.0 model for Advanced Manufacturing – AMP I4.0 2018

Detailed Program

www.mefics.org

June 5th– 7th 2018
Belgrade, Serbia

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Preface from the Conference Presidents

After the great successes of the "USA-EU-Japan-Serbia Manufacturing Summit", held in Belgrade, Serbia, on May 31st – June 2nd, 2016, and the "Industry 4.0 Conference – Smart and Intelligent Products", held in Belgrade, Serbia between June 7th and 9th 2017, it is our great pleasure to invite you to attend the:

2018 Conference on the Industry 4.0 Model for Advanced Manufacturing – AMP I4.0 2018 in Belgrade, Serbia, June 5th–7th, 2018

The main objective of this conference will be to bring together leading world experts to discuss the challenges and opportunities of the new Industry 4.0 model of manufacturing for SMEs. We are hoping that such an event will assist in the development and growth of the new and innovative manufacturing industries in Serbia, producing smart products with intelligent characteristics, while relying on modern, new manufacturing processes and systems.

Conference Organisation

Conference will be hosted by the Faculty of Mechanical Engineering of the University of Belgrade. Belgrade is the capital of Serbia, located at the scenic confluence of two major European rivers, with a uniquely remarkable and turbulent history, and a vibrant cultural and entertainment scene. University of Belgrade has a long tradition of academic excellence, where great minds from Nikola Tesla to Milutin Milanković held lectures or were faculty. Its engineering still remains exceptionally respected in Europe, with its alumni scattered in top universities around the globe. Faculty of Mechanical Engineering in Belgrade is the largest such school in South-Eastern Europe and one of the largest in Europe. Exciting lab tours and ample networking opportunities with faculty and students from this school will be organized for conference attendees.

Working part of the conference will consist of 3 days. During the first day, the Conference will consist of a series of presentations, lectures and panels on various aspects of manufacturing research and practices, offered by top international experts from industry and academy. During the second day of the Conference, conference participants and guests will have an opportunity to visit Fiat Chrysler Automobiles in Kragujevac. During the third day, the working group will focus on producing a manufacturing roadmap document that will be presented to the Government of the Republic of Serbia. The idea is that this roadmap document will be revisited and updated regularly after conferences of similar scale will be held in Belgrade every year.

Panelists: Invited experts and representatives from USA, EU, Far East, Australia and Serbia.

Common themes/main topics:

- Industry 4.0 model framework,
- Design of smart and Intelligent products,
- Innovative design and development of intelligent products,
- Big data challenges, data integrity, accuracy and authenticity,
- Cloud Computing, cloud-based products,
- Cyber-Phisical Manufactruring,
- Manufacturing automation in the Industry 4.0 model,
- Manufacturing systems and enterprise models for Industry 4.0,
- Advanced manufacturing,
- Engineering education for Industry 4.0.

Agenda of the Conference

Day 1: Lecturing and learning from the best in the world. Take global lessons. Hong-Kong is an example of launching advanced manufacturing (they did a workshop like this and are now acting upon recommendations from that Conference).
Day 2: Sessions in Fiat Chrysler Automobiles in Kragujevac.
Day 3: SWOT analysis and report writing (no need for everyone to be involved - this can be done by a few people, with strong knowledge of local environment). It is recommended to have involvement of government officials. Representative who supports our ideas, beliefs and understands the importance of HIGH TECH ADVANCED manufacturing.

The greatest value of this Conference refers to the **authors/participants from four continents.** Their high competence and high-quality floor of presentations have given the crucial contribution to the Conference.

Special gratitude goes to the **Honorary Presidents of the Conference, the members of International Program Committee and the Presidents of the Sessions/Panels**, for their personal contribution to the success of the Conference.

A large number of organizations, institutions and individuals contributed to the preparation of the Conference, for which we are especially grateful, so they deserve special acknowledgement: Belgrade Chamber of Commerce, Microelectronica S.A., Bucharest, Romania, CCI France Serbia, GIZ – Belgrade.

A special acknowledgment is extended to the **main patron –** Government of the Republic of Serbia, Ministry of Economy, Ministry of Education, Science and Tecnological Development, Belgrade, Serbia and **main sponsor** – AbelaPharm, Belgrade, which, by their contribution, enables a high level of arrangement and organisation of this Conference.

Welcome to the Conference of Industry 4.0 Model for Advanced Manufacturing – AMP I4.0 2018 in Belgrade, Serbia, June 5th–7th, 2018

Belgrade, April 20th 2018.

Prof. Dr. Jun Ni
Prof. Dr. Dragan Djurdjanović
Prof. Dr. Vidosav D. Majstorović
Prof. Dr. Radivoje Mitrović
Mihailo Vesović
Boris Popovski
Zorica Mihajlovic
Aleksandra Beslać
Gordana Danilović Grković

Acknowledgment

The University of Belgrade, Faculty of Mechanical Engineering, wishes to thank all authors, participants, institutions, associations, organizations and companies for their kind contributions and support in organizing **the *Third International Conference* "Advanced Manufacturing as the Foundation for a Successful Society – Challenges and Opportunities for Advanced-industrialization of Serbia/INDUSTRY 4.0 for SMEs"**. This Conference will be held between June 5th–7th, 2018 in Belgrade, Serbia.

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Conference Chair

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Prof. Dr. Vidosav Majstorović, Belgrade University, Faculty of Mechanical Engineering, Belgrade, Sebia;

Prof. Dr. Kornel Ehmann, Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA – for North America region;

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Prof. Dr. Yashiro Takaya, Osaka University, Osaka, Japan - for Far East region.

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Organized by

University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

AMP 2018 Conference Information

DATE: June 5^{th}–7^{th}, 2018.

VENUE: Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade/Hall 211 (second flor), Hall CeNT (first floor), Cocktails/Refreshments: Club CeNT (first floor), Registration desk Club CeNT (first floor).

Official Language

The official language of the Conference is English.

Web-Site and E-mail

For further information please visit web-site: www.mefics.org
E-mail: vidosav.majstorovic@sbb.rs or zjakovljevic@mas.bg.ac.rs

Important Dates

Early Registration:	Before May 15th, 2018.
Late Registration:	After May 15th, 2018.
Welcome Reception:	June 4^{th}, 2018.
Welcome Cocktail:	June 5^{th}, 2018.
Opening Session:	June 5^{th}, 2018.
Conference Dinner (informal):	June 6^{th}, 2018.
Closing Plenary Session:	June 7^{th}, 2018.
Farewell Cocktail:	June 7^{th}, 2018.

Conference Registration

You can register for the participation at the Conference on the following link: www.metfics.org

Conference Plan

Date: June 4th/ Monday	*Venue: Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade*

Registration desk: 17:00–18:30 Registration (CeNT – first floor)

19:30 *AMP Serbia 2018*/**Conference Welcome Reception at the Belgrade City Hall (informal dress code)**

Belgrade City Hall address: Dragoslava Jovanovića 2, Belgrade

Conference Plan

Date: June 5th/ Tuesday	*Venue: Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade*

Registration desk: 08:00–16:30 Registration (CeNT – first floor)

Time	Event
09:00–10:00	*Session **1: The Opening Ceremony and Plenary Presentation*** Opening addresses **Opening Plenary Presentation:** **MANUFUTURE VISIONS 2030, Prof. Dr. Francesco Jovane**, *Politechnico de Milano, Italy, Honorary CIRP Fellow, Former CIRP President, "Father" of Manufuture Program.* **A GLOBAL VIEW OF FUTURE OF PRODUCTION, Prof. Dr. Jun Ni,** *University of Michigan, Ann Arbor, USA* **Hall 211** (Second floor)
10:00–11:00	**Welcome Cocktail - Club 210** (Second floor)
11:00–13:00	*Session **2: Plenary Session/Panel 1*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 1** **Hall 211** (Second floor)
13:00–14:00	**Lunch break**
14:00–16:00	*Session **3: Plenary Session/Panel 2*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 2** **Hall 211** (Second floor)
16:00–16.30	**Coffee Break (CeNT – first floor)**

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Time	Event
16:30–18:30	*Session* ***4: Plenary Session/Panel 3*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 3** **Hall 211** (Second floor)

Conference Plan

Date: June 6th/Wednesday	***Venue: FCA Serbia, Kragujevac***

Time	Event
08:00	**CONFERENCE PARTICIPANTS GATHERING** **Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade** ***CeNT*** (First floor)
08:30–10:30	**Transfer to Kragujevac**
10:30–11:00	**Coffee break at Showroom**
11:00–11:30	**Welcome speech/Keynote address**
11:30–13:00	*Session* ***5: Plenary Session/Panel 4*** **Plenary Presentations:** **INDUSTRY 4.0 – PRACTICAL EXPERIENCES**
13:00–15:30	**Lunch** **Plant visit (groups)**
15:30	**Coffee break/refreshment before departure**
16:00–18:00	**Transfer to Belgrade**

20:00 *AMP Serbia 2018*/**Conference Dinner (informal dress code)**

Conference Plan

Date: June 7th/ Thursday	**Venue:** ***Science-technology park Beograde, Veljka Dugoševića 54, Belgrade***

Registration desk: 08:00–11:30 Registration **STP Conference center**

Time	Event
09:00–11:00	*Session* ***6: Plenary Session/Panel 5*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 4** **STP Conference center**
11:00–11:30	**Coffee Break (CeNT – first floor)**
11:30–13:30	*Session* ***7: Plenary Session*** **Round Table Discussion:** **KEY MESSAGES FOR SERBIAN ROADMAP TO INDUSTRY 4.0** **STP Conference center**
13:30–14:00	**Tour of Science-technology park Belgrade and photo opportunity**
14:00–14:30	**Farewell cocktail at STP Belgrade**

Conference Program

Date: June 4th/ Monday	***Venue: Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade***

Registration desk: 17:00–18:30 Registration (CeNT – first floor)

19:30 *AMP Serbia 2018*/**Conference Welcome Reception at the Belgrade City Hall (informal dress code)**

Belgrade City Hall address: Dragoslava Jovanovića 2, Belgrade

Conference Program

Date: June 5th/ Tuesday	***Venue: Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade***

Registration desk: 08:00–16:30 Registration (CeNT – first floor).

Time	Event
09:00–10:00	**Hall 211** (Second floor) *Session* ***1: The Opening Ceremony and Plenary Presentation*** **Conference/Session Speaker – Mrs. Gordana Stijačić, TV Journalist RTS** **Opening addresses:** • University of Belgrade, Faculty of Mechanical Engineering, **Prof. Dr. R. Mitrović, Dean**

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Time	Event
	• Main Sponsor-Abela Pharm, **MSc. D. J. Korčok, General Manager** • Government of Serbia, **(tbd) - Opening Conference** **Opening Plenary Presentations:** **MANUFUTURE VISIONS 2030, Prof. Dr. Francesco Jovane**, *Politechnico de Milano, Italy, Honorary CIRP Fellow, Former CIRP President, "Father" of Manufuture Program* **A GLOBAL VIEW OF FUTURE OF PRODUCTION, Prof. Dr. Jun Ni,** *University of Michigan, Ann Arbor, USA*
10:00–11:00	**Welcome Cocktail – Club 210** (Second floor)
11:00–13:00	**Hall 211** (Second floor) *Session **2: Plenary Session/Panel 1*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 1** **Session Chairmen:** **Prof. Dr. Lihui Wang,** KTH Stockholm, Sweden **Prof. Dr. Joseph Beaman,** University of Texas at Austin, USA **Prof. Dr. Jozsef Vancza,** SZTAKI, TU Budapest, Hungary **Prof. Dr. Wilfried Sihn,** TU Vienna, Institute of Managemet Science, Vienna, Austria **Prof. Dr. Erhan Budak,** Sabanci University, Istanbul, Turkey **Keynote Speakers:** 1.**Prof. Dr. Lihui Wang,** KTH Stockholm, Sweden; **CLOUD ENABLED CPS AND BIG DATA IN MANUFACTURING** 2.**Prof. Dr. Joseph Beaman,** University of Texas at Austin, USA **AN AUTOMATED LASER CONTROL TECHNIQUE FOR IMPROVING POWDER BED TEMPERATURE UNIFORMITY IN SELECTIVE LASER SINTERING** 3.**Prof. Dr. Jozsef Vancza,** SZTAKI, TU Budapest, Hungary **AUTOMATED PROCESS PLANNING FOR HUMAN-ROBOT ASSEMBLY** 4.**Prof. Dr. Wilfried Sihn,** TU Vienna, Institute of Managemet Science, Vienna, Austria **PRACTICAL EXAMPLES OF INDUSTRIE 4.0** 5.**Prof. Dr. Erhan Budak,** Sabanci University, Istanbul, Turkey **MACHINING PROCESS IMPROVEMENT THROUGH PROCESS TWINS**
13:00–14:00	**Lunch break**
14:00–16:00	**Hall 211** (Second floor) *Session **3: Plenary Session/Panel 2*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 2** **Session Chairmen:** **Prof. Dr. Lin Ma,** Queensland University of Technology, Brisbane, Australia **Prof. Dr. Luigi Maria Galantucci,** Politecnico di Bari, Italy **Prof. Dr. Marco Macchi,** Politecnico di Milano, Italy

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Time	Event
	Prof. Dr. Numan Durakbasa, TU Vienna, Manufacturing Metrology Lab., Vienna, Austria **Prof. Dr. Joseph Mathew,** Asset Institute, Australia **Dr. Hideaki Hohnoki,** COHO Consulting, LLC., New Technology Association of Japan, Chiba, Japan **Keynote Speakers:** 1.**Prof. Dr. Joseph Mathew,** Asset Institute, Australia **EMERGING TRENDS IN MANAGING COMPLEX ASSETS** 2.**Prof. Dr. Marco Macchi**, Politecnico di Milano, Italy **INTELLIGENT ASSET LIFECYCLE MANAGEMENT THROUGH INDUSTRY 4.0** 3.**Prof. Dr. Lin Ma,** Queensland University of Technology, Brisbane, Australia **OPPORTUNISTIC MAINTENANCE FOR WIND TURBINES CONSIDERING EXTERNAL OPPORTUNITIES – A CASE STUDY** 4.**Prof. Dr. Luigi Maria Galantucci,** Politecnico di Bari, Italy **PHOTOGRAMMETRY APPLIED TO SMALL AND MICRO SCALED OBJECTS: A REVIEW** 5.**Prof. Dr. Numan Durakbasa,** TU Vienna, Manufacturing Metrology Lab., Vienna, Austria **INTELLIGENT INTEGRATED MANAGEMENT AND ADVANCED METROLOGY FOR QUALITY TOWARD THE FACTORY OF THE FUTURE** 6.**Dr. Hideaki Hohnoki,** COHO Consulting, LLC., New Technology Association of Japan, Chiba, Japan **RECENT STREAMS OF DIGITAL MANUFACTURING, ITS EMERGING TREND AND FUTURE DIRECTIONS FOR SME IN JAPAN**
16:00–16:30	**Coffee Break (CeNT – first floor)**
16:30–18:30	**Hall 211** (Second floor) *Session **4: Plenary Session/Panel 3*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 3** **Session Chairmen:** **Prof. Dr. Emanuele Carpanzano,** Institute of Systems and Technologies for Sustainable Production, Manno, Switzerland **Prof. Dr. Dimitris Mourtzis,** University of Patras, Greece **Dr. Augusta Maria Paci,** National Research Council of Italy (CNR), Rome, Italy **Prof. Dr. Giovanni Moroni,** Politecnico di Milano, Italy **Prof. Dr. Jerzy Jedrzejewski,** Wroclaw University of Science and Technology, Poland **Bertil Wanner,** KTH Royal Institute of Technology, Stockholm, Sweden **Keynote Speakers:** 1.**Prof. Dr. Emanuele Carpanzano,** Institute of Systems and Technologies for Sustainable Production, Manno, Switzerland **CONNECTING HUMANS TO THE LOOP OF DIGITIZED FACTORIES' AUTOMATION SYSTEMS**

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Time	Event
	2.**Prof. Dr. Dimitris Mourtzis,** University of Patras, Greece **DEVELOPMENT OF SKILLS AND COMPETENCES IN MANUFACTURING TOWARDS EDUCATION 4.0: A TEACHING FACTORY APPROACH** 3.**Dr. Augusta Maria Paci,** National Research Council of Italy (CNR), Rome, Italy **STRATEGIC NOTE FOR A DIGITAL INNOVATION POLICY** 4.**Prof. Dr. Giovanni Moroni,** Politecnico di Milano, Italy **GEOMETRIC INSPECTION PLANNING AS A KEY ELEMENT IN INDUSTRY 4.0** 5.**Prof. Dr. Jerzy Jedrzejewski,** Wroclaw University of Science and Technology, Poland **MACHINE TOOL INTELLIGENCE DESIGN AND DEVELOPMENT CONCEPTS** 6.**Bertil Wanner,** KTH Royal Institute of Technology, Stockholm, Sweden **HYBRID MACHINING: AN INDUSTRIAL CASE-STUDY COMPARING INCONEL718 REAMING AND DRILLING WITH ABRASIVE WATERJET TECHNOLOGY**

Conference Program

Date: June 6th/Wednesday	***Venue: FCA Serbia, Kragujevac***

Time	Event
08:00	**CONFERENCE PARTICIPANTS GATHERING** **Faculty of Mechanical Engineering, Kraljice Marije 16, Belgrade** ***CeNT*** (First floor)
08:30–10:30	**Transfer to Kragujevac**
10:30–11:00	**Coffee break at Showroom**
11:00–11:30	**Welcome speech/Keynote address** **Alessio Leonardi, Plant Director, FCA Serbia** **Branimir Stojanović, State Secretary, Ministry of Economy, Belgrade, Serbia** **HE US Ambassador to the Republic of Serbia**
11:30–13:00	*Session* ***5: Plenary Session/Panel 4*** **Plenary Presentations:** **INDUSTRY 4.0 – PRACTICAL EXPERIENCES** **“Digital Manufacturing: from the FCA journey to a general framework” – Mauro Bosio, Global Program Manager for Digital Manufacturing Initiatives, FCA Group**

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Time	Event
	"Can making evolution through digital revolution" – Branislav Savić, Plant Manager, Ball Beverage Packaging Europe **"Digital transformation through automatization" – Stefan Lazarević, External Affairs Director, NCR Serbia&EMEA**
13:00–15:30	**Lunch** **Plant visit (groups)**
15:30	**Coffee break/refreshment before departure**
16:00–18:00	**Transfer to Belgrade**

20:00 *AMP Serbia 2018*/**Conference Dinner (informal dress code)**

Conference Program

Date: June 7th/ Thursday	*Venue: Science-technology park Beograde, Veljka Dugoševića 54, Belgrade*

Registration desk: 08:00–16:30 Registration (Conference center).

Time	Event
09:00–11:00	**STP Conference center, Veljka Dugoševića 54, Zvezdara, Beograd** *Session **6: Plenary Session/Panel 5*** **Plenary Presentations:** **INDUSTRY 4.0 – WORLD-WIDE APPROACHES, Part 4** **Welcome speech: Gordana Danilović Grković,** Acting Director, Science-technology park Belgrade. **Session Chairmen:** **Prof. Dr. Dragan Đuričin,** University of Belgrade – Faculty of Economics, Serbia **Prof. Dr. Peter Monka,** TU Presov, Presov, Slovakia **Prof. Dr. George Constantin,** Machine and Production Systems,TU Bucharest, Bucharest, Romania **Prof. Dr. Davorin Kramar,** FS, Ljubljana, Ljubljana, Slovenia **Prof. Dr. Dragan Đurđanović,** The University of Texas at Austin, Austin, USA **Dr. Liviu Jalba,** Microelectronica, Bucharest, Romania **Keynote Speakers:** 1.**Prof. Dr. Dragan Đuričin,** University of Belgrade– Faculty of Economics, Serbia **INDUSTRY 4.0 AND PARADIGM CHANGE IN ECONOMICS AND BUSINESS MANAGEMENT** 2.**Prof. Dr. Peter Monka,** TU Presov, Presov, Slovakia **FUNDAMENTAL REQUIREMENTS FOR CAPP SOFTWARE DESIGN FOCUSING ON INDUSTRY 4.0 SPECIFIC FEATURES**

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Time	Event
	3.**Prof. Dr. George Constantin,** Machine and Production Systems,TU Bucharest, Bucharest, Romania **DYNAMIC DEFINITION OF MACHINE TOOL FEED DRIVE MODELS IN ADVANCED MACHINE TOOLS** 4.**Prof. Dr. Davorin Kramar,** FS, Ljubljana, Ljubljana, Slovenia **HYBRID MACHINING PROCESSES** 5.**Prof. Dr. Dragan Đurđanović,** The University of Texas at Austin, Austin, USA **GAUSSIAN PROCESS REGRESSION FOR VIRTUAL METROLOGY OF MICROCHIP QUALITY AND THE RESULTING SELECTIVE SAMPLING SCHEME** 6.**Dr. Liviu Jalba,** Microelectronica, Bucharest, Romania **INNOVATION: THE ENGINEERING SCIENCE TOOL FOR SUSTAINABILITY** 7.**Prof. Dr. Bojan Lalić,** Faculty of Technical Science, University at Novi Sad, Novi Sad **STRATEGIC OUTSOURCING OF SMES IN THE CONTEXT OF INDUSTRY 4.0: EVIDENCE FROM SERBIA** 8.**Prof. Dr. Dragan Aleksandrić,** University of Belgrade – Faculty of Mechanical Engineering, Serbia **ARTIFICIAL NEURAL NETWORKS IN ADVANCED THERMOSET MATRIX COMPOSITE MANUFACTURING** 9.**Prof. Dr. Živana Jakovljević,** University of Belgrade – Faculty of Mechanical Engineering, Serbia **INTELLIGENT SENSING SYSTEMS – STATUS OF RESEARCH AT KAPROM** 10.**Prof. Dr. Vidosav Majstorović,** University of Belgrade – Faculty of Mechanical Engineering, Serbia **CYBER-PHYSICAL MANUFACTURING IN CONTEXT OF INDUSTRY 4.0 MODEL**
11:00–11:30	**Coffee Break (Conference center)**
11:30–13:30	**STP Conference center** *Session 7: **Plenary Session*** **Round Table Discussion:** **KEY MESSAGES FOR SERBIAN ROADMAP TO INDUSTRY 4.0** **Moderator:** **Ms. Vida Džagić,** Chamber of Commerce and Industry of Serbia **Panelists:** **Prof. Dr. Vidosav Majstorović,** University of Belgrade – Faculty of Mechanical Engineering, Serbia **Mihailo Vesović,** Chamber of Commerce and Industry of Serbia **Prof. Dr. Viktor Nedović (invited),** Assistant Ministar, Ministry of Education, Science and Technological Development, Belgrade, Serbia **Katarina Obradović - Jovanović (invited),** Assistant Ministar, Ministry of Economy, Belgrade, Serbia **Bojan Lalić,** Assistant Ministar, Ministry of Innovation and technological development, Belgrade, Serbia **Ilija Jaraković,** Servoteh, Belgrade

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Time	Event
	Srđan Živkov, Solfins, Belgrade
13:30–14:00	**Tour of Science-technology park Belgrade and photo opportunity**
14:00–14:30	**Farewell cocktail at STP Belgrade**

Welcome to Belgrade on AMP I4.0 Conference 2018!

Author Index

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