Design and management of manufacturing systems for production quality

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1. Introduction, motivation and objectives

Product quality and delivery reliability are key factors for success in the manufacturing industry. Moreover, the increasing emphasis on sustainable production requires maintaining the resource efficiency and effectiveness along the product, process and production system life cycle [274]. Quality, production planning and maintenance are fundamental functions for achieving these goals. They have been widely analysed in the literature over the past several decades. The production planning field has developed methods for reducing work in progress (WIP), while meeting desired production rate levels. The Statistical Quality Control (SQC) field has introduced optimized tools for monitoring the behaviour of processes to achieve the desired product quality. The Maintenance Management field has derived policies for preserving the efficiency of degrading resources over time by offering pro-active and predictive capabilities [112]. Traditionally, all these fields have been treated by scientists and industrialists almost in isolation. Yet it is clear that equipment availability, product quality and system productivity are strongly interrelated. As a matter of fact, 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.

For example, low WIP improves the ability of identifying quality problems in the system at an earlier stage but at the same time makes maintenance actions more critical to the system. More inspections make it possible to better assess the degradation state of the resources yet also increase the system lead-time. Frequent maintenance of resources tends to improve part quality, but reduces the operational time of the machines in the system, which affects the overall production.

It is clear, then, that the mutual relations among quality, production planning and maintenance control should not be underestimated while configuring and managing the manufacturing system as a whole. Important practical questions, such as “Which is the expected system effective production rate if the time to preventive maintenance of one machine is reduced?” and “Which is the effect of increasing the inspection frequency of one product feature on the overall production yield of the system?” remain unsolved. This lack of understanding results in sub-performing unbalanced systemic solutions that tend to privilege one of the aspects while penalizing the overall manufacturing system efficiency.

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The key questions that this paper addresses can be formulated as follows: "Which are the main industrial problems related to the achievement of *production quality* targets?" "Which tools can support the joint consideration of quality, production logistics and resource maintenance in manufacturing system design and operation?" and "Which are the main technical achievements and insights brought by the use of these tools in industry?"

Recently, several production paradigms have been proposed that are strongly related to and have an impact on *production quality*. These paradigms have considerably reshaped the boundaries within which the three aspects interact. Reconfigurability [134], flexibility [278], changeability [309] and co-evolution [280] stress the importance of aiming at a strong coordination between the dynamics of the system life cycle and the dynamics of the product and process life cycles. Takata et al. [274] introduce the notion of "life cycle maintenance" to be in phase with such requirements. Yet, if a system evolves with faster and faster dynamics, new challenges arise for *production quality*. In particular, the long-term performance of the system becomes less important, while *production quality* performance during system ramp-up assumes fundamental relevance [86]. Moreover, small-lot production becomes more frequent than mass production. Therefore, a new *production quality* paradigm is needed for mass customization [60] and mass personalization [282], for open architecture products [135] and for high product variety manufacturing [79]. Available concepts and programmes, such as Six-Sigma, Just In Time, Continuous Improvement, Total Quality Management, Toyota Production System and World Class Manufacturing, are not designed for such dynamically changing contexts. A new integrated concept of *production quality* needs to be developed to meet this aim.

Another industrial trend that has been recently investigated and framed [81] is the increase of the *complexity* of manufacturing systems, in terms of hardware, software and management rules. Complexity strongly undermines the achievement of the desired *production quality* performance. Complex systems are typically characterized by alternative process plans [208], multiple parallel resources, part type dependent routings, and late variant differentiation [102]. The resulting challenge lies in the additional burden placed on diagnosis, root-cause analysis, and error budgeting.

In response to these innovative aspects of manufacturing systems, multiple in-line technologies for data gathering and performance monitoring have emerged. A considerable amount of data is typically made available on modern shop floors by multi-sensor technologies [304]. However, most of the time this information is treated only locally and is not spread among different company functions nor among partners within a production network. For example, it is not infrequent for a quality management department to ignore the reliability statistics of the machines on the shop floor [152]. This behaviour makes it hard to correlate disruptive phenomena taking place at shop floor level with the product quality and to gather insights in the behaviour of the system as a whole. It would be necessary to move from isolated engineering practices to more integrated ones such as advocated by System Engineering initiative [105]. Therefore, these data are not fully exploited and translated into a business competitive advantage for the company.

The impact of complexity on *production quality* is even more significant when considering the production network level. For example, except for the period of the deep economic crisis 2009–2010, the number of recalls has been constantly increasing also due the lack of inter-organizational quality systems [61]. Product recalls indicate that manufacturing companies are particularly vulnerable to ensure quality when they source via a global supply chain with poor visibility [164]. Global automotive warranties are estimated at USD 40 billion per year, i.e. a 3–5% loss in sales [89]. Low priced production often leads to quality problems, and outsourcing leads to a shift in knowledge concerning techniques and processes. Thus, technical failures are more likely to occur due to communication failures among the different parties engaged in the supply chain and to missing definitions for technical interfaces. Since most of the flaws that eventually cause failures are introduced in the production phase, early failure analysis can avert high recall costs and loss of image.

Legislation that limits industrial waste production, increases target product recyclability rates and places the manufacturer at the centre of the end-of-life treatment process through the Extended Product Responsibility (EPR) principle is an additional driver that strongly influences the *production quality* paradigm by penalizing the generation of defects and waste in manufacturing. Moreover, sustainability issues related to energy efficient production [76] have to be taken into account while designing and operating the system as a whole for a desired output *production quality*-related performance target.

To promote intense and coordinated research activities aimed at developing innovative technological and methodological solutions to the aforementioned challenges, industrial organization and funding bodies have recently launched several actions. For example, at European level, the Factories of the Future (FoF) Public Private Partnership has included the topic "Zero Defect Manufacturing" as a priority in its FoF 2020 Roadmap. Moreover, under the FP7 call on "Zero Defect Manufacturing" four projects have been funded boosting cross-sectorial research and aiming at achieving the largest possible target impact for the developed technologies. These activities share the objective of supporting the development of a knowledge-based manufacturing and quality control culture within the EU. Similar activities have also been promoted in the USA within the Advanced Manufacturing Partnership (AMP).

This paper provides an overview and a framework of the industrial practices, scientific methodologies, and enabling technologies to profitably manage the *production quality* targets in advanced manufacturing industries. It also identifies key open research and practical issues that need to be addressed by the research community. The paper is structured as follows: the next paragraph presents a set of real cases that demonstrate the industrial motivation to the problem. Section 2 proposes a new system dynamics model for highlighting the relevant quality, maintenance and production logistics interactions. Sections 3 and 4 discuss, respectively, the state-of-the art methods and tools and the enabling technologies supporting the *production quality* paradigm. Finally, Section 5 describes the most promising future research topics in this area.

1.1. Industrial motivation

In order to highlight the main practical implications related to the interactions among quality, production logistics and maintenance and to point out how these challenges are currently tackled by companies, a comprehensive set of real industrial examples have been collected. These case studies have been gathered by analysing existing publications, running industrial projects, both publically and privately funded, and by gathering authors expertise. They include both traditional production sectors such as the automotive and electronics sector and emerging sectors of certain interest for the worldwide manufacturing context, including the production of medical devices as well as the green energy production industry. Moreover, they include a reasonably wide spectrum of manufacturing processes, such as machining, assembly and forming, at both macro and micro scales, and on both metallic and non-metallic workpieces.

The industrial cases support the following considerations:

- The interaction among quality, production logistics and maintenance aspects is a complex issue to be managed.
- This problem involves different companies and different departments within each company. The coordination and cooperation among them in achieving a right balance between these conflicting goals is seen as a key issue for success.
- Depending on the specific product and market context, companies tend to prioritize one of the aspects. Finding the right balance boosts the long-term company profitability.

- The increasing complexity of products, processes, and systems is one of the major challenges for *production quality*.
- Emerging ICT and inspection technologies as well as cooperation based on risk-sharing contracts are seen as fundamental enablers to meet *production quality* targets.
- Emerging production paradigms, such as reconfigurability and flexibility, pose new challenges for *production quality*.
- Industrial companies are experiencing a trend towards increased investments in their ability to profitably drive *production quality* trade-offs.

1.2. *Analysis of real cases*

The first example refers to the production of batteries for electric vehicles in the electric mobility industry. The e-mobility industry is expected to reach its target production by 2020.

As demand is still limited, manufacturers are putting great emphasis on quality improvement. Dominating technologies to be adopted for the production and inspection of batteries are still lacking [143]. Error propagation is the major cause for defects. Different quality tests take place such as electric test, stacking test, leaking test, and temperature tests. However, not all the root causes for defects are known since the quality management is still in a learning phase. Therefore, a specific procedure is adopted to manage the ramp-up during the introduction of new technologies in the plant. The quality planning process starts with the identification of critical product characteristics to be used to determine the product quality level. First, new production and inspection technologies are temporarily integrated off-line in the factory to avoid interference with the cycle time of the main line during the ramp-up phase (Fig. 1). In this phase, technology improvement practices are implemented and knowledge of the process behaviour is gathered. Once the process is made stable, the technologies are developed as on-line integrated operations. In this context (German BMBF Project "ProBat" [149]), the main relevant questions are "where to integrate the measurement, with which technologies and which strategies? What are the consequences of these choices on the quality and production logistics performance?" Only by integrating quality management in factory planning can these implications be captured.

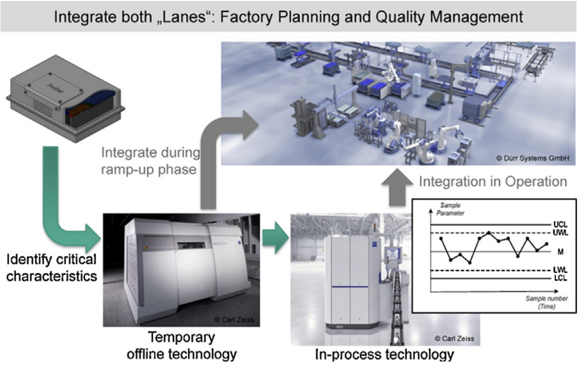

Fig. 1. Procedure adopted by the company for managing the ramp-up of new technologies in a plant assembling car batteries.

The needs for in-line inspection in multi-stage manufacturing processes are also addressed in the following real-life example related to the production of electrical engines for the automotive industry at Robert Bosch GmbH (Fig. 2(a)). This real case is one of the demonstrators in the *MuProD* FP7 EU-funded project [200]. The proposed example is specifically related to the assembly line of electrical drives. This is a multi-stage system typically involving 20–30 process stages. Three main flows are found, the first dedicated to the assembly of the magnetic rotor, the second related to the assembly of the stator and the last related to the coupling of stator and rotor to produce the complete engine.


(a) (b)

Fig. 2. Electric drive produced at Robert Bosch GmbH (a) and Planet Carrier produced at Gamesa (b).

State-of-the-art inspection technologies facilitate assessing the quality of the engine by end-of-line testing of several product features, the most important being the magnetic torque of the rotor. However, in order to better understand the causes for deviations and to allow process control and improvement at early process stages, innovative inspection technologies need to be developed and distributed in the upstream rotor assembly process stages. The rotor is composed of a set of magnets assembled on the surface of multiple laminated stacks. These stacks are then axially assembled to produce the rotor. The number of assembled stacks determines the specific product type.

Knowing the effect of stack magnetization on the rotor magnetic intensity and, ultimately, on the final engine torque is a major issue in this manufacturing process. This would allow characterizing the correlation between production stages, consequently controlling the upstream stack assembly strategy to obtain the desired engine quality levels. Another challenge is to determine ad-hoc assembly strategies that can prevent the propagation of defects from the early stages to the final assembly stage. In MuProD, one of the considered options exploits the quality correlation between the stage where the stacks are magnetized and the stage where the rotor is assembled. A defective stack can be turned into a good quality rotor if the assembly angle is suitably compensated at the downstream stage.

The second considered solution is to integrate selective and adaptive assembly strategies in the rotor assembly system [126]. Selective assembly entails on-line part inspection, clustering parts into bins according to specific key quality characteristic values and subsequent matching only from coupled classes according to some predetermined matching criterion. This approach makes possible to change a product quality problem into a system design and operation problem. In the case of rotor assembly the introduction of selective assembly can increase *production quality* significantly by reducing scrap and incrementing the yield of the system.

The third example refers to the manufacturing of small-lot large parts (i.e. planet carriers) for windmill gear boxes in the wind power sector at Gamesa (Fig. 2(b)) [200]. The continuously increasing demand for energy is leading to the manufacturing of eolic towers that are able to produce more power. These towers demand larger components and require new and lighter materials for easier assembly. The machining of components such as the planet carrier is critical, since very small product features have to be machined at very tight tolerance requirements [93] (normally tenth of microns on dimensional and geometrical features) on very large parts (outer diameters up to 2500 mm, weight up to 7000 kg). The production system adopted in the reference case is composed of parallel machining centres dedicated to roughing and finishing operations. The causes of defects are related to the input casted material, part deformation due to fixturing, tool wear, vibrations, etc. In order to achieve such highly demanding manufacturing goals, the company makes use of a hybrid inspection procedure. The first part of the lot is extensively measured at the CMM for compensating possible deteriorations by machining parameter adjustment. Then, the lot production is started. For each processed feature, extensive in-process part verification is carried out to avoid the generation of any possible type of defect, due to the high value of casting parts. However, these continuous machining, measuring and adjustment loops interfere with the cycle time and the productivity of the plant. Therefore, this is an example where the solution adopted by the company is strongly polarized on quality performance, with negative consequences for production logistics performance. This approach is also evident in other sectors, such as the production of critical mechanical components, i.e. engines, in the aeronautic industry.

A fourth example is related to the production of customized micro-intravascular catheters as high value medical products for the ageing society in the medical technology sector, as at ENKI S.r.l in Italy (Fig. 3).

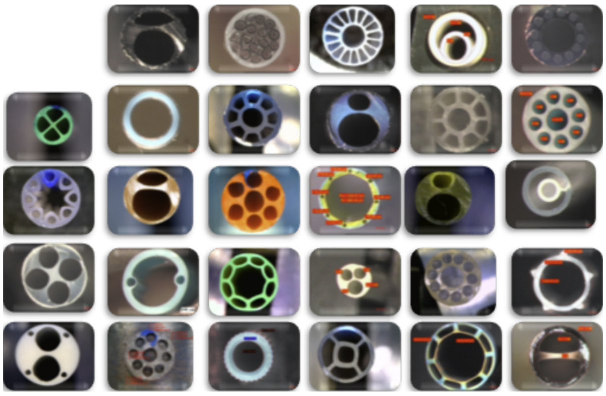

Fig. 3. Multi-lumen and multi-layer catheters for medical applications.

Medical technology is one of the most innovative industry in the world, with an increase of 15% in turnover since 2005. As opposed to the previous case, this example shows a completely different manufacturing context that is related to micro-machining and micro-forming operations and one-of-a-kind customized products. These types of catheters have applications in oncology, angiology, angiography and angioplasty, where the demand for customized single-use products is increasing to solve sterilization problems and to reduce the risk of contamination inherent in multiple-use products. Over the last years, a trend towards miniaturization of these devices is in place. The successful achievement of this goal will facilitate the use of these catheters in smaller arteries, thus having a great impact on the number of curable diseases and ultimately saving lives.

These micro-catheters are composed mainly of a micro-tube and, depending on the specific application, an injection moulded part that makes it possible to carry out the surgery. The micro-tubes can be either single lumen or multi-lumen facilitating the transportation of multiple substances to the zone of interest, as well as single layer or multi-layer for high-pressure resistance. The manufacturing process is composed of four main phases: (i) material compound preparation and control, (ii) micro-machining of the extrusion die (micro-milling, micro-Electrical Discharge Machining – EDM) for each specific part type, (iii) micro-extrusion of the micro-tubes and (iv) final micro-catheter assembly. The major causes of defects are related to defects in die production that cause defects in the micro-tubes and geometrical defects generated within the micro-extrusion process.

The above defects lead to an extremely high defect rates (up to 70% in standard production). These defects are certified mainly by 100% micro-tube inspection at the end of the line, which is manually driven and expensive. This high defect rate also undermines the possibility of robust production scheduling and is translated directly into service level issues. Moreover, this huge amount of generated scrap results in a massive waste flow, which is an additional cost for the company that must pay for its treatment. This example shows how in the context of high process variability, poor controllability and automatic inspection, as well as relatively low material value, the company strategy may be highly polarized on productivity performance, thus penalizing process control and first-time-right quality strategies.

Another example is related to the recently designed engine block production line at Scania CV AB, Sweden. Scania is a worldwide manufacturer of trucks and buses. All Swedish production was recently moved to Sodertalje. A serial production line layout with multiple parallel machining processes per stage has been designed with the goal of producing different engine block types in the same system at a very high production rate. As a result, some 400 product paths are possible while considering all possible routing alternatives in the system. The adoption of parallel processes increases the reliability of the system, thus making it possible to reach increased productivity targets. Nevertheless, this poses additional challenges regarding quality control and part deviation verification with respect to serial system layouts. Indeed, multiple product paths generate a mixing effect, loss of process signature and loss of FIFO rules, thus reducing traceability in the system, i.e. the ability to connect a defect with the process that generated it. Moreover, in the presence of end-of-line inspections, long delays in quality feedback are generated. This clearly reduces the ability to close a reactive quality control loop but increases the total production rate of the system. Therefore, in order to increase the visibility of quality and process deviations, in-line inspection points need to be distributed that will have a positive impact on quality and a negative impact on production logistics performance. This example proves that manufacturing system design affects product quality and that product inspection design affects the production logistics performance of the system.

The assessment of customer perception of products in multi-stage manufacturing systems is one of the main challenges of production and quality engineering and the main topic of the BMW Group case study [244,248]. This real case study is also demonstration scenario of the *Cluster of Excellence 'Integrative Production Technology for High-Wage Countries'* [240]. The vehicle acoustics is a product feature that is important to the customer perception of the product quality. It has very complex and multifaceted mechanisms that generate structure-borne sound, which is then transferred to the interior of the vehicle via the car body. When the noise reaches a particular level inside the car, it may be perceived by the customer as annoying. The technical analysis shows that the rear axle drive has a pronounced effect on the acoustics within the vehicle (see Fig. 4).

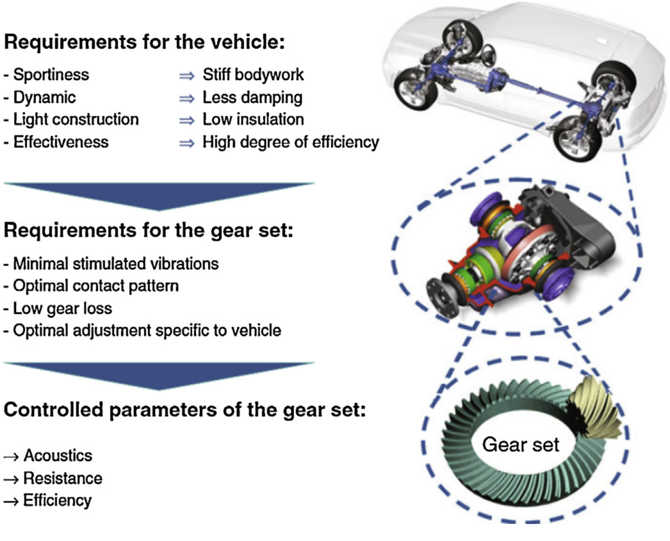

Fig. 4. List of requirements on the hypoid gear sets for passenger vehicle axle drives of standard design.

In order to ensure this customer requirement, advanced tools for inspection planning and quality control methods in multi-stage production systems are required. The manufacturing of rear axle drives, is characterized by many variants, which are produced at medium lot sizes (~10,000 units). Different manufacturing processes are used for different variants. The frequent change in variants leads to a high planning effort for the necessary adaptation of the manufacturing processes. The analysed process chain is shown in Fig. 5. The main challenges in this multi-stage production line are:

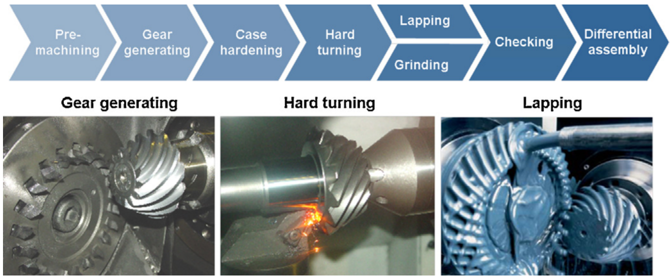

Fig. 5. The BMW production process, characterized by many sensitive tolerances with complex dependencies.

- measurement of the acoustic perception of the customer;
- parameterization of the customer specification for in-line process inspection;
- challenging assembly concept from FIFO production towards a tolerance optimized assembly concept.

In order to close the loop between customer perception, inspection planning and quality control, first of all perceived quality methods for the measurement of customer perception regarding the acoustics of the rear axle are needed. By identifying the relevant process parameters in a dynamic in-line inspection the acoustic behaviour can be then forecasted. Even when inline-inspections are installed and all processes are stable deviations in the multi-stage production system can cause critical acoustic behaviour after the differential assembly. Hence, advanced tolerance-oriented part matching tools could forecast the acoustic fit of the gear wheel and ring gear pair, assembled to the gear set. This means both expanding any unnecessarily tight tolerances to save costs and defining the critical tolerances more precisely to ensure the desired functionality of the end product. In order to reduce scrap rates the concept of just-in-sequence production has to be extended to a tolerance-oriented production control principle, where production and quality control are integrated.

The *production quality* paradigm in contexts characterized by deteriorating products, such as fresh food or yoghurt, is addressed next. Food production is pervaded by strict requirements on hygiene and delivery precision. The production plants have to quickly respond to the market demands and current order situation. A typical production sequence for yoghurt includes mixing/standardizing of milk, pasteurization, fermentation, cooling, addition of fruit additives and packaging. The production planning involves very complex problems due to the maximum allowed storage time before packaging. If the time the product flows in the system exceeds this limit, it has to be scrapped. Changeovers are typically sequence-dependent (increasing fat level is preferred giving shorter set-ups) and up to 25 products variants may be produced in the same system, with different processing times. In these plants the primary objective is to control the production of the different products for reducing the changeover number (typically 100/week) and time (typically 20 h/week). Secondly, the objective is the reduction of the product scraps (typically around 10%) due to obsolescence of inventory by achieving a better synchronization of the process phases, an effective joint control of the tank sizes (buffers) and the product quality. The removal of this bottlenecks and the reduction of WIP is a priority for these industries. Therefore, inventory management and line balancing play a fundamental role in achieving the *production quality* targets.

In automotive paint shops [120], to ensure high paint quality, multiple inspection stations are usually allocated along the cleaning and painting processes. Vehicles failed in inspection will be repaired or repainted before moving to the next station. Therefore, to improve the performance of paint shops, reducing quality failure rates while keeping the production rate within the target is of significant importance. An automotive paint shop typically consists of the following major processes. In the pre-treatment section, each vehicle body is submerged in a phosphate liquid to get a layer of coat on the surface of the steel. In the next ELPO process (electro coat paint operation) the body of the vehicle is covered with a special substance to protect it from corrosion. Then, the body needs to be heated and baked in the ELPO oven, and finally sanded to finish the ELPO process. Afterwards, there is an intermediate stage where the pre-treatment quality is inspected. The vehicle is then moved to the sand section followed by seal inspection. The next is the painting section that starts by spraying primer on the vehicle, which improves the adherence of the paint to the vehicle body. Afterwards, base coat and clear coat are performed. Then, the body of the vehicle needs to be baked. After this process, the final inspection (finesse) and, in case a defect is detected, the repair processes are applied. Here, defects, such as scratch, dirt, dent will be identified and fixed. After repair, these vehicles are sent to the next operations. In automotive paint shops, imperfect dirt cleaning in the upstream sanding operations will result in more paint defects in downstream colour coatings. Therefore, the stage correlation and the management of defects through part re-processing are the main issues to be addressed at system level.

Production quality is of significant importance also in the semiconductor industry and, specifically, in wafer fabrication. A semiconductor manufacturing process has the following characteristics. The production is performed through multiple stages. Some of these stages work in batches, including the slicing process, lapping, and polishing. Multiple parallel processors are commonly adopted to achieve the required production rate. Each product may undergo several re-entry loops in the system. The production yield is generally very low (around 50%) and the requirements on due-date performance are very strict. The flow time is extremely high thus mining the reactiveness of the quality control system. High priority lots typically share the production resources with low priority lots, thus generating non-FIFO production sequences. In this context, the complexity is the major barrier for *production quality*.

1.3. The production quality *paradigm*

In the literature as well as in the industrial practice there are many different Key Performance Indicators (KPIs), or performance measures, that individually relate to quality, production logistics and maintenance. In the following, the most widely adopted KPIs at system level are considered. In manufacturing systems they are complex non-linear functions of single process or single stage KPIs. Typical system level production logistics KPIs include:

- The *production rate*, i.e. the number of parts produced in a given time (also called throughput). It is usually measured in terms of Jobs Per Hour (JPH).
- The *total inventory*, or WIP, i.e. the total amount of parts flowing in a system.
- The *flow time*, i.e. the time required for parts to cross the system.
- The *interdeparture time*, i.e. the time between consecutive deliveries of output products.

These performance measures can be considered in the long term or in the short term. Moreover, the first moment (mean) or higher moments of these measures can be taken into account. The consideration of higher moments in the short term can be used, for instance, to evaluate the so-called due-date performance. For example, the service level of a system, which is the probability of delivering a lot of a certain size X before its fixed deadline T, is a due-date performance. From a "quality-oriented" point of view, typical KPIs of interest are:

- The *system yield*, or quality buy rate, i.e. the number of conforming parts delivered by the system over the number of conforming parts going into that system, in a specified period of time. In case of 100% conforming input flow, it is simply the fraction of good parts delivered by a system.
- The *first-time quality*, or first-time right rate, or first-pass yield, i.e. the good job ratio of all the first-time processed jobs.
- The *defect rate*, i.e. the fraction of non-conforming jobs delivered by the system.

From a maintenance point of view, typical system KPIs include:

- The *system availability*, i.e. the time a system is capable of being operational in a given total time.

This analysis shows a fundamental lack of a clear taxonomy for integrated quality, production logistics and maintenance performance measures [122,141]. An attempt towards the formalization of a taxonomy has been recently proposed in [239]. Moreover, the Total Quality Management (TQM) and Total Productive Maintenance (TPM) paradigms have proposed integrated KPIs to evaluate the effectiveness of the implementation of a specific improvement plan in industrial contexts. Although TQM and TPM share a lot of similarities, are in fact considered as two different approaches in the literature. TQM attempts to increase the quality of goods, services and concomitant customer satisfaction by raising awareness of quality concerns across the organization. Total Productive Maintenance (TPM) is a system of maintaining and improving the integrity of production machines that add business value to the organization. These methodologies suggest that the most relevant integrated performance measure is:

- the *effective throughput*, or the net throughput, also called OEE (Overall Equipment Effectiveness), that is the number of conforming parts produced by the system in a given time.

Grounding on this background knowledge, the *production quality* paradigm can be formulated in the following terms:

Production quality is the discipline that combines quality, production logistics, and maintenance methods and tools to maintain the throughput and the service level of conforming parts under control and to improve them over time, with minimal waste of resources and materials.

2. Quality, production, and maintenance "Interaction Model"

Several empirical studies have discussed the interaction among quality, production logistics and maintenance in manufacturing systems. For example, in [27] a survey approach is used to identify potential correlations between the application of JIT and TQM lean practices in the automotive and electronic industries. The main result of this analysis is that those companies that are more successful in limiting their inventory and in better organizing their production through JIT policies also achieve better quality performance and apply more effective defect reduction programs. This positive correlation highlights the need for a deeper understanding of the interaction dynamics between these relevant aspects in manufacturing.

2.1. The "Interaction Model"

The complex dynamics of the interactions among quality, production logistics and maintenance requires considerable effort to be modelled and understood. This activity is important to identify and explain the many existing trade-offs. The literature includes models developed to capture and explain the dynamics of this interaction. Among these, a very powerful set of tools is business and system dynamics Causal Loop Diagrams (CLD). These tools have been proposed for modelling complex interactions between quantitative and qualitative variables in a number of complex business management problems. Their application to the analysis of the interactions between quality, maintenance and productivity performance indicators is reported in [117,230,270]. The main goal of these models is to identify all possible interactions among variables and decisions in order to support the definition and implementation of continuous improvement programs that do not fail to meet the goals due to unexpected interactions. Understanding the relevant interactions then makes it possible to avoid local improvements that deteriorate the global performance due to neglected impacts. CLD charts are diagrams in which the relevant variables of a problem are listed and connected by directed arrows. In this format, A pointing at B with a positive arrow means that, given that everything else is fixed, an increase of variable A causes B to increase more than it would normally. A pointing at B with a negative arrow means that, given that everything else is fixed, an increase of variable A causes B to decrease more than it would normally. Only direct and easily explicable cause-effect connections have to be reported. CLD are very powerful tools for finding existing control loops in complex, multidisciplinary and dynamic contexts and in making them explicit.

Although they have been widely used for consulting activities and for policy making, state-of-the-art CLD models do not focus on the production system design and operational levels but rather try to see the problem more generally from a managerial point of view. For example, the implications of continuous improvement programs that take into consideration worker motivation, learning cycles and company emphasis achieving performance targets, have been investigated. One of the highlighted loops is the following: More defects reduce net process throughput (effective throughput in our notation). This in turn increases the actual versus target throughput gap. This negative performance increases worker effort, which positively affects gross process throughput (total throughput). This in turn has a positive impact on net process throughput. This reinforcement loop is called the "Work Harder" loop.

Although this dynamics plays a relevant role in the achievement of satisfactory *production quality* performance, the goal of this keynote paper is to consider manufacturing and shop floor related aspects. Therefore, a new interaction model is needed with the specific goal of answering the following question: "What are the cause-effect relations explaining the mutual interactions among quality, maintenance and production logistics in manufacturing systems?" Based on the real-life examples provided in the previous section, in this paper an interaction model is developed and proposed. The main objective of the proposed model is to define and characterize all major sources of interactions affecting *production quality* at the shop floor level. These interactions are consistent with the Functional Enterprise-Control Model as proposed by the IEC/ISO 62264 standard [111].

The aggregated representation of the model is reported in Fig. 6. This simple graph shows that bi-directional mutual cause-effect relations can be found among quality, maintenance and production logistics. A more comprehensive definition of these links in manufacturing systems is provided in the detailed CLD model

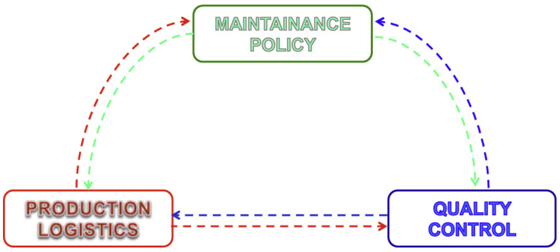

Fig. 6. High-level representation of the "Interaction Model".

depicted in Fig. 7. The red, blue and green regions refer to variables related to production logistics, quality control and maintenance, respectively. The links of greatest interest in this paper are represented by those arrows that cross regions of different colours.

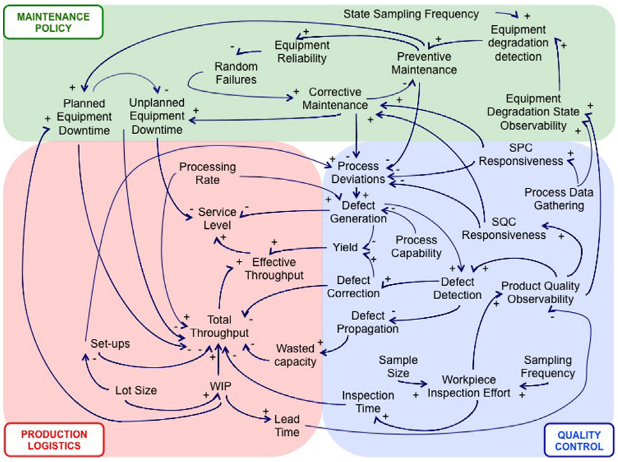

Fig. 7. Details of the "Interaction Model" developed in this paper.

For example, following the arrows in Fig. 7, increasing the WIP, in turn increases both the total throughput and the lead-time of the system. The increase in lead-time, however, also causes quality-related phenomena. Indeed, it reduces the observability of the critical product quality feature in the system, which in turn reduces the ability to detect a potentially generated defect within a short time. This directly translates into the propagation of more defects between the processing stages in the system and a waste of production capacity in processing parts that are already defective. A loss of capacity leads to a loss of total throughput. This example of balancing loop highlights the importance of this approach. If the effects of the WIP increase on the product quality were overlooked, quality and production logistics would be treated in isolation and erroneous design and management decisions could easily be made.

Focusing on maintenance and production logistics interactions, a second link made explicit by the diagram in Fig. 7 is explained in the following. Equipment condition-based preventive maintenance is typically supported by sensorial data collected from the field while the equipment is operational. If these data are properly analysed, they can be used to make inferences about the degradation state of the equipment. If the sampling frequency of this monitoring system is increased, the ability to detect the equipment degradation state increases. This increases the chances that an undesired degradation state will be correctly identified and preventive maintenance practices will be promptly activated, thus increasing equipment reliability, decreasing the frequency of unexpected random failures and ultimately decreasing corrective maintenance interventions. This maintenance-related loop also has an impact on system logistics. Indeed, less corrective maintenance generates less unplanned equipment downtime, while more preventive maintenance causes an increase in planned equipment maintenance interventions. Theses both affect the production rate of the system. If this interaction is overlooked, overall myopic decisions can be taken.

In the following, the relevant phenomena characterizing two of the real cases investigated in Section 1.2 are framed within the "Interaction model". These few examples show that real cases can be mapped within this "Interaction Model". With reference to the Gamesa case, the high workpiece inspection effort leads to high observability of the product quality characteristics. This positively affects the ability to detect and correct defects as soon as they are generated. This is beneficial for the system yield but detrimental for the total throughput, as the production resources are used to re-process parts and correct defects. The high inspection effort also leads to high inspection time and, consequently, low total throughput. With reference to the ENKI case, the wide mix of personalized parts and the small lot sizes lead to extensive set-ups. Set-ups are detrimental for the total throughput and for process deviations, thus leading to consistent generation of defects. In addition, the poor process data gathering undermines the possibility to observe the equipment degradation state, thus making preventive maintenance hard to be implemented. This, in turn, leads to short planned equipment downtimes, thus high total throughput, but also to consistent process deviations, thus high defect generation and low yield.

As these few examples show, the proposed "Interaction Model" can be used by scientists to identify relevant unexplored problems that need to be further investigated, as well as by practitioners to motivate and gather insights on unexplained phenomena on the boundaries of these three areas. In this paper, this model will be used as a reference framework to structurally explore the topics already addressed in the literature and to highlight promising research areas for the future.

2.2. Using the "Interaction Model" to classify the scientific literature

About 300 papers, mostly from leading international journals, have been classified and framed within the "Interaction Model" (Fig. 8). Specifically, the papers have been clustered according to two-dimensional axes. The first axis relates to the specific "phase" in the paper where the interaction is addressed. More specifically, the design and planning phase and the operational, control and the management phase have been taken into account. The second axis relates to the type of interaction addressed. According to the proposed interaction model, possible interactions are quality-production logistics interaction, production logistics-maintenance interaction, quality-maintenance interactions, and complete interaction among quality, production logistics and maintenance. In Fig. 8, the bullets represent the cluster of papers addressing common problems as framed within the interaction model. The size of the bullet represents the population magnitude of the cluster. Most of the contributions cover areas related to the interaction among quality and production logistics, while only a few contributions address problems under a fully integrated view.

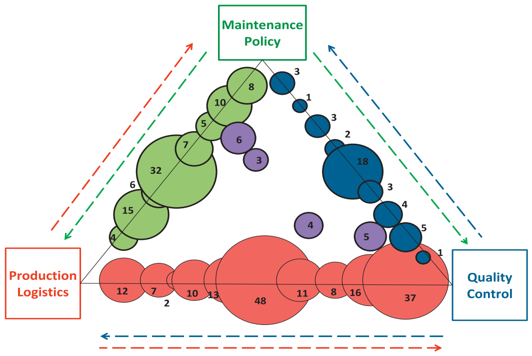

Fig. 8. Paper distributions within the "Interaction Model".

3. Problems and methodologies

3.1. Design and planning phase

In the following sections, the existing literature addressing the links between quality, productivity and maintenance in the design phase are revised. The focus is mainly on system and process related design decisions while product and tolerance design decisions, in spite of being important factors within the *production quality* target, are not explicitly considered in order to avoid deviations from the main scope on this paper. For a recent review on the link between product design and quality see [180].

3.1.1. Impact of manufacturing system design on quality

There are many aspects that demonstrate that the production system architecture affects the *production quality* performance, as highlighted in [109] based on the analysis carried out in General Motors. This review has been updated in [107], where recent works focusing on this specific link have been framed.

In mass production systems the simulation works proposed in [25,165] contributed to the assessment of a fundamental principle: while changing the system architecture the fraction of conforming products may drastically drop. A similar result was achieved by [136]. The authors compared six alternative configurations, including serial and parallel lines, and hybrid configurations, in terms of multiple performance measures, including the system capability to produce parts with limited variations and the expected availability. The authors show that serial lines perform better than parallel lines in terms of dimensional variation of products, because there is only one possible path in the part flow and the *mixing effect* is avoided. The mixing effect means that multiple processing stages show different degradation patterns and actual capabilities and this phenomenon increases the variability in the key quality characteristics of the output products. The mixing effect in parallel machine lines has been further studied in [233]. The authors analysed by simulation the consequence of the mixing effect on the ability of performing a root cause analysis at the inspection points in the system. Other undesired phenomena, such as possible job order loss and sampling frequency mismatch, have also been identified in parallel processes. In [38,94,189] it was shown that U-shaped lines may perform better than serial lines in terms of quality of the released output. The reason is that the operators assisting the line can visually detect quality problems in the system earlier than in serial lines and, consequently, can react more promptly to these defects.

The impact of buffers on *production quality* has also been analysed in the literature. The *Lean Production* area has shown that the reduction of inventory has a positive impact on product quality, since quality defects are identified earlier and are not propagated throughout the system stages [310]. As a matter of fact, *Toyota Production System* (TPS) advocates see in-process stocks as waste (*muda*), which often hides production problems. However, from the *Manufacturing System Engineering* area it is known that the production rate of the system is positively affected by the presence of buffers, since they decouple the behaviour of the unreliable machines [65]. This trade-off has been studied analytically in [52] and [131] from an integrated quality-logistics point of view. The authors found cases in which the effective throughput is maximized for a given buffer capacity. This behaviour is due to the coupling of two contrasting effects, in the presence of *remote* or *ubiquitous* inspections, where a product feature manufactured at a certain processing stage is inspected at a monitoring station located further downstream in the line. One effect is the positive impact of the buffer capacity on the total throughput of the system. The other effect is due to the *delay of the quality information feedback* when remote inspection is performed. Processed parts do not instantaneously reach the inspection point, but are stored in the inventory queue before being measured. Large buffers between the monitored station and the inspection point increase the time parts spend in this portion of system. This causes long reaction time in identifying out of control conditions and decreases the system yield. This behaviour generates interesting considerations on the joint design of buffers and quality control parameters in manufacturing lines [51]. Nada et al. [201] developed a comprehensive framework to address the aforementioned issue during the design phase of manufacturing systems. A Configurator Capability Indicator (CCI) is developed, by using hierarchical fuzzy inference, to select the most proper architectural parameters of the system, under *production quality* considerations.

The design of in-process buffers has a relevant impact on the product quality also in those industries producing *perishable* or *deteriorating* components and products. The quality characteristics of perishable products deteriorate over time. For example, as commented in Section 1.2, in food industry there is a maximum storage time before packaging. The product has to be scrapped if the time spent in the system overpasses a certain fixed limit. This problem has been addressed in [169]. A project to determine cost-efficient ways of speeding up the croissant processing lines of Chipita International Inc. is reported. The installation of a properly sized in-process buffer led to a reduction in failure impact on product quality and an increase of the system efficiency. In [168] the authors focused on the production rate of asynchronous production lines in which machines are subject to failures. If the failure of a machine is long enough, the material under processing in the upstream machines must be scrapped by the system. In [295] a transient analysis is proposed to design the size of the buffers needed in dairy filling and packaging lines. The distribution of the flow time in unreliable multi-stage manufacturing systems was evaluated in [260]. This method can support the design of buffers for achieving a certain accepted scrap rate in perishable good production. In [272] an inventory model for perishable products with random perishability and alternating production rate is proposed. As shown in these works, buffers should be designed by using an integrated *production quality* oriented approach.

In machining and assembly operations it has been shown that the design decisions concerning the system *operating speed* are strongly correlated to the product quality [214]. Improving the machines' processing rate has a positive impact on the system production rate, but may negatively affects the system yield. For example, in robotic assembly the quality of the production process is related to the robot repeatability and the output rate is related to the robot speed. Robot repeatability deteriorates with the robot speed [129]. This behaviour has been investigated in [186]. The authors modelled multi-stage systems with quality-quantity coupling machines. In these machines, the correlation between efficiency and yield is made explicit through an analytic relation. The method supports the design of the optimal processing speed of the machines in the system and has been applied to an automotive case study [12].

The link between mix *flexibility* and quality in flexible machining systems has also received attention in the literature. A taxonomy for flexible manufacturing systems is proposed in [278]. A flexibility evaluation toolbox in modern manufacturing systems is addressed in [91]. Moreover, a method for assessing the flexibility of a manufacturing system, in an uncertain market environment, under lifecycle considerations is developed in [7]. Part mix flexibility provides to a system the ability of processing different part types with relatively limited set-up times and changeover costs. The level of flexibility of a system affects the product quality [161]. There are few examples showing that system flexibility is positively correlated with product quality [232]. In [303] the author argues that flexible modular assembly systems support the achievement of higher product quality. However, increased flexibility can also deteriorate quality. For example, consider a flexible automotive paint shop [298]. When shifting between different part batches characterized by different colours a certain amount of defective parts that need to be reworked is produced in the transient period since the colour is contaminated by the one used for the previous batch. This phenomenon is clearly strongly affected by decisions concerning the set-up times and the job sequencing (see Section 3.2.5).

The effect of the design of *reconfigurable* systems on the production logistics and quality performance has also received attention in the past. [23,101] presented an approach for designing system reconfiguration options according to a multi-criteria decision making framework (Fig. 9). Starting from the analysis of the product feature and demand requirements, and from a database of available equipment modules a system-level tool generates different potential reconfiguration alternatives. Their KPIs are evaluated within a simulation environment and dominant solutions are selected. ElMaraghy and Meselhy [80] proposed a

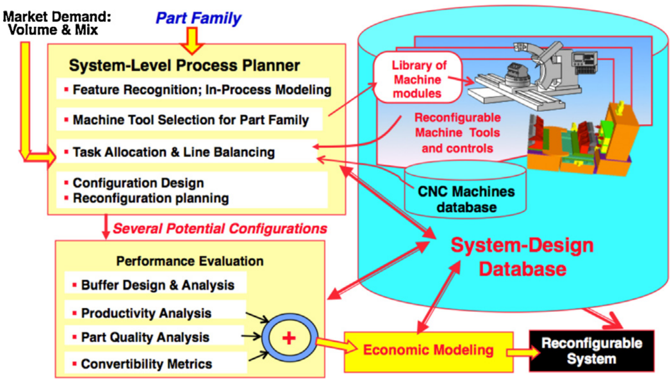

Fig. 9. Integrated approach for quality oriented design of RMSs [101].

framework to study the relation between maintainability and quality in changeable manufacturing systems.

The impact of *complexity* in manufacturing and assembly systems on several performance measures including quality and production logistics metrics has been revised in [81,144]. Moreover, in [103] the impact of different plant complexity sources on product quality was investigated based on the analysis of real data from an automotive company. The results prove that there exists a negative correlation between the number of chassis produced in the plant and quality. Although system complexity has many dimensions, product variety seems to be the most important factor affecting *production quality* performance. In fact, the number of product variants decreases the ability of learning from repetitive operations and increases the probability of human errors. The link between assembly system design for product variety and performance was explored in [102]. Many papers address the issue of quality and human induced errors in mixed-model assembly systems [325]. Mixed-model assembly systems were recognized as enablers for mass customization manufacturing. However, highly proactive and knowledgeable workforce is needed to effectively implement mixed-model systems in industry. In [2] the quality and productivity performance of mixed-model assembly systems under human errors was evaluated. In [271] it was reported that about 20% of the defects in the Fuji Xerox China photocopy machine assembly systems was connected to operators errors. It was the second cause for defects in the analysed plant. Product and process related complexity metrics were proposed to tackle this problem. The link between complexity and performance measures in mixed-model assembly was also algebraically analysed in [1].

3.1.2. *Impact of process planning on quality*

Manufacturing process planning is among the most knowledge intensive decision-making activities undertaken in factories. In this activity the product information is mapped on to the available information for the various existing manufacturing resources to determine a plan of action to convert the raw material into the final product. Process planning is normally carried out by a specific human resource and depends on individual experience. Methodologies supporting process planners have been deeply analysed since the 80s [42] and, over the last 10 years, a significant number of software tools focusing on Computer-Aided Process Planning (CAPP) approaches have been developed [293]. CAPP systems use, among others, artificial intelligence methods to enable human operators to select the most appropriate operations for manufacturing. Currently the knowledge used within this activity has been based on nominal models of manufacturing resources [40,313]. While the nominal information pertaining to manufacturing resource is static and does not change over time, the capabilities of physical resources do, due to wearing of mechanical components and tools. Capability profiling [203] is a method for recording these changes in the various capabilities of manufacturing resources. With capability profiling techniques, it is possible to optimize the generation of the process plan to develop solutions that are appropriate for the actual available hardware and software rather than the nominal values. Capability profiles are generated by combining the nominal resource models with actual values obtained from sensors on the shop floor and predictive models.

In a production environment of resources with mixed capability profiles and varying reliability, both process planners and schedulers tend to give priority to machines with more advanced and unfailing services. All in all, this results in an uneven, distorted load of these resources: while they are busy all the time, others are idling. The throughput of such so-called flexible job shops can, however, substantially be improved if products are manufactured via alternative routings. Nonaka et al. [208] presents a CAPP method that, departing from the geometric product model and the description of machining resources, generates a portfolio of process plans with the objective to maximize the throughput. The model is open to include quality related constraints, too. Next, efficient load balancing and operation sequencing methods are applied to schedule flexible job shops by using the alternative routings (i.e. process plans) for producing the same product. The method that maximized a workshop's throughput proved to be robust and applicable even in large-scale industrial scenarios [209]. The generation of alternative process plans is also the main objective of the Network Part Program (NPP) approach [87] and of non-linear process planning, in general. Non-linear process planning goes beyond the static and strictly sequential nature of traditional process plans that are often carried out without considering the manufacturing system information [139]. The idea of network part program is to delete non-technological constraints from among the operations, transforming the sequential part program into a network of operations, each one characterized by a set of G-M instructions. For instance, the part program for the machining of a pallet can be easily built and re-built according to the workpieces that are really mounted on the fixture as a consequence of changes in demand mix and quantity [218]. In case of unavailable resources part programs can be easily adjusted and eventually split on different machine tools.

A first attempt to develop NPP on industrial scale was led in the Italian national project NetPP [21] where the approach was limited to the production of pallets mounting one single part type on one work area. Non-linear process planning able to support the configuration of multi-fixtures (pallet) with different parts has been later developed [217] for managing small batches and a high number of product variants. Currently, 12 installations of the NPP are available in Europe. A process planning approach based on network part program has been developed in the DEMAT EU project [64] for a manufacturing system composed of ultra-light, eco-compatible and energy efficient machine tools. Other European projects, such as ENEPLAN [83], analyse and propose non-linear process planning techniques for hybrid processes, such as milling, turning and laser cutting. One of the key challenges while applying the NPP in industry is the need for specific procedures to provide a quality certification of the entire Network Part Program, considering all the process path alternatives, instead of only certifying one specific part program, as typically done with the traditional G-code part programs.

3.1.3. *Inspection planning in multi-stage systems*

Inspection planning deals with the definition of the part quality inspections in the production system and with the definition of the multi-sensor system for process monitoring. Both technologies serve as data gathering systems to feed SQC, *Statistical Process Control* (SPC) and *Condition Based Maintenance* (CBM) procedures with useful information to perform a machine and process state diagnosis and the implementation of corrective or preventive actions to restore in-control manufacturing system behaviour. This diagnosis-oriented strategy focuses on the near-zero level of *defect generation*. Here, the part quality inspection plans feed product quality assurance and the consequent activation of defect management strategies, including scrap, rework and repair. These strategies allow smoothing the *defect propagation* throughout process stages and to the final customer. A review of the most advanced automatic inspection and process data gathering technologies is provided in Section 4. The use of these technologies for complex product validation is revised in [180]. While product inspection allocation techniques have been revised since 1980 [225], less attention has been given to process sensor distribution strategies. Concerning part inspection planning, two major tasks have to be solved:

- *Inspection characteristics identification and analysis.* The necessary inspection characteristics have to be identified and analysed at each process stage.
- *Inspection process conception and allocation*. According to the identified and analysed inspection characteristics, inspection strategies have to be developed, which define the test procedures, cases and resources and align the inspection steps to the test sequence in multi-stage production systems.

The first task is essential for the overall success of inspection planning, since all characteristics which are neglected might cause fatal damages to tools, personnel, products or customers and, on the contrary, unreasonable inspections cause inefficient test steps and increased process complexity. A common consequence of wrong characteristics identification in the planning phase is the occurrence of No-Fault-Found failures made visible during the use phase of the product [179,220,221]. These are in-tolerance failures due to unexplored interactions during the process/inspection planning phases, performed without taking into consideration process capability profiles. Hence, [242] introduced the concept of *perceived quality*, which provides methodologies to identify and measure customer demands, and add the requirements from different product stakeholders in order to develop a holistic product and system specification [11,243]. The risk assessed specifications are the input for the second major task of inspection planning, i.e. the inspection strategy planning and execution. This phase entails:

- Determination of the point in time of inspection (when?).
- Determination of the proper technologies for inspection (how?).
- Determination of the inspection extend (how much?).
- Determination of the inspection location (where?).
- Determination of the inspection personnel (who?).
- Selection of the inspection equipment (whereby?).

Although heavy interdependencies between the inspection planning steps do exist [246], scientific approaches mainly focus on the optimization of single inspection planning tasks. These works mainly address the inspection extend problem, against economical KPIs using statistical methods [82,125].Van Volsem et al. [287] derives an algorithm for the cost-optimal inspection extend, place, type and amount of inspection stations. The lack of a holistic consideration of all inspection planning tasks was addressed by Schmitt et al. [250] where the model was extended to calculate business cases based on the risk attitude of the inspection management. With this idea, the optimal solution is the one that maximizes the decision maker's value of benefit.

Concerning the area of sensors allocation for process monitoring only few recent contributions are available. In a manufacturing process, sensor distribution involves the determination of: (i) the workstations at which to place the sensing devices; (ii) the number of sensors required at individual stations; (iii) the location of sensors within individual stations. Three major types of problems have been considered in the literature [178]: (i) for a given number of sensors, find the optimal sensor locations; (ii) find the minimal number of sensors as well as the corresponding locations; and (iii) given the distribution of q sensors, where to distribute additional s sensors. These formulations lead to a constrained non-linear optimization problem [71,108]. Wang and Nagarkar [302] proposed a two-level hierarchical approach to solve problems (i) and (ii) simultaneously.

Part quality inspection and process sensor planning have a strong impact on the production logistics performance of the manufacturing system. It has been shown by [238] that, for a production line with 15 machines, the effective production rate of the system if inspection stations are poorly allocated can be 15% lower than the one corresponding to a good allocation of the same number of inspection stations. As investigated in [55] three fundamental phenomena determine this effect. Firstly, if a critical product feature is remotely monitored, a quality information feedback delay is generated. If dedicated inspection stages are designed, i.e. each critical product quality characteristic is measured by a dedicated inspection device, local monitoring should be adopted. However, in order to save equipment costs and to increase the inspection system life-cycle, reconfigurable and flexible inspection technologies have been recently proposed [15,137] which are able to adapt to and to measure a set of product features. In this case, remote monitoring is inevitable.

Secondly, the part inspection interferes with the cycle time of the system, while process monitoring activities typically do not. Therefore, a more extensive product inspection provides more accurate information about the product quality but decreases the total production rate of the system. Thirdly, as it will be discussed in Section 3.2.3, the implementation of defect management strategies affects the system dynamics and its performance. An algorithm to allocate inspection stations in order to maximize the throughput of conforming parts, considering the effect of these three phenomena under predetermined inspection technologies and tasks, has been proposed in [188]. Moreover the concept of quality bottleneck in a system in addition to the traditionally investigated productivity bottleneck concept has been formulated in [296]. A quality bottleneck is a stage in a multi-stage system that more severely affects the system yield [185]. Identifying quality and productivity bottlenecks is an important activity for prioritizing sensor and part quality inspection distribution. However, more extensive research on inspection and sensor planning for *production quality* targets should be developed, jointly taking into account all the aforementioned aspects.

3.1.4. Quality control planning in multi-stage systems

In multi-stage systems the design of an effective and cost-efficient quality control strategy is of critical importance. For recent reviews of quality control planning methods in multi-stage systems see [262,283]. The major challenges that have been tackled by researchers in this area include multi-stage variational propagation modelling for quality control, process monitoring, and root cause identification for multi-stage systems. The first area will be revised in Section 3.2.1. Concerning process monitoring for multi-stage systems, SPC is the main technique used in practice for quality and process monitoring. Control charts are the most commonly adopted tools. However, most conventional SPC techniques treat the multi-stage system as a whole and lack the capability to discriminate among changes at different stages [192]. To overcome this problem, multivariate control charts based on principal components and partial least squares analyses seem attractive for multi-stage systems. More recently, some specific SPC techniques have been developed to exploit the detailed structure of multi-stage systems to achieve high detection power and diagnostic capability. For example, an exponential weighted moving average scheme has been proposed as a monitoring method for multi-stage systems [312,326]. In the SPC area, after a process change is detected, the diagnosis of root causes is left to human operators. Significant progress has been made towards intelligent root cause diagnostics. These methodologies can be roughly classified as (i) statistical-estimation-based methods [72] and (ii) pattern-matching-based methods [175]. Both methods are based on mathematical models that link the system error and the system quality measurements. As a matter of fact, the majority of available SPC approaches tackle the quality control planning problem by selecting the optimal control chart parameters (sampling frequency, sample size and control limits) with respect to an economic objective function. Multiple criteria including production logistics and maintenance performance are usually neglected. According to [262] the complexity of multi-stage systems requires a holistic system-level approach for effective quality control. By intermeshing and linking closed-loop quality control systems at various levels of the company unambiguous rules for decisions at engineering and organizational levels emerge (Fig. 10).

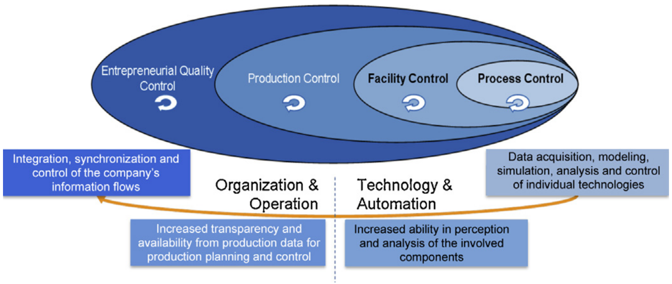

Fig. 10. Cascaded closed-loop quality control systems [249].

The continuous alignment between actual and target state enables continuous improvement to be institutionalized in the company. In this direction Wiendahl introduced the characteristic curves in order to describe production flows based on the bottleneck theory and theory of constraints (TOC) [307]. The underlying idea is to jointly perform quality control planning at the facility and process control levels. In order to improve the transparency of quality control planning in multi-stage systems, the method “Quality Value Stream Mapping” [96], can be used to develop an optimal configuration of quality control along the process chain [148]. By means of “Quality Value Stream Mapping” the occurrence of defects, the effective integration of inspection stations as well as the design of quality control loops can be systematically visualized, analysed and improved.

3.1.5. *Personnel allocation in multi-stage systems*

The human factor has a fundamental role in achieving the required *production quality* performance of a manufacturing system [308]. The human element is considered as a key factor in all the discussed company functions, i.e. production, quality and maintenance. Root cause analysis and final product verification still mainly ground on humanly driven operations, also in highly automated contexts such as the automotive industry. As a matter of fact, all traditional quality improvement programs, such as the World Class Manufacturing, ground on the attitude of workers towards problem solving and waste elimination. Moreover, corrective and preventive maintenance procedures require highly skilled personnel to be performed in compliancy with the target times and cost requirements. Furthermore, complex manufacturing and assembly tasks still entail manual operations in almost all industrial sectors. Even the human-robot interaction paradigm, that is currently under investigation and testing [138], stresses the importance of the role of humans in advanced manufacturing systems for performing non-repetitive assembly tasks. Due to these implications between the workforce organization and the operational performance of a plant, the allocation and management of personnel in manufacturing systems have motivated significant amount of work in the past. Sterman [270] showed that the *production quality* strategy fixed by the company strategic goals may activate virtuous (work wiser) or vicious (work harder) loops in the behaviour of the workforce towards these targets, depending on the vision imposed by the management. From an operational point of view, the problem of allocating maintenance personnel in complex multi-stage systems has been investigated. Automated flow lines where human operators are allocated to cope with machine breakdowns and other tasks such as inspection, support and control have been considered. In these systems, machine failures and consequent repair actions play a dominant effect on the performance. To cope with machine failures, a repair crew is usually dedicated to the line. However, in order to save operating costs, the repair capacity is generally limited and the repair crew availability can be a performance bottleneck for the whole line. In other words, when a failure occurs and all operators are busy in repairing other stations, the machine is forced to wait before a repair intervention is started, queued with other contingent maintenance requests. This kind of machine idleness is known in literature as *interference* [300] and the related problem is known as the “*Machine Interference Problem*” (MIP) [269]. A literature survey on methods to solve MIPs can be found in [98]. An advanced approach to iteratively solve this problem has been proposed in [140]. The author modelled the original system as two interacting systems the first being the automated flow line and the second being the repair crew system. This approach has been applied to a real engine block production line at Scania in [45], showing great operational benefits for the plant obtained by optimally allocating repairmen to stations. Moreover, the effect of mixed workforce skill levels has been analysed in [48]. In [75] the problem of distributing an available repair effort in the system, considering the impact on the system dynamics have been solved by an analytical approach. Currently, approaches that include quality considerations in these frameworks are not available. From a quality point of view, an approach to optimally design SPC control chart parameters, also considering the limited manpower, is proposed in [311]. Another area that has received attention in the last years is the analysis of the impact of the workforce behaviour on the operational performance of the system. In [106] the impact of workers absenteeism on the performance of assembly lines is investigated. The authors found that specific cross-training strategies may reduce the loss of performance due to absenteeism. However, cross training may reduce quality [108,182]. Furthermore, the impact of workforce learning on the system performance improvement during the ramp-up phase has been analysed in [67]. Although preliminary approaches exist, the analysis of the impact of workforce on the *production quality* performance of a manufacturing system is a relatively new research area where the main challenges is the difficulty in developing reliable models of the human behaviour.

3.1.6. *Advanced integrated business models for production quality*

Business model innovation is a relatively new concept in the manufacturing industry. Traditionally, innovation in this sector was primarily based on technology innovation. In the last decade, industry competitiveness has been stained by the increasing turbulence of the market. To face this situation, companies were motivated to innovate their business models towards the establishment of long-term relationships with their customers, and the provision of value-added services beyond the technical ones [306]. The topic of proposing new business models for machine tool builders has attracted the attention of researchers and industrialist only in recent years. The concept of Reconfigurable Manufacturing Systems [18] paved the way to the idea of establishing a collaborative relation between producer and customers to design and manage the system over its life-cycle. Later in [258] the idea of delivering services for the system adaptation and enable module re-use for different customers was proposed. A strategic approach for developing such services has been suggested [256]. Moreover, a CIRP Collaborative Working Group – Industrial Product Service Systems (IPS^2) [187] – has been launched, with the objective of investigating benefits and operating modes for implementing the product-service idea in B2B relations. The implementation of such concepts is the core idea of the EU funded project RobustPlaNet [229]. In this project, guidelines to select the best business model and collaboration mechanism depending on the stakeholders' situation are proposed. In recent years full-service contracts and reliability warranties have widely spread in almost all kinds of business, starting with the aerospace and defence industry. Today automotive OEMs for instance make contracts with their equipment suppliers for a period of up to 10 years fixing maintenance costs and performance figures.

Within the new product-service oriented business models the suppliers benefit by gathering detailed data on how their machines perform in real-case application in the global field. Moreover, if additional warranties on the quality of parts produced by the equipment are integrated, detailed statistics on defects and root causes are made available [148]. This is made possible by remote monitoring systems implemented on the machines [193]. For example, such a service is provided by Mori-Seiki when they remotely monitor, and if possible, maintain, their CNC machine tools via mobile communication networks worldwide (in 2011, almost 6000 machines). As declared by the company, this service affects not only the availability of resources, but also product quality and resource efficiency. In this context, a company delivering the product-service will be able to increase the profitability of the business only by considering the quality, productivity and maintenance aspects under an integrated view. Indeed, any inefficiency in one of these aspects may result in a penalty and a value loss in the service provision. Therefore, the contracts regulating the implementation of these new business models and the *production quality* targets should be designed in a coherent and non-conflicting way.

3.1.7. Supply-chain design for production quality targets

To design a supply chain from a *production quality* point of view, a detailed understanding of the failure propagation, the behaviour of individual nodes in the chain and the overall tolerance management are required. Within the German AiF Project iQ.net a multi-agent simulation approach was developed to find best configurations of networks towards an integrated quality target systems [19,146]. A similar problem was addressed in [196] where the performance and viability of centralized and decentralized production networks, under heavy product customization, were investigated.

One of the major challenges in managing *production quality* in globalized and highly distributed supply chains is the distribution of *production quality* targets to a multitude of suppliers distributed worldwide, each one having specific process capabilities and production management strategies and goals [266]. A significant example is provided by Wiendahl, who studied the production network of a German company producing weighing systems [309]. The competitiveness of the company was based on a solid standardization of the modules composing the product and a rationalized design of the variant differentiation. The *production quality* standards were achieved by manufacturing high added-value components in production sites characterized by highly skilled personnel and highly capable systems and to dedicate to the less capable sites the production of low technological content parts. This leaning affected the way the production system was designed in the different sites, requiring dedicated solutions in the early stages of production and flexible solutions in the product customization stages.

The problem is even more complex if differentiated products dedicated to markets with specific, location-dependent *production quality* requirements are considered. This is a growing trend in globalized production networks, due to the rapid demand growth in BRICS countries. To cope with this challenge the idea of "frugal products" has been developed [183]. Frugal product innovation is the process of removing nonessential features from a durable good, such as a car or phone, in order to sell it in developing countries. According to [3] in the automotive industry about 90% of components are globally standardized while only 10% are adapted to specific market requirements. On the contrary, in consumer goods, these figures are almost reversed. Therefore, specific advantages of the location are to be incorporated into the product and production design processes, such as site-specific conditions regarding production technologies and capabilities. From a *production quality* point of view this translates into additional burden on the design process. Indeed, not only the local production process capabilities have to be considered but also the location-dependent product quality specifications have to be met. Although several works have addressed and formalized this challenge [195] approaches to support decision making in this context have not been developed.

Another relevant phenomenon, which reduces the ability of meeting *production quality* targets, is the generation of obsolete components caused by poor information exchange between stakeholders in presence of highly customized products and unexpected change of demand. These obsolete components are excess inventory for the suppliers, which ultimately result in parts to be scrapped and recycled. This problem is in the core of many manufacturer-supplier relations where the parties have asymmetric information about the demand and cost items and should share not only the benefits but also the risks of operating the channel [290]. Advanced technologies and cooperation-oriented contracts can help reducing the impact of this phenomenon. For example, in [197] a method of dynamically querying supply chain partners to provide real time or near real time information regarding the availability of parts required for the production of highly customizable products is developed. This method utilizes Internet-based communication and real time information from RFID sensors. The feasibility of this approach is demonstrated with its implementation in a typical automotive case. The implementation of advanced information technologies in supply chain for improving product quality is also stressed in [290,313]. Egri and Váncza [77] surveyed short-term two-echelon supply channel coordination methods and presented a decentralized version of the newsvendor model where the parties have the right incentive for sharing their private information. The decision on production quantities is in the hand of the supplier whose rational decision concurs with the overall optimum. Hence, local decisions based on asymmetric information coordinate the channel. Further work resulted in a methodology for designing decentralized coordination protocols for supply chains where autonomous partners operate in an asymmetric information setting, under the burden of some uncertainty [78,288,289].

3.2. Operational, control and management phase

3.2.1. Multi-stage quality correlation analysis

Modern multi-stage manufacturing processes typically involve processing and assembly stages whose output quality is significantly affected by the output quality of preceding stages in the system [171]. In multi-stage manufacturing processes, understanding how a defect generated in a specific process stage propagates to the next process stages and what effect this propagation has on the final product quality is a complex task. Two major types of correlations can be found in multi-stage manufacturing systems:

- *Quality correlation:* the quality of the product processed at a given stage is highly dependent on the quality of the output at specific upstream processes.
- *Failure correlation:* the propagation of a defect generated in upstream processes causes machine or tool integrity problems in downstream processes, such as increased degradation and tool wear, or sudden tool breakage, or process instability.

The most diffused market available Six-Sigma and SPC software tools do not analyse stage correlations in multi-stage systems, but concentrate on single process monitoring, control and optimization. Engineering methods and advanced Multivariate Statistical Process Control (MSPC) methods have been proposed to model and monitor correlations in multi-stage processes.

Of the engineering methods, SOVA (Stream of Variations Analysis) has been proposed for assembly systems and machining process-chains [261]. This approach is based on a state-space representation of the correlation between the product deviations at consecutive process stages whose structure is driven by engineering knowledge about the processes and whose coefficients are tuned by KPC (Key Product Characteristics) measurements at the different stages [70] (Fig. 11). A detailed description and review of SOVA model with applications to quality control for multi-stage manufacturing processes is presented in [34]. Applications of the SOVA model to predict the propagation of variation in the assembly are found in [29,28]. The SOVA model has also been used to determine adjustments in multi-station assembly processes [73].

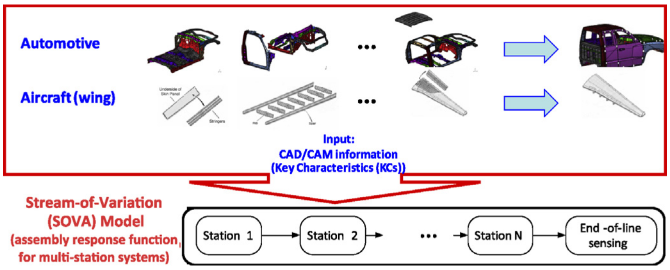

Fig. 11. Main characteristics of the “Stream of Variation Analysis”.

In contrast, advanced MSPC methods are based on elaborating KPCs measurements to find the parameters of simplified multiple process statistical models [162]. In other words, they do not a priori assume any specific structure of this correlation. Both approaches support only quality correlation modelling, but do not offer the possibility of eliminating defects at downstream correlated stages, as a mean to achieve zero defect propagation.

These methods overlook the logistics analysis of the product flow throughout the process stages. A recent contribution [210] goes in the direction of overcoming these limitations. The authors empirically studied the correlation between the occurrence of machine failures and the quality problems in the produced parts. The authors concluded that this correlation is the main cause for quality problems in the analysed semiconductor manufacturing fab (*tsunami effect*) and used this result for bottleneck identification. This paper gives a clear idea of the potential industrial benefits of methodologies addressing this problem.

Variation modelling in correlated serial-parallel multi-stage systems has also been studied. The main problem in this context is the presence of multiple variation propagation modes in the production run when process routes vary from part to part. For a practical example, refer to the automotive and semiconductor cases reported in Section 1.2. If the different multiple process routes share at least one workstation, the SOVA approach proposed in [104] is applicable to model variation propagation. If there are multiple variation propagation modes, only MSPC approaches can be applied for modelling and monitoring [118].

3.2.2. *Integrated methods for production quality prediction*

Grounded on manufacturing system engineering background, integrated models and analysis tools for predicting quality and productivity performance measures in manufacturing systems have been proposed. These models integrate product features and specifications, process out-of-controls, typical logistics parameters, such as machine failures and limited capacity buffers, and corrective maintenance into a unique framework. The representation of a system including these aspects [279] is presented in Fig. 12. Most of the methodological contributions in this area are focused on serial production lines. The existing approaches mainly differ in the type of *operational* and *quality failures* and quality control mechanisms they model. In [185] the performance of systems where quality failures exhibit Bernoulli-type behaviour and no correlation exists between consecutive parts are analysed. However, in production systems Markovian-type out-of-controls, where the quality of parts is dependent on the machine state, are commonly observed. In [131], an analytical method to estimate the yield and the total and effective production rates of asynchronous lines having machines subject to Markovian quality failures is proposed. When in normal operating conditions the machine does not produce any defective item; after transition to the quality failure state occurs, the machine produces only defective products. The quality control action is modelled through a transition that forces the machine to shift to an un-operational state, for the repairing process.

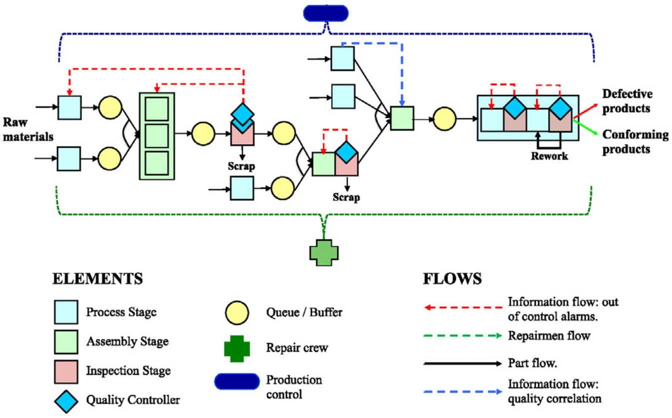

Fig. 12. Representation of a manufacturing/assembly system with SPC and corrective maintenance [279].

This transition is considered to be fixed and is taken as input, therefore no link to specific quality control practices is assumed. The authors later extended the approach to longer production lines in [132] by proposing a decomposition approach. In [52] and [54], approaches to evaluate the performance of synchronous manufacturing lines, considering quality control actions triggered by statistical control charts are proposed. The previous binary quality failure model was replaced by considering multiple operational states, each one characterized by its specific fraction of defective parts produced. As in the previous contribution, the control mechanism is modelled through a transition probability that takes the machine to an un-operational state. However, this probability is analytically derived by combining the control chart and the system parameters. In [41] a queuing model was proposed to investigate in detail the link between SPC delay and flow time in a system with inspection stations. The applications of these methods have led to the identification of interesting phenomena due to the trade-off between quality and production logistics performance and to the derivation of design and operational decisions to exploit this trade-off. As emerges from this analysis, currently the research integrating production logistics and quality aspects has only concentrated on first order performance measures of the system, while due-date performance measures are neglected. Although manufacturing system oriented methods for estimating the variance of the cumulated output have been proposed [49], they do not consider the implication with the quality performance. A recent review of these approaches can be found in [275]. The only study on quality robustness in manufacturing system is proposed in [157] where Bernoulli production lines are investigated.

3.2.3. *System level defect management policies*

Defect management policies in manufacturing systems can be activated after the defect has been detected by part inspection technologies or visual inspection performed by human operators. A framework for characterizing defect management policies in manufacturing systems has been proposed in [44]. These policies include scrap, in-line rework, off-line rework, repair, and downgrade. The implementation of these policies affects the overall system performance in terms of quality, production logistics and maintenance KPIs. Therefore, the selection of the most proper defect management policy for each specific defect type should be taken under an integrated *production quality* view. A method to quantitatively predict the *production quality* implication of these policies is shown in [44], where the approach is applied to the electric drive assembly system described in Section 1.2. The impact of scrap policies on the manufacturing system performance has been widely studied in the literature. Helber [99] and Han and Park [97] proposed decomposition methods for the performance evaluation of multi-stage production lines in which the fraction of non-conforming parts is scrapped by the system. In these contributions, the production of non-conformities is a random event and it is not related to the machine state. Colledani and Tolio [53] analysed the performance of a manufacturing system with off-line inspection stations and scrapping of defective items. In this work, the fraction of defective parts at the scrapping stage is a function of the rate of occurrence of a process out-of-control, of the system dynamics and of the sampling frequency at the inspection stations. In general, scrapping positively affects the system yield at the cost of reducing the total throughput of a system and of loosing the workpiece value accumulated until the stage where scrapping takes place. Scrapping causes waste. Therefore, suitable waste management policies have to be defined in view of the zero-waste manufacturing paradigm. Recently, an attractive option for industrial waste management is the principle of *industrial symbiosis*. According to this principle, the waste of a company is transformed into raw materials for another company. The EU funded project ZERO-WIN [323] addresses this challenge and proposes several demonstrators in different sectors including electronic products, buildings, automotive and consumer goods. Rework policies have also been extensively investigated. The first works in this area only considered the implications of rework with the total production rate of the system, neglecting the impact on the product quality. In [155] the performance of the systems with rework are analysed through an overlapping decomposition approach. Defective parts are extracted from the main flow, undergo preparation processes in off-line stages and then are re-inserted upstream in the line for reprocessing. This method is applied to a real paint shop in [156]. In [31] a model of a manufacturing system with multiple rework loops is developed. More recently, the impact of rework on the quality and productivity performance has been jointly analysed. In [158] a method to evaluate first time quality and quality buy rate in a rework/repair paint shop in the automotive industry is proposed. This work has been extended to include a model of the part variations along the process stages [120]. In [20] the authors analysed the performance of production systems monitored by on-line SPC and rework of defective products. They considered for the first time the dependency of the rework probability on the quality control system parameters and on the machine deterioration dynamics. The application to a real system in the white good industry is reported. Product repair has attracted less attention in the literature. Repair differs from rework since re-processing is not applied. Repair can be performed manually or automatically in the same stage where the defect is generated or downstream at correlated process stages. For example, in [43] repair strategies for restoring the quality of electric drives are discussed from a technical feasibility point of view. Product repair strategies have also been applied in manufacturing systems producing batteries for electric cars [121].

3.2.4. *Integrated production control and quality control strategies*

Pull-type production control policies have been developed with the objective of coordinating different stages in manufacturing systems to react to actual occurrences of demand rather than future demand forecasts like in push systems, according to the JIT principles. These policies include kanban, basestock, CONWIP policies. For a recent review and a comparison of these policies see [167]. These mechanisms control part releases at the stages in order to resolve the trade-off between unsatisfied demand and holding costs. A pull mechanism explicitly controls the WIP in the system. Other dynamic production control policies, based on indirect WIP control activated by workstation processing rate adjustments, are proposed in [14,176,281,130]. These policies have been traditionally compared in terms of production logistics performance and due-date performance. However, since the inventory has a relevant impact on quality, as commented in Section 3.1.1, production control policies affect *production quality* performance. A comparison between quality and productivity performance in pull and push systems is discussed in [165]. In [57] the effective production rate of a CONWIP controlled production system where machines are monitored by SPC is analysed. A CONWIP population level that maximizes the effective throughput was found for any closed-loop system configuration, including those providing a flatness region in the total production rate curve. In [55] an optimization method for jointly setting kanban card levels and the parameters of statistical control charts has been proposed. The objective is the maximization of an income function, obtained by combining both production and quality related costs and the constraint include the satisfaction of a target production rate of the system. The authors showed that the optimal solution obtained by the joint approach has an income that can be 40% higher than the impact obtained by isolated approaches. Other approaches have tackled the problem from a quality-oriented perspective. Del Castillo [63] investigated how the parameters of a statistical control chart affect the service level of a small production-inventory system with stochastic demand by proposing a semi-Markov model of the system. In [259] a production-inventory-inspection system is analysed modelling a specific portion of a front-end semiconductor facility comprising an etching tool. The product is defective if the dust level caused by the etching tool increases a fixed value. An optimal part release policy from the production station into the buffer is developed to reduce the number of inspected items under a given defect risk. In [301] the problem of batch release control in the semiconductor industry is taken into account. In detail, incoming parts are selected in order to minimize the within batch variability. Then, for each specific batch, the production parameters at the downstream stages are adjusted in order to reduce the between-batch variability observed at the end of the line. Selective assembly can be also seen as an integration of quality and production control. In the literature, quality-oriented approaches have been developed that study the effect of the component sorting policy on the assembled product quality [184]. Other studies investigate the effects of process adaptation on the performance of selective assembly systems [126]. Process adaptation means that the nominal value of the key quality characteristics of the component produced with the more capable production process can be adjusted according to pre-defined states of the system, in order to increase the component matching. Recently, simulation and analytical methods have been used for predicting the impact of specific adaptation policies on the *production quality* performance [174]. An attempt to apply selective assembly to address the part gap control problem in automotive remote laser welding applications is done in the EU project RLW Navigator [228]. Self-optimizing, advanced cognitive methods have been proposed for tolerance matching problems. A cognitive architecture for advanced production and quality control systems was set up by Schmitt et al. [248,251,252] based on the generic human cognitive process model. An essential requirement upon cognitive architecture is to build a model of the production processes to be optimized and to be equipped with learning capability.

3.2.5. *Set-up and batching for quality and productivity*

In a flexible, multi-product manufacturing system, set-ups are detrimental for the system production rate as they increase the system unproductive time. Substantial research has been devoted to product sequencing considering set-ups [22]. Mathematical programming [222] and soft computing techniques [90] are usually used to find the optimal sequence in multi-product contexts. Recently, a real time control strategy has been proposed for production control in flexible manufacturing with set-ups based on an extension of the hedging point policy, called hedging zone policy [284]. All these works neglect the implications with product quality. Set-ups are usually considered as detrimental to product quality, especially in those contexts where a ramp-up operation is required after the set-up has been performed. This phenomenon has been studied in [298] where the authors developed a Markovian approach to predict the fraction of defective parts produced in a flexible system producing in batch with set-ups. This work is extended to product sequencing problems with quality considerations [297]. Methods to identify the quality bottleneck sequence in flexible manufacturing systems are developed in [296] and [299] based on data collected from the shop floor. In [172] an approach to set-up planning for ensuring the achievement of desired quality specifications is proposed. A part variation model is developed and dynamic programming is used for the optimization. The authors showed that currently adopted experience-based approaches tend to be conservative and allocate work to the most capable processes, since a model of the variational patterns is not available. Frequent machine set-ups among different part types also generate small production runs (batches) and this may be disruptive for product quality since process learning through data analysis is prevented [116]. The area of quality control and process improvement in small-batch production has been recently investigated. Small batches can benefit very little from statistical inference built exclusively on work piece-related dimensional data. Therefore, correlation and behavioural patterns that link machine-process related status parameters with more general dimensional and shape-related metrological parameters are needed [58]. To this purpose, multi-sensor data fusion has been applied (see Section 4.3). Another promising technology to address this problem is profile monitoring where functional features instead of dimensional features are monitored [194]. All these methods have been traditionally evaluated in terms of quality responsiveness performance. The implications with production logistics and maintenance are typically neglected. Another non-negligible implication of set-ups needs to be taken into account. A higher number of set-ups and lower batch size decrease the WIP. Therefore, by the decreasing the WIP they positively impact on product quality, for two reasons. With small batches the quality information feedback can be propagated with short delays, thus enabling a more reactive control of the system. Moreover, if goods are perishable, small lots are beneficial. [30] formulates a mixed-integer non-linear programming model for optimal lot splitting to account for possible effects of production run length on product quality in cellular manufacturing systems. The main idea is that when a production lot is split into several alternative routes, the production run in each route will be shortened and this may result in better product quality. Production planning and lot sizing with variable and uncertain yield has also been addressed. Yield decrease causes the need for larger lots to be able to deliver to the customer the required quantities of conforming items, given that a certain fraction will be defective [285]. For a review of first works in this area see [318]. In [36] a lot sizing model with quality and maintenance considerations is proposed. Sarker et al. [236] developed models for an optimal batch quantity for a manufacturing system with rework of defects. A closed-form formula for the system performance is developed and non-linear optimization techniques are used for deriving the optimal lot size.

3.2.6. *Maintenance in multi-stage systems*

A multi-stage system is a multi-components system built on different interactions between components by considering that the states of components influence the states of others. From a dependability point of view, influences are materialized by the principle of failure interaction or stochastic dependency [205]. Traditionally, the performance of manufacturing systems under corrective maintenance operations has been estimated. *Corrective maintenance* means that the maintenance activity is only activated after a failure has been realized. For a review of methods for throughput estimation in unreliable manufacturing systems under corrective maintenance see [159]. For a review of methods focusing on assembly systems see [100]. More recently, the impact of *preventive maintenance* policies, including both *Age Based* (*ABM*) and *Condition Based* (*CBM*), on the system productivity performance has been considered [115]. A key issue in analysing the impact of preventive maintenance is the modelling of degradation processes. For instance, degradation can be due to the wear of tools, fixtures, or machine components. Degradation is a progressive process that increases the probability of breakdown over time. A degrading process has been usually modelled as a homogenous or inhomogeneous Markov chain with increasing failure rate [320]. In practice, in order to select the number of operational states and the elements of the transition rate matrix that better approximate a real degradation process two approaches can be coupled. Firstly, a transition from one operational state to another may correspond to a specific physical event and the states to a specific machine, component, or tool condition. For example, in [264] a multi-state degradation model for a friction drilling process subject to tool wear was developed. Secondly, the states can be thought of in an abstract way as representing a discretization of the deterioration process. In this way, generally distributed degradation processes can be modelled by using acyclic continuous Phase Type (PH) distributions [213]. Such process and equipment degradation models have been incorporated in manufacturing lines [47,316] and assembly systems [234] in order to approximate the productivity performance of the entire line. These models have shown that, in multistage systems, optimal single stage, isolated maintenance policies can be weak if applied to multi-stage systems due to the locations of the bottlenecks in the system [10].

In multi-stage systems, when a component is failing, one or several components can be impacted and require to be maintained. Indeed inspection or replacement action on one component can initiate, at the same time, another action on a "dependent" component, as advocated by *Block Replacement Policy* (BRP). In this sense, the downtime to repair a component is an "opportunity" to maintain other components in the system. This opportunity is offering an additional solution space to the conventional planning and scheduling of maintenance activities for anticipating failures, reducing system unavailability and maintenance costs (both direct and indirect). Such opportunity can be detected by prognostics tools, which allow assessing the degradation state and the performance level of each component, also taking into account the dependencies and the dynamics of the whole system [204]. Opportunity is the central concept of "Opportunistic Maintenance", initially defined in [181] as "Opportunistic Replacement and Inspection Policy". For a recent review see [24]. Opportunistic Maintenance may entail (i) grouping several maintenance actions together [69,100], (ii) associating a preventive maintenance task to a corrective maintenance action [16,237], or (iii) performing a maintenance action during an opportunity [6,114,133,154]. Opportunistic Maintenance can be implemented only when technical and economic conditions are satisfied in a way to achieve optimal maintenance in terms of a balance between maintenance cost and component/system reliability.

3.2.7. *Joint maintenance and production scheduling*

The problem of planning maintenance and production operations in manufacturing systems has been widely addressed by researchers, mainly in isolation. The survey by Wang discusses the major contributions of the maintenance policies of deteriorating systems [294]. These contributions and methods do not take into account any other system information, such as inventory levels or the states of the other resources in the system. Therefore opportunistic maintenance policies cannot be considered. In the production planning area, machine failures are usually considered, but without having any control over the failure occurrence. Indeed, optimal production policies often model only two-state Markovian failure mechanisms, which means that component lifetime is exponentially distributed, thus precluding preventive maintenance with increasing failure rate from being modelled [319]. Recently, the idea of jointly planning production and maintenance has received attention in the literature [39,267,268]. The common features of these studies are that they examine the joint optimal production and maintenance policy for a machine and an inventory that decouples the facility with the stochastic market demand. In [33] the value of the integration of production and maintenance in planning and scheduling is a 30% reduction in mean job tardiness. Jin et al. [119] proposed an option-based model for a joint production and maintenance planning system to avoid backlog in case of non-deterministic demand. Kaihara et al. [124] proposed a model for the optimal maintenance and production planning in re-entrant lines. Moreover, [317] analysed the benefits of adjusting the throughput of degrading machines on the maintenance scheduling efficiency. The idea is that the throughput of a resource in highly degraded states can be adjusted in order to control the remaining life before the next maintenance operation. The authors investigated the joint control of machine reconfiguration and maintenance in a parallel-serial manufacturing system by simulation [324]. Other works addressing simultaneous planning of production and maintenance are [5,35,92,211]. This integration is studied also in [4,62,127] with considerations related to deterioration processes with increasing failure rate. In particular, in [68] a buffered two stage system where the first stage goes through degradation was considered. A Markov decision model was proposed to optimally select the critical state of the first stage that activates preventive maintenance, for each buffer level. The rationale is that when the buffer is close to empty, maintenance should be activated only in very critical degradation states [145,286].

3.2.8. *Joint maintenance and quality control strategies*

In all the previously revised works, degradation only entails and increased chance of a failure to happen. However, degradation of a component/system is one of the major factors that cause defective product output [142]. In that way, one conventional solution to reduce the number of defective units, is to conduct preventive maintenance strategy on the component/system to keep it in acceptable conditions, in phase with requirements expected on the product quality. Another solution is to sample the output to screen out the defective units. An innovative way is to combine these two approaches in order to integrate these two management practices (e.g. Preventive Maintenance (PM) and SQC) for finding the optimal policy minimizing the total expected cost. The combined application of SQC techniques and PM methods for achieving higher product quality and more effective use of resources has been investigated at single machine level [32,321]. Later [170,265] combined the two approaches, at system level. In [142] an optimal adaptive control policy for machine maintenance and product quality control is derived. Moreover, [215] developed an optimal process control and maintenance procedure under general deterioration patterns, and [37] minimized the cost of an integrated systemic approach to process control and maintenance based on EWMA control charts by using genetic algorithm. A performance measurement system for integrated SPC and CBM procedures is proposed in [122]. These works show that quality control based on product measurements can be useful for enhancing improved maintenance procedures.

3.2.9. *Joint maintenance, production logistics and quality control*

The interactions between quality, production logistics and maintenance have been mainly analysed at managerial, tactical and strategic levels [147]. Only few recent works have proposed quantitative tools and methods to address operational issues with integrated approaches. In [9] a conceptual model for planning maintenance operations in view of the overall plant effectiveness, including quality and productivity considerations, and profitability was proposed. Its application to a Swedish paper-mill plant showed that an extra profit of about 8 million SEK per year could be achieved. In [128] a regression model linking quality and maintenance hours to productivity performance is proposed for the food industry. The authors show that significant correlations exist between these aspects. Pandey et al. [216] proposed an integrated planning model to improve the performance of a single stage system. Firstly, the selection of the optimal maintenance interval and process quality control parameters is jointly performed. Then the optimal preventive maintenance interval is integrated within the production planning problem in order to determine the optimal batch sequence that will minimize penalty-cost incurred due to schedule delay. The results show that cost savings up to 80% can be achieved. Radhoui et al. [224] investigated the full integration of these areas under a different perspective in a single stage system. They proposed to use the fraction of defective parts delivered by the system as the monitored variable that can activate maintenance activities if a fixed threshold is exceed. Then, a buffer of finite size is located. The parameters of this control system are jointly optimized. Dhouib et al. [66] proposed an hedging point policy approach to control a degrading quality machine, where a security stock of finished products is maintained in order to respond to demand and to avoid shortages during maintenance actions. These works extend the approaches revised in Section 3.2.8 to the case of imperfect quality. The only work integrating all aspects in a multi-stage model has been proposed by Colledani and Tolio [56]. The authors developed a model of a multi-stage asynchronous serial line where machines are subject to deterioration. While going through deteriorated states, increasing failure rate and decreasing yield are observed. For this machine, a maintenance action based on SPC or PM or both can be carried out. The authors showed that in multi-stage systems, while selecting the optimal maintenance thresholds, the solutions obtained by neglecting quality deterioration and the system dynamics are always sub performing in terms of effective production rate and always overestimate the length of maintenance cycles. Moreover, the optimal maintenance policy at one machine is highly affected by the parameters of the other machines in the system. The benefits in the effective production rate can be as high as 30%.

4. Enabling technologies

The improvement of *production quality* targets in industrial processes requires the development of new and emerging technologies. This section revises advanced technology and ICT solutions supporting the *production quality* target.

4.1. *Product inspection technologies*

The implementation of the *production quality* paradigm requires advanced technologies for on-line data gathering, incorporating:

- 3D flexible part verification through integration of multi-sensor, multi-resolution systems.
- ICT architectures to support in-line inspection and data sharing at system level.

Manufacturing of complex 3D parts for highly customized small batch production is creating a strong demand of advanced inspection systems to characterize the physical aspects of the produced parts. During the last years, efforts was made to increase the availability of affordable point-based measurement systems, capable of acquiring large amounts of data as point coordinates, with high accuracy. Although very accurate in measurements, these technologies are very difficult to be implemented on-line due to the invasive interference with the process cycle time. To overcome these limitations, 3D inspection analysis has progressed significantly, where advanced sensors have evolved from single sensors into multi-sensors [17,88].

Multi-sensors have several advantages: (i) different inspection technologies can be used; (ii) the number and type of sensors are not limited; (iii) diverse data can be added adaptively; and (iv) multi-scale data can be merged into a single multi-scale model. Today, sensors are classified as contact and non-contact types based on the interaction with the inspected part. A typical multi-sensor configuration includes both contact sensors (e.g. touch probes) and non-contact sensors (e.g. video cameras, laser scanners and micro-probes) mounted on the same machine. The multi-sensor head of the Nikon scanning system [206] is depicted in Fig. 13. Contact and non-contact sensors each have their own working principles and properties, simultaneously providing diverse and complementary data that can considerably improve inspection. Customers continue to demand smaller, faster, cheaper, easier and more precise metric solutions. Multi-sensors can meet these demands more effectively than can multiple single-sensors [173]. Contact sensors usually provide sparse and very accurate high-resolution (HR) data with long inspection time, while non-contact sensors [226] provide dense and less accurate low-resolution (LR) data but can measure thousands of points per second. Due to their differing accuracies, these two data sets can be regarded as multi-resolution data. However, the majority of multi-sensor data is often lost and unutilized. Therefore, the main challenge lies in how to utilize the LR data despite its lower accuracy.

Fig. 13. Multi-sensor head: laser scanner (left) and touch probe (right).

The automation of such inspection technologies inline poses interesting challenges to data acquisition. Large information volume acquired through multiple advanced sensors will have to be processed, fused, organized and stored in the data repository so that it can be used both on-line and off-line, at any stage of the product life-cycle where it is requested. The use of MTConnect, the open software standard for data exchange and communication between manufacturing equipment recently launched by the Association for Manufacturing Technology [292] as well as other communication standards [207] can potentially support this task. Such information-sharing platform would enable interoperability among (i) the different heterogeneous sensors distributed in the process chain and among (ii) the data gathering system and the data processing models and methods that have been developed for the *production quality* paradigm.

Moreover, the availability of on-line data gathering technologies will support the achievement of dynamic inspection planning decisions, according to the "real" state of the processes and resources. One of the first attempts in this direction was done by [227] with the Productivity+ tool. This tool implements process probing checks and dynamically modifies the inspection process plan. This solution can support maintenance decision making at shop floor level. This aspect is a fundamental step towards the implementation of integrated quality, maintenance and production logistics tools.

4.2. Process monitoring technologies

The *production quality* paradigm needs technologies to provide higher degree of machine-condition awareness and advanced diagnostics and maintenance ability with lower interference with the system production rate.

There are specific machining processes, e.g. precision grinding, centerless grinding, that may offer superior accuracy and stability because of their own inherent properties combined with the possibility to check the machine parameters and to measure the work piece during machining [305]. When this intimate level of integration between machining and checking is attainable, it is usually called "in process" control, to differentiate it as a special case of in-line control. For a variety of reasons, machining such as turning or milling do not yet easily afford in-process control, though they certainly give room to off-process, in-line measurement. However, still there is chance to monitor machine critical parameters (e.g. spindle stray vibrations, spindle torque and axial force, lubricant pressure, tool integrity and in-fly kinematics, instantaneous power profiles, etc.) as the machining occurs. A review on techniques for sensor monitoring of machining operations is presented in [277]. The scheme of a sensorized turning machine provided by Artis GmbH, a Company of Marposs Group, is represented in Fig. 14. However, correlating process signals and product geometry metrological data is still a challenge in manufacturing operations.

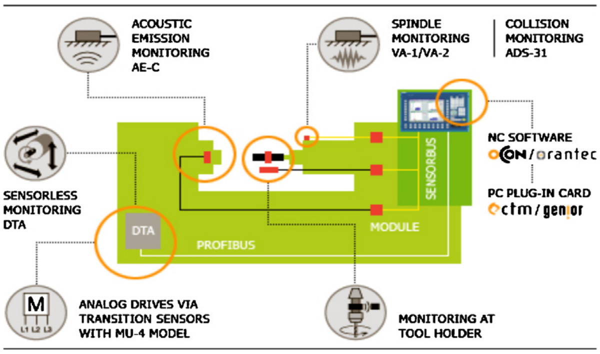

Fig. 14. Multi-sensor system for process monitoring.

4.3. Multi-sensor data fusion technologies

Multi-sensor data fusion technology is usually applied to metrology data [304] and signal data [84]. With reference to metrology data, more frequently companies face the problem of inspecting Geometric Product Specifications (GPS) of complex and freeform surfaces [110], rather than simple dimensions. Currently, a trade-off between resolution and inspection time is defined per single-sensor processes. Most of the approaches for data and signals fusion from multi-sensors consider AI-based tools (e.g. neural networks) that usually need long training times [166]. Current data fusion approaches lack in the ability of coping simultaneously with metrology data and signal data, and do not refer to the correlation between them [59].

Multi-resolution modelling has been explored by a variety of algorithms over the years [190,276]. The underlying idea behind all these algorithms is to adapt the resolution to the features' level-of-detail. Multi-resolution methods can be applied to a variety of engineering problems such as reconstruction of 3D models from cloud of points [13,263], reconstruction from 2D images acquired by Scanning Electron Microscope (SEM) [235], and verification of 3D freeform parts with noise. After the 3D model is reconstructed, it can be analysed utilizing multi-scale finite element methods [219] or optimized applying domain decomposition re-meshing techniques [322].

4.4. Learning technologies and cognitive computing methods.

Since most of the methods revised in Section 4 rely on resource reliability and degradation models obtained from field data, learning technologies and cognitive computing methods are relevant for the *production quality* scope. Intelligent data analysis and classification methodologies have been proposed in the last years in order to predict behaviours of machines and processes and to provide fault diagnosis based on predictor variables. A comprehensive review of these approaches can be found in

[277]. Thus, taking into account the results and the conclusions achieved from such methods, knowledge extraction and decision making support tasks can be accomplished with the aim of reinforcing holistic quality system and suggest actions to be performed in order to maintain the resources in the system. There exist several recent techniques to deal with this issue. The most important include Decision and Regression Trees, Classification Rules, Fuzzy Models, Genetic Algorithms, Bayesian Networks, Artificial Neural Networks. Failure detection and classification are, in general, well established and accomplished nowadays [199]; however, prognosis procedures based on multiple conditions are not yet well defined [85].

4.5. E-maintenance technologies

Internet and tether-free technologies contributed to a transition from traditional "fail and fix" maintenance practices to a "predict and prevent" e-maintenance approach [151,198]. Through e-Maintenance relevant data, information, knowledge, and intelligence is made available and usable at the right place, at the right time for anticipated maintenance decisions. E-Maintenance is a holistic enterprise process which integrates the principles already implemented by tele-maintenance [150] into web-services and collaboration platforms, thus encompassing traditional synchronization principles [113]. These systems are supported by technologies such as wireless communications, mobile components (e.g. Personal Digital Assistant, SmartPhones, Graphic tablets, harden laptops), smart sensors, MEMS, Global Positioning System (GPS), and Web CMMS. E-maintenance is offering services/processes and tools to monitor the asset degradation, to diagnose its root cause and to prognosticate its remaining useful life in order to optimize the asset utilization in the facility. The performance assessment and prediction tools can also be used with links to Product LifeCycle Management (PLM) applications [95,291]. For example, [74] proposes the concept of "Watchdog Agent" as an infrotronics-based prognostics approach for product performance degradation assessment and prediction. Yang and Lee [315] develops a "Bayesian Belief Network" to investigate the causal relationship among process variables on the tool and evaluate their influence on wafer quality in semiconductor manufacturing.

4.6. Product traceability technology

In complex manufacturing system layouts featuring parallel machines, non-linear material flows and split-merge stages tracking the product throughout the process-chain stages and correlating its features to the specific processes that manufactured/assembled the product is a priority for improved maintenance, quality and logistics control. The introduction of product data into the conventional control system ensures the arrival of the correct items for manufacturing and to trace the product (and its subcomponents) through the different stages of system. Product traceability through RFID technologies has been proposed as a solution to this problem [253]. With this technology traceability and quality error management can be performed. Direct tracking of the items moving through the system enables accurate status of each item to be maintained in a suitable data store. This provides correlation information that can be used with any error that is detected, enabling simpler root cause analysis and fault diagnostics [256]. Moreover, defect management policies implemented at shop floor can benefit from this technology, as specific knowledge of the process sequence can improve product rework and repair operations.

4.7. Production monitoring technologies

Production monitoring technologies at shop floor level can support the *production quality* paradigm by providing the required set of data about the timed sequences of the states of the resources in the system to enable the joint production, quality and maintenance procedures. In [273] the most promising production monitoring tools are revised. In particular, the 'andon' system has been recognized as an important enabler for quality and maintenance operations. The andon system is one of the elements that make up the principle of 'jidoka'. It consists in an intuitive stage visualization system with a suitable human machine interface (HMI). Recent works have quantitatively investigated the impact of andon on production, quality and maintenance performance [160], showing benefits at system level. Production monitoring systems can be also support system performance monitoring [223] and bottleneck identification [163], which are fundamental tools for production improvement.

4.8. ICT and digital manufacturing technologies

ICT solutions can support the *production quality* principle by vertically transferring process, quality control and diagnostics data at decision making level and vice versa, by achieving interoperability and integration of multi-scale and heterogeneous shop floor data and by avoiding defect generation in manual operations through virtual and augmented reality tools.

As concern the first issue, an ICT architecture to support visualizing and managing interactions among different quality and process control loops at shop floor level has been developed [247]. The concept of the software combines the assessment of a quality control loop and its step-by-step improvement. The tool can additionally be used to efficiently guide the user through all the steps that are required for defining a new quality control loop to be implemented. A Man, Machine, Maintenance and Economy (MMME) software tool has been developed and applied to FIAT in [8]. It enables to vertically connect maintenance data to production and business data for improved decision making.

Concerning the second requirement, recently knowledge-based virtual platforms have been developed for enabling data exchange and interoperability among heterogeneous ICT tools for factory planning, reconfiguration and management. For example, in the "*Virtual Factory Framework*" (VFF) EU funded project the application of a semantic data model for virtual factories to support the design of manufacturing systems is proposed [123]. An ontology-based framework can be used to share consistent design and shop-floor data between different heterogeneous software tools including, 3D virtual environments, discrete event simulation models and analytical models, at both process and system levels. Similarly, Industrie 4.0 is an initiative focused on "*Cyber-Physical Systems*" (CPS) with approaches to opportunistic maintenance, self-sensing and self-configuring components and plug-and-produce manufacturing.

Concerning the support of complex manual operations, augmented reality solutions have been proposed for improved assembly [177] and maintenance tasks [202,212]. These technologies proved to be effective in different business cases in reducing the defect generation during assembly tasks, in limiting the time, and increasing the capabilities in complex repair and maintenance operations. Moreover, they have been suitably applied for operator training programs in manufacturing [153].

5. Future research priorities

The classification of methodologies and the results illustrated in Sections 3 and 4 have been used to identify regions of the interaction model where methodologies are still missing and attention by the research community is required.

Proactive on-line defect repair policies. The traditional belief that stage correlation raises a problem for control in multi-stage systems should be drastically changed into an opportunity for improvement. Indeed, if the result of a downstream process stage is affected by the incoming product quality, then the downstream process stage can have an impact on the incoming product quality, and, if properly controlled, can possibly correct a defect generated in the upstream stages.

Joint analysis of quality correlations and system dynamics. Quality variation propagation in correlated multi-stage systems and production logistics performance of manufacturing systems have been typically analysed as two independent areas. However, in correlated multi-stage manufacturing systems, there are chances of integrating these models to provide a comprehensive and integrated model of the quality and equipment failure propagation dynamics at system level.

Preventive maintenance to improve quality robustness. The quality robustness of a system with machines having out-of-controls have only been tackled under simple machine reliability models (single state model). Preventive maintenance not only enables high service levels but it also affects the quality of the parts produced. If properly controlled, preventive maintenance operations can thus reduce the variance of the output, thus increasing the service level. Therefore models are required to jointly consider preventive maintenance and quality robustness.

Production quality in complex system architectures. The *production quality* problem has been investigated only in relatively simple manufacturing system architectures. However, modern systems frequently feature resource by-pass strategies, re-entrant flows, and process multiple part types in the same system. At present, only the production flow performance of these systems has been investigated. Re-entrant lines have been studied in [253,257,314]. Multiple part types systems have also received attention [46], as well as systems with split and merge operations [50]. However, there is a lack of comprehensive models that can consider *production quality* issues in complex system architectures combining many of the features described above.

Production quality in advanced material flow control policies. Similar to the previous case, there is a need to analyse *production quality* in systems with non-FIFO dispatching and sequencing rules. The advent of agent-based systems [191], intelligent product principles and autonomous control methods have proposed real-time decisions for dispatching parts to the available resources, to increase the system resilience to disturbances [26,254,255]. However, the implications of this complex management rules on the product quality and on the degradation of resources is at present almost unexplored.

Multi-level, multi-scale modelling, simulation and analytics for production quality. Capturing the interactions between the manufacturing and assembly process layer, where the defects are generated, and the system layer, where the defects are propagated, seems to be a promising potential solution to move towards a balanced design and management of manufacturing systems for *production quality*. The coupling of these layers into a comprehensive modelling platform could support the selection of process parameters in view of the overall *production quality* system performance as well a the selection of the optimal system architecture and part routing considering different process capabilities. However, this would require the proper integration of multi-physics, multi-scale models of manufacturing processes and systems that are currently designed as isolated tools.

Formalized data structures and interaction mechanisms among maintenance, quality and production departments. One of the major challenges to be solved to achieve high *production quality* is the lack of formalized data structures integrating product quality, resource maintenance and productivity areas. These data are commonly collected in separated databases by departments that rarely share these data. Moreover, these departments do not share company control objectives. This situation tends to generate conflicts among the competing *production quality* elements instead of privileging the search for a negotiated, overall balanced solution. Therefore, the company structure, the management control systems, and the ICT infrastructure should be re-designed and aligned, possibly with the help of ontologies, to reach *production quality* goals.

Dynamic control of production quality in the system life-cycle. To achieve a proper co-evolution level between product, process and system life-cycles, statistics on production quality targets should be more extensively collected. Moreover, transitions among different production, quality control strategies should be planned with an integrated view of the problem. In particular, although preliminary research has been carried out in this direction, the transient analysis of production quality performance in manufacturing systems ramp-up needs to be further investigated to develop suitable technologies and methodologies to reduce the costs and times of system ramp-ups.

New strategies and business models for production quality. It is well known in the manufacturing strategy literature that the company's strategy, the business model, and the operational performance need to be perfectly aligned in order to gain competitiveness in the market. The new *production quality* paradigm needs to be supported by a specific manufacturing strategy and business model. The alignment between maintenance and manufacturing strategies has been recently recognized as a key enabler for competitiveness in modern manufacturing industries [231]. Traditional quality management models tend to incorporate the zero-defect vision by maximizing the overlap of customer demands and delivered product features, while costs have to be minimized. The potentials of *production quality* is in this way heavily reduced via two implied restrictions: (i) market-sided assumption, i.e. companies cannot decide about their target *production quality* level; (ii) organizational-sided assumption, i.e. the companies' processes contain all the skills to operate exactly according to the desired product features. A new model has to allow companies to identify strategic targets and balance them towards their desired equilibrium.

An entrepreneurially influenced understanding of quality management should be defined as the immediate and waste-free fulfilment of customer demands under consideration of the strategic objectives, the conditions and the actual company's resources/skills. In this line, the Aachen Quality Model [241,245], Fig. 15, takes strategic objectives, the entrepreneurial conditions and the company's capabilities into account.

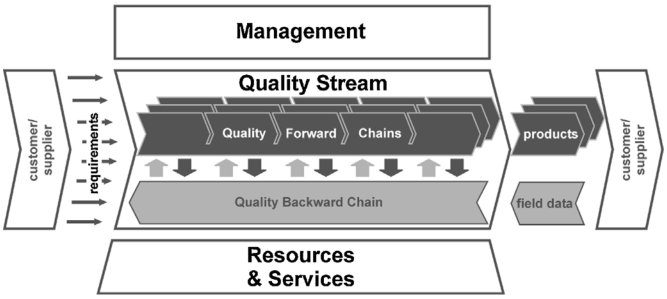

Fig. 15. Aachen quality model for entrepreneurial quality.

6. Concluding remarks

This paper has formalized the basic hypothesis of a new *production quality* paradigm for modern, zero-defect oriented, manufacturing industries. This new paradigm relies on a strong interaction among production logistics, quality and maintenance functions. The major interactions among production logistics, quality and maintenance variables have been formalized and mapped into a model that can represent a practical tool to support companies to characterize significant trade-offs in their plants. The most advanced methodologies and enabling technologies facilitating the implementation of this new paradigm in industry have been revised and directions for future research have been provided. The *production quality* paradigm represents a valuable opportunity for modern manufacturing organizations and, at the same time, a challenge calling for the development of new advanced knowledge-based manufacturing models and tools.

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References

[1] Abad AG, Guo W, Jin J (2013) Algebraic Expression of System Configurations and Performance Metrics for Mixed Model Assembly Systems. *IIE Transactions* 46(3):230–248.

[2] Abad AG, Paynabar K, Jin JJ (2011) Modeling and Analysis of Operator Effects on Process Quality and Throughput in Mixed Model Assembly Systems. *Journal of Manufacturing Science and Engineering* 133(2):1–9.

[3] Abele E, Meyer T, Näher U (2007) *Global Production: A Handbook for Strategy and Implementation*, Springer.

[4] Aghezzaf E, Najid NM (2008) Integrated Production Planning and Preventive Maintenance in Deteriorating Production Systems. *Information Sciences* 178(17):3382–3392.

[5] Aghezzaf EH, Jamali MA, Ait-Kadi D (2007) An Integrated Production and Preventive Maintenance Planning Model. *Operational Research* 181(2):679–685.

[6] AlDurgam MM, Duffuaa SO (2013) Optimal Joint Maintenance and Operation Policies to Maximize Overall Systems Effectiveness. *International Journal of Production Research* 51(5):1319–1330.

[7] Alexopoulos K, Mourtzis D, Papakostas N, Chryssolouris G (2007) DESYMA: Assessing Flexibility for the Lifecycle of Manufacturing Systems. *International Journal of Production Research* 45(7):1683–1694.

[8] Al-Najjar B, Jacobsson M (2013) A Computerised Model to Enhance the Cost-Effectiveness of Production and Maintenance Dynamic Decisions: A Case Study at Fiat. *Journal of Quality in Maintenance Engineering* 19(2):114–127.

[9] Alsyouf I (2007) The Role of Maintenance in Improving Companies' Productivity and Profitability. *International Journal of Production Economics* 105(1):70–78.

[10] Ambani S, Li L, Ni J (2009) Condition-Based Maintenance Decision-Making for Multiple Machine Systems. *Journal of Manufacturing Science and Engineering* 131(3):31009.

[11] Amini P, Schmitt R (2013) Analyzing the Deviation of Product Value Judgment. *Smart Product Engineering – 23rd CIRP Design Conference*, 765–775.

[12] Arinez J, Biller S, Meerkov SM, Zhang L (2010) Quality/Quantity Improvement in an Automotive Paint Shop: A Case Study. *IEEE Transactions on Automation Science and Engineering* 7(4):755–761.

[13] Azernikov S, Miropolsky A, Fischer A (2003) Surface Reconstruction of Freeform Objects from 3D Camera Data Based on Multiresolution Volumetric Method. *ASME Transactions Journal of Computing and Information Science in Engineering* 3(4):334–338.

[14] Bai SX, Gershwin SB (1995) Scheduling Manufacturing Systems with Work-In-Process Inventory Control: Single-Part-Type Systems. *IIE Transactions* 27(5):618–624.

[15] Barhak J, Djurdjanovic D, Spicer P, Katz R (2005) Integration of Reconfigurable Inspection with Stream of Variations Methodology. *International Journal of Machine Tools and Manufacture* 45(4):407–419.

[16] Bedford T, Dewan I, Meilijson I, Zitrou A (2011) The Signal Model: A Model for Competing Risks of Opportunistic Maintenance. *European Journal of Operational Research* 214(3):665–673.

[17] Bernard A, Fischer A (2002) New Trends in Rapid Product Development. *CIRP Annals – Manufacturing Technology* 51(2):635–652.

[18] Bi ZM, Lang SYT, Shen W, Wang L (2008) Reconfigurable Manufacturing Systems: The State of the Art. *International Journal of Production Research* 46(4):967–992.

[19] Book J, Kumar M, Lanza G, Srai J (2012) Quality Risk Management in Global Supply Networks: An Agent-Based Approach. *Proceedings of The Annual Cambridge International Manufacturing Symposium*, 1–40.

[20] Borgh D, Colledani M, Simone F, Tolio T (2007) Integrated Analysis of Production Logistics and Quality Performance in Transfer Lines with Rework. *Proceedings of the 6th International Conference on Analysis of Manufacturing Systems*, 15–20.

[21] Borgia S, Pellegrinelli S, Petrò S, Tolio T (2014) Network Part Program Approach Based on the Step-NC Data Structure for the Machining of Multiple Fixture Pallets. *International Journal of Computer Integrated Manufacturing* 27(3):281–300.

[22] Boysen N, Fliedner M, Scholl A (2009) Sequencing Mixed-Model Assembly Lines: Survey, Classification and Model Critique. *European Journal of Operational Research* 192(2):349–373.

[23] Bryan A, Ko J, Hu SJ, Koren Y (2007) Co-Evolution of Product Families and Assembly Systems. *CIRP Annals – Manufacturing Technology* 56(1):41–44.

[24] Budai G, Dekker R, Nicolai RP (2006) *A Review of Planning Models for Maintenance and Production, Economic Institute Report, 2006-44*.

[25] Bulgak AA (1992) Impact of Quality Improvement on Optimal Buffer Design and Productivity in Automatic Assembly Systems. *Journal of Manufacturing Systems* 11(2):124–136.

[26] Butala P, Sluga A (2006) Autonomous Work Systems in Manufacturing Networks. *CIRP Annals – Manufacturing Technology* 55(1):521–524.

[27] Callen JL, Fader C, Krinsky I (2000) Just-In-Time: A Cross-Sectional Plant Analysis. *International Journal of Production Economics* 63(3):277–301.

[28] Camelio JA, Hu SJ, Marin SP (2004) Compliant Assembly Variation Analysis Using Component Geometric Covariance. *Journal of Manufacturing Science and Engineering* 126(2):355–360.

[29] Camelio J, Hu SJ, Ceglarek D (2003) Modeling Variation Propagation of Multi-Station Assembly Systems with Compliant Parts. *Journal of Mechanical Design* 125(4):673–681.

[30] Cao D, Defersha FM, Chen M (2009) Grouping Operations in Cellular Manufacturing Considering Alternative Routings and the Impact of Run Length on Product Quality. *International Journal of Production Research* 47(4):989–1013.

[31] Cao Y, Subramaniam V, Chen R (2012) Performance Evaluation and Enhancement of Multistage Manufacturing Systems with Rework Loops. *Computers & Industrial Engineering* 62(1):161–176.

[32] Cassady CR, Bowden RO, Liew L, Pohl EA (2000) Combining Preventive Maintenance and Statistical Process Control: A Preliminary Investigation. *IIE Transactions* 32(6):471–478.

[33] Cassady CR, Kutanoglu E (2003) Minimizing Job Tardiness Using Integrated Preventive Maintenance Planning and Production Scheduling. *IIE Transactions* 35(6):503–513.

[34] Ceglarek D, Huang W, Zhou S, Ding Y, Kumar R, Zhou Y (2004) Time-Based Competition in Multistage Manufacturing: Stream-of-Variation Analysis (Sova) Methodology – Review. *International Journal of Flexible Manufacturing Systems* 16(1):11–44.

[35] Celen M, Djurdjanovic D (2012) Operation-Dependent Maintenance Scheduling in Flexible Manufacturing Systems. *CIRP Journal of Manufacturing Science and Technology* 5(4):296–308.

[36] Chakraborty T, Giri C, Chaudhuri S (2008) Production Lot Sizing with Process Deterioration and Machine Breakdown. *European Journal of Operational Research* 185(2):606–618.

[37] Charongrattanasakul P, Pongpullponsak A (2011) Minimizing the Cost of Integrated Systems Approach to Process Control and Maintenance Model by EWMA Control Chart Using Genetic Algorithm. *Expert Systems with Applications* 38(5):5178–5186.

[38] Cheng CH, Miltenburg J, Motwani J (2000) The Effect of Straight and U-Shaped Lines on Quality. *IEEE Transactions on Engineering Management* 47(3):321–334.

[39] Cheung KL, Hausman WH (1997) Joint Determination of Preventive Maintenance and Safety Stocks in an Unreliable Production Environment. *Naval Research Logistics* 44(3):257–272.

[40] Chin K-S, Zheng L-Y, Wei L (2003) A Hybrid Rough-Cut Process Planning for Quality. *International Journal of Advanced Manufacturing Technology* 22(9):733–743.

[41] Chincholkar M, Herrmann W (2008) Estimating Manufacturing Cycle Time and Throughput in Flow Shops with Process Drift and Inspection. *International Journal of Production Research* 46(24):7057–7072.

[42] Chryssolouris G, Chan S, Cobb W (1984) Decision Making on the Factory Floor: An Integrated Approach to Process Planning and Scheduling. *Robotics and Computer-Integrated Manufacturing* 1(3):315–319.

[43] Colledani M, Coupek D, Aichele J (2013) Proactive Quality Control System for Defect Reduction in the Production of Electric Drives. *3rd International Electric Drives Production Conference and Exhibition*, Nuremberg, Germany.

[44] Colledani M, Coupek D, Verl A, Aichele J, Yemane A (2014) Design and Evaluation of In-Line Product Repair Strategies for Defect Reduction in the Production of Electric Drives. *Proceedings of the 24th CIRP Design Conference*, Milano, Italy.

[45] Colledani M, Ekvall M, Lundholm T, Moriggi P, Polato A, Tolio T (2010) Analytical Methods to Support Continuous Improvements at Scania. *International Journal of Production Research* 48(7):1913–1945.

[46] Colledani M, Gandola F, Matta A, Tolio T (2008) Performance Evaluation of Linear and Non Linear Multi-Product Multi-Stage Lines with Unreliable Machines and Finite Homogeneous Buffers. *IIE Transactions* 40(6):612–626.

[47] Colledani M, Gershwin SB (2013) A Decomposition Method for Approximate Evaluation of Continuous Flow Multi-Stage Lines WITH General Markovian Machines. *Annals of Operations Research* 209(1):5–40.

[48] Colledani M, Lundholm T, Ratti A, Tolio T (2012) Analytical Methods for Performance Evaluation of Transfer Lines with Shared Repair Capacity at Scania. *VTI 2012 – Vehicle Technology Integration Conference*, 573–578.

[49] Colledani M, Matta A, Tolio T (2010) Analysis of the Production Variability in Multi-Stage Manufacturing Systems. *CIRP Annals – Manufacturing Technology* 59(1):449–452.

[50] Colledani M, Tolio T (2005) A Decomposition Method to Support the Configuration/Reconfiguration of Production Systems. *CIRP Annals – Manufacturing Technology* 54(1):441–444.

[51] Colledani M, Tolio T (2006) An Analytical Method to Support the Design of Production Systems Monitored by Statistical Process Control. *CIRP Seminar on Manufacturing Systems* 423–431.

[52] Colledani M, Tolio T (2006) Impact of Quality Control on Production System Performance. *CIRP Annals – Manufacturing Technology* 55(1):453–456.

[53] Colledani M, Tolio T (2009) Performance Evaluation of Production Systems Monitored by Statistical Process Control and Off-Line Inspections. *International Journal of Production Economics* 120(2):348–367.

[54] Colledani M, Tolio T (2011) Joint Design of Quality and Production Control in Manufacturing Systems. *CIRP Journal of Manufacturing Science and Technology* 4(3):281–289.

[55] Colledani M, Tolio T (2011) Integrated Analysis of Quality and Production Logistics Performance in Manufacturing Lines. *International Journal of Production Research* 49(2):485–518.

[56] Colledani M, Tolio T (2012) Integrated Quality, Production Logistics and Maintenance Analysis of Multi-Stage Asynchronous Manufacturing Systems with Degrading Machines. *CIRP Annals – Manufacturing Technology* 61(1):455–458.

[57] Colledani M, Yemane A (2010) Integrated Quality and Production Logistics Analysis of Closed Loop Manufacturing Systems. *IEEE Conference on Emerging Technologies and Factory Automation*, 1–8.

[58] Colosimo BM, Semeraro Q, Pacella M (2008) Statistical Process Control for Geometric Specifications: On the Monitoring of Roundness Profiles. *Journal of Quality Technology* 40(1):1–18.

[59] Colosimo BM, Senin N (2011) *Geometric Tolerances: Impact on Product Design, Quality Inspection and Statistical Process Monitoring*, Springer.

[60] Daaboul J, Da Cunha C, Bernard A, Laroche F (2011) Design for Mass Customization: Product Variety vs. Process Variety. *CIRP Annals – Manufacturing Technology* 60(1):169–174.

[61] De Jong A, Smit K (2012) Collaborative Contracts for Inter-Organisational Quality Systems. *Journal of Quality in Maintenance Engineering* 18(2):171–182.

[62] Dehayem Nodem FI, Kenné JP, Gharbi A (2011) Simultaneous Control of Production, Repair/Replacement and Preventive Maintenance of Deteriorating Manufacturing Systems. *International Journal of Production Economics* 134(1):271–282.

[63] Del Castillo E (1995) Relations Between Control Chart Design Variables and Production Control. *International Journal of Production Research* 33(10): 2709–2721.

[64] DEMAT, De-materialized manufacturing systems, EU FP7. Grant agreement 246020.

[65] Demir L, Tunali S, Eliiyi DT (2012) The State of the Art on Buffer Allocation Problem: A Comprehensive Survey. *Journal of Intelligent Manufacturing* 9(2):1–22.

[66] Dhouib K, Gharbi A, Ben Aziza MN (2012) Joint Optimal Production Control/Preventive Maintenance Policy for Imperfect Process Manufacturing Cell. *International Journal of Production Economics* 137(1):126–136.

[67] Digiesi S, Kock AA, Mummolo G, Rooda JE (2009) The Effect of Dynamic Worker Behavior on Flow Line Performance. *International Journal of Production Economics* 120(2):368–377.

[68] Dimitrakos TD, Kyriakidis EG (2008) A Semi-Markov Decision Algorithm for the Maintenance of a Production System with Buffer Capacity and Continuous Repair Times. *International Journal of Production Economics* 111:752–762.

[69] Ding F, Tian Z (2012) Opportunistic Maintenance for Wind Farms Considering Multi-Level Imperfect Maintenance Thresholds. *Renewable Energy* 45:175–182.

[70] Ding Y, Ceglarek D, Shi J (2002) Fault Diagnosis of Multistage Manufacturing Processes by Using State Space Approach. *Journal of Manufacturing Science and Engineering* 124(2):313–322.

[71] Ding Y, Elsayed EA, Kumara S, Lu JC, Niu F, Shi J (2006) Distributed Sensing for Quality and Productivity Improvements. *IEEE Transactions on Automation Science and Engineering* 3(4):344–359.

[72] Ding Y, Zhou S, Chen Y (2005) A Comparison of Process Variation Estimators for In-Process Dimensional Measurements and Control. *ASME Transactions Journal of Dynamic Systems Measurement and Control* 127(1):69–79.

[73] Djurdjanovic D, Zhu J (2005) Stream of Variation Based Error Compensation Strategy in Multi-Stage Manufacturing Processes. *ASME Conference Proceedings* 42231:1223–1230.

[74] Djurdjanovic D, Lee J, Ni J (2003) Watchdog Agent – An Infotronics-Based Prognostics Approach for Product Performance Degradation Assessment and Prediction. *Advanced Engineering Informatics* 17(3–4):109–125.

[75] Dogan-Sahiner E, Altiok T (1998) Planning Repair Effort in Transfer Lines. *IIE Transactions* 30(10):867–882.

[76] Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, Hauschild M, Kellens K (2012) Towards Energy and Resource Efficient Manufacturing: A Processes and Systems Approach. *CIRP Annals – Manufacturing Technology* 61(2):587–609.

[77] Egri P, Váncza J (2012) Channel Coordination with the Newsvendor Model Using Asymmetric Information. *International Journal of Production Economics* 135(1):491–499.

[78] Egri P, Váncza J (2013) A Distributed Coordination Mechanism for Supply Networks with Asymmetric Information. *European Journal of Operational Research* 226(3):452–460.

[79] ElMaraghy H, Schuh G, ElMaraghy W, Piller F, Schönsleben P, Tseng M, Bernard A (2013) Product Variety Management. *CIRP Annals – Manufacturing Technology* 62(2):629–652.

[80] ElMaraghy WH, Meselhy KT (2009) Quality and Maintainability Frameworks for Changeable and Reconfigurable Manufacturing. *Changeable and Reconfigurable Manufacturing Systems*, 321–336.

[81] ElMaraghy W, ElMaraghy H, Tomiyama T, Monostori L (2012) Complexity in Engineering Design and Manufacturing. *CIRP Annals – Manufacturing Technology* 61(2):793–814.

[82] Emmons H, Rabinowitz G (2002) Inspection Allocation for Multistage Deteriorating Production Systems. *IIE Transactions* 34(12):1031–1041.

[83] ENEPLAN – Energy efficient process planning system, www.eneplan.eu.

[84] Esteban J, Starr A, Willetts R, Hannah P, Bryanston-Cross P (2005) A Review of Data Fusion Models and Architectures: Towards Engineering Guidelines. *Neural Computing and Applications* 14(4):273–281.

[85] Ferreiro S, Arana R, Aizpurua G, Aramendi G, Arnaiz A, Sierra B (2009) Data Mining for Burr Detection (in the Drilling Process). *Distributed Computing, Artificial Intelligence, Bioinformatics, Soft Computing, and Ambient Assisted Living*, Springer, Berlin, Heidelberg1264–1273.

[86] Fleischer J, Spath D, Lanza G (2003) Quality Simulation for Fast Ramp Up. *36th CIRP International Seminar on Manufacturing Systems, 33/6*.

[87] Fogliazza G (2004) How Information Technology Enables the Potential Flexibility and Re-Configurability of Highly Automated Manufacturing Plants. *IFAC International Control Problems in Manufacturing*, 389–404.

[88] Fraden J (2010) *Handbook of Modern Sensors: Physics, Designs, and Applications*, 4th ed. Springer, New York.

[89] From Recall to Prevention, SGS Consumer Information Bulletin, 11/15/2012.

[90] Gagné C, Gravel M, Price WL (2006) Solving Real Car Sequencing Problems With Ant Colony Optimization. *European Journal of Operational Research* 174(3):1427–1448.

[91] Georgoulias K, Papakostas N, Makris S, Chryssolouris G (2007) A Toolbox Approach for Flexibility Measurements in Diverse Environments. *CIRP Annals – Manufacturing Technology* 56(1):423–426.

[92] Gharbi A, Kenné JP (2005) Maintenance Scheduling and Production Control of Multiple-Machine Manufacturing Systems. *Computers & Industrial Engineering* 48:693–707.

[93] Goch G, Knapp W, Härtig F (2012) Precision Engineering for Wind Energy Systems. *CIRP Annals – Manufacturing Technology* 61:611–634.

[94] Guerriero F, Miltenburg J (2003) The Stochastic U-Line Balancing Problem. *Naval Research Logistics* 50:31–57.

[95] Gulledge T, Hiroshige S, Iyer R (2010) Condition-Based Maintenance and the Product Improvement Process. *Computers in Industry* 61(9):813–832.

[96] Haefner B, Kraemer A, Stauss T, Lanza G (2014) Quality Value Stream Mapping. *Procedia CIRP* 17:254–259.

[97] Han MS, Park DJ (2002) Optimal Buffer Allocation of Serial Production Lines with Quality Inspection Machines. *Computers & Industrial Engineering* 42(1):75–89.

[98] Haque L, Armstrong MJ (2007) A Survey of the Machine Interference Problem. *European Journal of Operational Research* 179:469–482.

[99] Helber S (1999) *Performance Analysis of Flow Lines With Non-Linear Flow of Material*, Springer-Verlag.

[100] Hu J, Zhang L, Liang W (2012) Opportunistic Predictive Maintenance for Complex Multi-Component Systems Based on DBN-HAZOP Model. *Process Safety and Environmental Protection* 90(5):376–388.

[101] Hu J (2006) Co-Evolution of Product Families and Manufacturing Systems. *Presentation at the Species WG meeting in Kobe*.

[102] Hu SJ, Ko J, Weyand L, ElMaraghy HA, Lien TK, Koren Y, Shpitalni M (2011) Assembly System Design and Operations for Product Variety. *CIRP Annals – Manufacturing Technology* 60(2):715–733.

[103] Huang N, Inman R (2010) Product Quality and Plant Build Complexity. *International Journal of Production Research* 48(11):3105–3128.

[104] Huang Q, Shi J (2004) Variation Transmission Analysis and Diagnosis of Multi-Operational Machining Processes. *IIE Transactions* 36(9):807–815.

[105] INCOSE, International Council on Systems Engineering (2010) *System Engineering Handbook v.3.2*, INCOSE, San Diego, USA.

[106] Inman RR, Blumenfeld DE (2010) Assembly Line Team Sizing with Absenteeism. *International Journal of Production Research* 48(22):6537–6558.

[107] Inman RR, Blumenfeld DE, Huang N, Li J, Li J (2013) Survey of Recent Advances on the Interface Between Production System Design and Quality. *IIE Transactions* 45(6):557–574.

[108] Inman RR, Jordan WC, Blumenfeld DE (2004) Chained Cross-Training of Assembly Line Workers. *International Journal of Production Research* 42(10):1899–1910.

[109] Inman R, Blumenfeld E, Huang N, Li J (2003) Designing Production Systems for Quality: Research Opportunities from an Automotive Industry Perspective. *International Journal of Production Research* 41(9):1953–1971.

[110] I SO TC 213 Dimensional and Geometrical Product Specifications and Verification.

[111] IEC/ISO62264-1 (2003) *Enterprise-Control System Integration – Part 1: Models and Terminology, ISO Edition*.

[112] Iung B, Levrat E, Crespo Marquez A, Erbe H (2009) Conceptual Framework for e-Maintenance: Illustration by e-Maintenance Technologies and Platform. *Annual Review in Control* 33(2):220–229.

[113] Iung B (2003) From Remote Maintenance to MAS-Based e-Maintenance of an Industrial Process. *Journal of Intelligent Manufacturing* 14(1):59–82.

[114] Iung B, Levrat E, Thomas E (2007) 'Odds Algorithm'-Based Opportunistic Maintenance Task Execution for Preserving Product Conditions. *Annals of the CIRP – Manufacturing Technology* 56(1):13–16.

[115] Iung B, Veron M, Suhner MC, Muller A (2005) Integration of Maintenance Strategies into Prognosis Process to Decision-Making Aid on System Operation. *CIRP Annals – Manufacturing Technology* 54(1):5–8.

[116] Jaber Y, Khan M (2010) Managing Yield by Lot Splitting in a Serial Production Line with Learning, Rework and Scrap. *International Journal of Production Economics* 124(1):32–39.

[117] Jambekar AB (2000) A Systems Thinking Perspective of Maintenance, Operations, and Process Quality. *Journal of Quality in Maintenance Engineering* 6(2):123–132.

[118] Jin R, Liu K (2013) Multimode Variation Modeling and Process Monitoring for Serial-Parallel Multistage Manufacturing Processes. *IIE Transactions* 45(6):617–629.

[119] Jin X, Li L, Ni J (2009) Option Model for Joint Production and Preventive Maintenance System. *International Journal of Production Economics* 119:347–353.

[120] Ju F, Li J, Xiao G, Arinez J (2013) Quality Flow Model in Automotive Paint Shops. *International Journal of Production Research* 51(21):6470–6483.

[121] Ju F, Li J, Xiao G, Huang N, Biller S (2014) A Quality Flow Model in Battery Manufacturing Systems for Electric Vehicles. *IEEE Transactions on Automation Science and Engineering* 11(1):230–244.

[122] Juuso EK, Lahdelma S (2013) Intelligent Performance Measures for Condition-based Maintenance. *Journal of Quality in Maintenance Engineering* 19(3):278–294.

[123] Kádár B, Terkaj W, Sacco M (2013) Semantic Virtual Factory Supporting Interoperable Modelling and Evaluation of Production Systems. *CIRP Annals – Manufacturing Technology* 62(1):443–447.

[124] Kaihara T, Fujii N, Tsujibe A, Nonaka Y (2010) Proactive Maintenance Scheduling in a Re-Entrant Flow Shop Using Lagrangian Decomposition Coordination Method. *CIRP Annals – Manufacturing Technology* 59(1):453–456.

[125] Kakade V, Valenzuela F, Smith S (2004) An Optimization Model for Selective Inspection in Serial Manufacturing Systems. *International Journal of Production Research* 42(18):3891–3909.

[126] Kayasa MJ, Herrmann C (2012) A Simulation-Based Evaluation of Selective and Adaptive Production Systems (SAPS) Supported by Quality Strategy in Production. *Procedia CIRP* 3:14–19.

[127] Kazaz B, Sloan TW (2012) The Impact of Process Deterioration on Production and Maintenance Policies. *European Journal of Operational Research* 227(1):88–100.

[128] Khan MR, Darrab IA (2010) Development of Analytical Relation Between Maintenance, Quality and Productivity. *Journal of Quality in Maintenance Engineering* 16(4):341–353.

[129] Khouja M, Rabinowitz G, Mehrez A (1995) Optimal Robot Operation and Selection Using Quality and Output Trade-Off. *International Journal of Advanced Manufacturing Technology* 10(5):342–355.

[130] Kim JH, Duffie NA (2005) Design and Analysis of Closed-Loop Capacity Control for a Multi-Workstation Production Systems. *CIRP Annals – Manufacturing Technology* 54(1):455–458.

[131] Kim J, Gershwin SB (2005) Integrated Quality and Quantity Modeling of a Production Line. *OR Spectrum* 27(2):287–314.

[132] Kim J, Gershwin SB (2008) Analysis of Long Flow Lines with Quality and Operational Failures. *IIE Transactions* 40(3):284–296.

[133] Koochaki J, Bokhorst JA, Wortmann H, Klingenberg W (2012) Condition Based Maintenance in the Context of Opportunistic Maintenance. *International Journal of Production Research* 50(23):6918–6929.

[134] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, Brussel HV (1999) Reconfigurable Manufacturing Systems. *CIRP Annals – Manufacturing Technology* 48(2):527–540.

[135] Koren Y, Hu SJ, Gu P, Shpitalni M (2013) Open-Architecture Products. *CIRP Annals – Manufacturing Technology* 62(2):719–729.

[136] Koren Y, Hu SJ, Weber TW (1998) Impact of Manufacturing System Configuration on Performance. *CIRP Annals – Manufacturing Technology* 47(1):369–372.

[137] Koren, Y., Katz, R., 2003, Reconfigurable apparatus and method for inspection during a manufacturing process, United States Patent 6567162.

[138] Krüger J, Lien TK, Verl A (2009) Cooperation of Human and Machines in Assembly Lines. *CIRP Annals – Manufacturing Technology* 58(2):628–646.

[139] Kruth JP, Detand J (1992) A CAPP System for Nonlinear Process Plans. *CIRP Annals – Manufacturing Technology* 41(1):489–492.

[140] Kuhn H (2003) Analysis of Automated Flow Line Systems with Repair Crew Interference. *Analysis and Modeling of Manufacturing Systems*, Springer: 155–179.

[141] Kumar U, Galar D, Parida A, Stenström C, Berges L (2013) Maintenance Performance Metrics: A State-of-the-Art Review. *Journal of Quality in Maintenance Engineering* 19(3):3-3.

[142] Kuo Y (2006) Optimal Adaptive Control Policy for Joint Machine Maintenance and Product Quality Control. *European Journal of Operational Research* 171(2):586–597.

[143] Kurfer J, Westermeier M, Tammer C, Reinhart G (2012) Production of Large-Area Lithium-Ion Cells – Preconditioning, Cell Stacking and Quality Assurance. *CIRP Annals – Manufacturing Technology* 61(1):1–4.

[144] Kuzgunkaya O, ElMaraghy H (2006) Assessing the Structural Complexity of Manufacturing Systems Configurations. *International Journal of Flexible Manufacturing Systems* 18(2):145–171.

[145] Kyriakidis EG, Dimitrakos TD (2006) Optimal Preventive Maintenance of a Production System with an Intermediate Buffer. *European Journal of Operational Research* 168:86–99.

[146] Lanza G, Book J, Kippenbrock K, Saxena A (2013) Innovative Quality Strategies for Global Value-Added-Networks. *Robust Manufacturing Control*, 271–286.

[147] Lanza G, Peters S (2012) Integrated Capacity Planning Over Highly Volatile Horizons. *CIRP Annals – Manufacturing Technology* 61(1):395–398.

[148] Lanza G, Stricker N, Peters S (2013) Ad-Hoc Rescheduling and Innovative Business Models for Shock-robust Production Systems. *Procedia CIRP* 7:121–126.

[149] Lanza G, Sauer A, Kölmel A (2012) Configuration of a Multi-Use Battery Production. *CIRP 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production*, 473–478.

[150] Lee J (1998) Teleservice Engineering in Manufacturing: Challenges and Opportunities. *International Journal of Machine Tools & Manufacture* 38:901–910.

[151] Lee J, Ni J, Djurdjanovic D, Qiu H, Liao H (2006) Intelligent Prognostics Tools and e-Maintenance. *Computers in Industry Special Issue on e-Maintenance* 57(6):476–489.

[152] Lee WR, Beruvides MG, Chiu YD (2007) A Study on the Quality–Productivity Relationship and its Verification in Manufacturing Industries. *The Engineering Economist* 52(2):117–139.

[153] Leu MC, ElMaraghy HA, Nee AY, Ong SK, Lanzetta M, Putz M, Bernard A (2013) CAD Model Based Virtual Assembly Simulation, Planning and Training. *CIRP Annals – Manufacturing Technology* 62(2):799–822.

[154] Levrat E, Thomas E, Lung B (2008) 'Odds'-Based Decision-Making Tool for Opportunistic Production-Maintenance Synchronisation. *International Journal of Production Research* 46(19):5263–5287.

[155] Li J (2004) Performance Analysis of Production Systems with Rework Loops. *IIE Transactions* 36(8):755–765.

[156] Li J (2004) Throughput Analysis in Automotive Paint Shops: A Case Study. *IEEE Transactions on Automation Science and Engineering* 1(1):90–98.

[157] Li J, Blumenfeld DE, Marin SP (2008) Production System Design for Quality Robustness. *IIE Transactions* 40(3):162–176.

[158] Li J, Blumenfeld DE, Marin SP (2007) Manufacturing System Design to Improve Quality Buy Rate: An Automotive Paint Shop Application Study. *IEEE Transactions on Automation Science and Engineering* 4(1):75–79.

[159] Li J, Blumenfeld DE, Huang N, Alden JM (2009) Throughput Analysis of Production Systems: Recent Advances and Future Topics. *International Journal of Production Research* 47(14):3823–3851.

[160] Li J, Blumenfeld E (2006) Quantitative Analysis of a Transfer Production Line with Andon. *IIE Transactions* 38(10):837–846.

[161] Li J, Huang N (2007) Quality Evaluation in Flexible Manufacturing Systems: A Markovian Approach. *Mathematical Problems in Engineering* 2007.

[162] Li J, Jin J, Shi J (2008) Causation-Based t2 Decomposition for Multivariate Process Monitoring and Diagnosis. *Journal of Quality Technology* 40(1):46.

[163] Li L, Chang Q, Ni J, Xiao G, Biller S (2007) Bottleneck Detection of Manufacturing Systems Using Data Driven Method. *Assembly and Manufacturing, ISAM '07 IEEE International Symposium*, 76–81.

[164] Li L, Warfield JN (2011) Perspectives on Quality Coordination and Assurance in Global Supply Chains. *International Journal of Production Research* 49(1):1–4.

[165] Li W (2005) Comparative Study of Push and Pull Systems Considering Quality Performance in a Cell-Based Job Shop Environment. *International Journal of Production Research* 43(23):4999–5017.

[166] Liana SY, Hecker RL, Landers RG (2004) Machining Process Monitoring and Control: The State-of-the-Art. *Journal of Manufacturing Science and Engineering* 126(2):297–310.

[167] Liberopoulos G (2013) Production Release Control: Paced, WIP-Based, or Demand-Driven? Revisiting the Push/Pull and Make-to-Order/Make-to-Stock Distinctions.Smith JM, Tan B, (Eds.) *Handbook of Stochastic Models and Analysis of Manufacturing System Operations International Series in Operations Research and Management Science*, vol. 192. Springer, New York, NY 211–247.

[168] Liberopoulos G, Kozanidis G, Tsarouhas P (2007) Performance Evaluation of an Automatic Transfer Line with WIP Scrapping During Long Failures. *Manufacturing and Service Operations* 9(1):62–83.

[169] Liberopoulos G, Tsarouhas PH (2002) Systems Analysis Speeds Up Chipita's Food Processing Line. *Interfaces* 32(3):62–76.

[170] Linderman K, McKone-Sweet KE, Anderson JC (2005) An Integrated Systems Approach to Process Control and Maintenance. *European Journal of Operational Research* 164:324–340.

[171] Liu J (2010) Variation Reduction for Multistage Manufacturing Processes: A Comparison Survey of Statistical-Process-Control vs Stream-of-Variation Methodologies. *Quality and Reliability Engineering International* 26(7):645–661.

[172] Liu J, Shi J, Hu SJ (2009) Quality-Assured Setup Planning Based on the Stream-of-Variation Model for Multi-Stage Machining Processes. *IIE Transactions* 41(4):323–334.

[173] Llinas J, Hall DL (1997) An Introduction to Multi-sensor Data Fusion. *Proceedings of IEEE* 6–23.

[174] Löchte C, Kayasa J, Herrmann C, Raatz A (2012) Methods for Implementing Compensation Strategies in Micro Production Systems Supported by a Simulation Approach. *Precision Assembly Technologies and Systems* 371:118–125.

[175] Loose J, Zhou S, Ceglarek D (2007) Kinematic Analysis of Dimensional Variation Propagation for Multistage Machining Processes with General Fixture Layouts. *IEEE Transactions on Automation Science and Engineering* 4(2):141–152.

[176] Ma YHK, Koren Y (2004) Operation of Manufacturing Systems with Work-in-process Inventory and Production Control. *CIRP Annals – Manufacturing Technology* 53(1):361–365.

[177] Makris S, Pintzos G, Rentzos L, Chryssolouris G (2013) Assembly Support Using AR Technology Based on Automatic Sequence Generation. *CIRP Annals – Manufacturing Technology* 62(1):9–13.

[178] Mandroli SS, Shrivastava AK, Ding Y (2006) A Survey of Inspection Strategy and Sensor Distribution Studies in Discrete-Part Manufacturing Processes. *IIE Transactions* 38(4):309–328.

[179] Mannar K, Ceglarek D, Niu F, Abifaraj B (2006) Fault Region Localization: Product and Process Improvement Based on Field Performance and Manufacturing Measurements. *IEEE Transactions on Automation Science and Engineering* 3(4):423–439.

[180] Maropoulos PG, Ceglarek D (2010) Design Verification and Validation in Product Lifecycle. *CIRP Annals – Manufacturing Technology* 59(2):740–759.

[181] McCall JJ (1963) Operating Characteristics of Opportunistic Replacement and Inspection Policies. *Management Science* 10(1):85–97.

[182] McDonald T, Ellis KP, Van Aken EM, Patrick Koelling C (2009) Development and Application of a Worker Assignment Model to Evaluate a Lean Manufacturing Cell. *International Journal of Production Research* 47(9): 2427–2447.

[183] McKinsey&Company (2013) *Manufacturing the Future: The Next Era of Global Growth and Innovation*.

[184] Mease DA, Sudjinato V, Nair N (2004) Selective Assembly in Manufacturing: Statistical Issues and Optimal Binning Strategies. *Technometrics* 46(2):165–175.

[185] Meerkov SM, Zhang L (2010) Product Quality Inspection in Bernoulli Lines: Analysis, Bottlenecks, and Design. *International Journal of Production Research* 48(16):4745–4766.

[186] Meerkov SM, Zhang L (2011) Bernoulli Production Lines with Quality–Quantity Coupling Machines: Monotonicity Properties and Bottlenecks. *Annals of Operations Research* 182(1):119–131.

[187] Meier H, Roy R, Seliger G (2010) Industrial Product-Service Systems-IPS2. *CIRP Annals – Manufacturing Technology* 59(2):607–627.

[188] Mhada FZ, Malhamé RP, Pellerin R (2013) Joint Assignment of Buffer Sizes and Inspection Points in Unreliable Transfer Lines with Scrapping of Defective Parts. *Production & Manufacturing Research* 1(1):79–101.

[189] Miltenburg J (2001) U-Shaped Production Lines: A Review of Theory and Practice. *International Journal of Production Economics* 70(3):201–214.

[190] Miropolsky A, Fischer A (2006) A Uniform Approach for Utilizing Synergy between Inspection Technologies and Computational Methods. *CIRP Annals – Manufacturing Technology* 55(1):123–126.

[191] Monostori L, Váncza J, Kumara S (2006) Agent-Based Systems for Manufacturing. *CIRP Annals – Manufacturing Technology* 55(2):97–720.

[192] Montgomery DC, Woodall WH (1997) A Discussion on Statistically-Based Process Monitoring and Control. *Journal of Quality Technology* 29(2):121–162.

[193] Mori M, Fujishima M, Komatsu M, Zhao B, Liu Y (2008) Development of Remote Monitoring and Maintenance System for Machine Tools. *CIRP Annals – Manufacturing Technology* 57(1):433–436.

[194] Moroni G, Pacella M (2008) An Approach Based on Process Signature Modeling for Roundness Evaluation of Manufactured Items. *Journal of Computing and Information Science in Engineering* 8(2).

[195] Mourtzis D, Doukas M (2013) Decentralized Manufacturing Systems Review: Challenges and Outlook. *Robust Manufacturing Control*, Springer: 355–369.

[196] Mourtzis D, Doukas M, Psarommatis F (2012) A Multi-Criteria Evaluation of Centralized and Decentralized Production Networks in a Highly Customer-Driven Environment. *CIRP Annals – Manufacturing Technology* 61(1):427–430.

[197] Mourtzis D, Papakostas N, Makris S, Xanthakis V, Chryssolouris G (2008) Supply Chain Modeling and Control for Producing Highly Customized Products. *CIRP Annals – Manufacturing Technology* 57(1):451–454.

[198] Muller A, Crespo Marquez A, Iung B (2008) On the Concept of e-Maintenance, Review and Current Research. *Reliability Engineering and System Safety* 93(8):1165–1187.

[199] Muller A, Suhner MC, Iung B (2008) Formalisation of a New Prognosis Model for Supporting Proactive Maintenance Implementation on Industrial System. *Reliability Engineering & System Safety* 93(2):234–253.

[200] MuProD, Innovative proactive Quality Control system for in-process multi-stage defect reduction, European Union FP7. Grant agreement n° 285075.

[201] Nada OA, ElMaraghy HA, ElMaraghy WH (2006) Quality Prediction in Manufacturing System Design. *Journal of Manufacturing systems* 25(3):153–171.

[202] Nee AYC, Ong SK, Chryssolouris G, Mourtzis D (2012) Augmented Reality Applications in Design and Manufacturing. *CIRP Annals – Manufacturing Technology* 61(2):657–679.

[203] Newman ST, Nassehi A (2009) Machine Tool Capability Profile for Intelligent Process Planning. *CIRP Annals – Manufacturing Technology* 58:421–424.

[204] Ni J, Jin X, Koren Y (2012) Decision Support Systems for Effective Maintenance Operations. *CIRP Annals – Manufacturing Technology* 61(1):411–414.

[205] Nicolai R, Dekker R (2008) *Optimal Maintenance of Multi-component Systems: A Review. Complex System Maintenance Handbook*, Springer: 263–286.

[206] Nikon. On-line Documentation, www.nikonmetrology.com.

[207] NIST (2008) *NIST IEEE-P1451 Draft Standard Home Page*. http://ieee1451.nist.gov/accessed (accessed 1.10.09).

[208] Nonaka Y, Erdős G, Kis T, Kovács A, Monostori L, Nakano T, Váncza J (2013) Generating Alternative Process Plans for Complex Parts. *CIRP Annals – Manufacturing Technology* 62(1):453–458.

[209] Nonaka Y, Erdős G, Kis T, Nakano T, Váncza J (2012) Scheduling with Alternative Routings in CNC Workshops. *CIRP Annals – Manufacturing Technology* 61(1):449–454.

[210] Nonaka Y, Suginishi Y, Lengyel A, Ono M, Sugimoto K (2008) TSUNAMI Effect Prediction Methodology for Critical Resource Analysis. *Manufacturing Systems and Technologies for the New Frontier*, Springer, London337–340.

[211] Nourelfath ME, Châtelet (2012) Integrating Production, Inventory and Maintenance Planning for a Parallel System with Dependent Components. *Reliability Engineering & System Safety* 101:59–66.

[212] Ong SK, Zhu J (2013) A Novel Maintenance System for Equipment Serviceability Improvement. *CIRP Annals – Manufacturing Technology* 39.

[213] Osogami T, Harchol Balter M (2006) Closed Form Solutions for Mapping General Distributions to Quasi-minimal PH Distributions. *Performance Evaluation* 62:524–552.

[214] Owen H, Blumenfeld E (2008) Effects of Operating Speed on Production Quality and Throughput. *International Journal of Production Research* 46(24):7039–7056.

[215] Panagiotidou S, Tagaras G (2012) Optimal Integrated Process Control and Maintenance under General Deterioration. *Reliability Engineering & System Safety* 104:58–70.

[216] Pandey D, Kulkarni MS, Vrat P (2011) A Methodology for Joint Optimization for Maintenance Planning, Process Quality and Production Scheduling. *Computers & Industrial Engineering* 61(4):1098–1106.

[217] Pellegrinelli S, Borgia S, Tolio T (2010) Step-NC Compliant Approach for Workpiece Setup Planning Problem on Transfer Line. *Proceedings of 43rd CIRP Conference on Manufacturing Systems*, 433–440IBN: 978-3-7083-0686-5.

[218] Pellegrinelli S, Tolio T (2013) Pallet Operation Sequencing Based on Network Part Program Logic. *Robotics and Computer-Integrated Manufacturing* 29(5):322–345.

[219] Podshivalov L, Fischer A, Bar-Yoseph PZ (2010) Multiresolution 2D Geometric Meshing for Multiscale Finite Element Analysis of Bone Micro-Structures. *Virtual and Physical Prototyping* 5(1):33–43.

[220] Prakash. Izquierdo LE, Ceglarek D (2009) Functional Process Adjustments to Reduce No-Fault-Found Product Failures in Service Caused by In-Tolerance Faults. *CIRP Annals – Manufacturing Technology* 58(1):37–40.

[221] Prakash PKS, Ceglarek D (2013) Multi-Step Functional Process Adjustments to Reduce No-Fault-Found Product Failures in Service Caused by In-tolerance Faults. *Procedia CIRP* 11:38–43.

[222] Prandtstetter M, Raidl GR (2008) An Integer Linear Programming Approach and a Hybrid Variable Neighborhood Search for the Car Sequencing Problem. *European Journal of Operational Research* 191(3):1004–1022.

[223] Putz M, Langer T (2012) Determination of Extended Availability and Productivity for Assembly Systems Using Existing Database. *CIRP Annals – Manufacturing Technology* 61(1):17–20.

[224] Radhoui M, Rezg N, Chelbi A (2009) Integrated Model of Preventive Maintenance, Quality Control and Buffer Sizing for Unreliable and Imperfect Production Systems. *International Journal of Production Research* 47(2):389–402.

[225] Raz T (1986) A Survey of Model for Allocation Inspection Effort in Multistage Production System. *Journal of Quality Technology* 18(4):239–247.

[226] Reinhart G, Tekouo W (2009) Automatic Programming of Robot-Mounted 3D Optical Scanning Devices to Easily Measure Parts in High-Variant Assembly. *CIRP Annals – Manufacturing Technology* 58(1):25–29.

[227] Renishaw (2008) *Probing Systems for CNC Machine Tools*, Renishaw Plc: 1–72.

[228] RLW Navigator, FP7 2011, European Project Remote Laser Welding System Navigator for Eco & Resilient Automotive Factories. Grant Agreement 285051.

[229] RobustPlaNet, FP7 2013 European Project RobustPlaNet, Shock-Robust Design of Plants and their Supply Chain Networks. Grant Agreement 609087.

[230] Repenning NP, Sterman JD (2002) Capability Traps and Self-Confirming Attribution Errors in the Dynamics of Process Improvement. *Administrative Science Quarterly* 47(2):265–295.

[231] Robson K, MacIntyre J, Trimble R (2013) Measuring the status and alignment of maintenance and manufacturing strategies–the development of a new model and diagnostic tool. *Journal of Quality in Maintenance Engineering* 381–397.

[232] Rosenzweig ED, Easton GS (2010) Tradeoffs in Manufacturing? A Meta-Analysis and Critique of the Literature. *Production and Operations Management* 19(2):127–141.

[233] Rotondo A, Young P, Geraghty J (2012) Quality Risk Prediction at a Non-Sampling Station Machine in a Multi-Product, Multi-Stage, Parallel Processing Manufacturing System Subjected to Sequence Disorder and Multiple Stream Effects. *Annals of Operations Research* 209(1):255–277.

[234] Ruifeng C, Subramaniam V (2011) Increasing Production Rate in Kanban Controlled Assembly Lines Through Preventive Maintenance. *International Journal of Production Research* 1–18.

[235] Samak D, Fischer A, Rittel D (2007) 3D Reconstruction and Visualization of Microstructure Surfaces from 2D Images. *CIRP Annals – Manufacturing Technology* 56(1):149–152.

[236] Sarker BR, Jamal AMM, Mondal S (2008) Optimal Batch Sizing in a Multi-Stage Production System with Rework Consideration. *European Journal of Operational Research* 184(3):915–929.

[237] Satow T, Osaki S (2003) Opportunity-Based Age Replacement with Different Intensity Rates. *Mathematical and Computer Modelling* 38(11–13):1419–1426.

[238] Schick IC, Gershwin SB, Kim J (2005) Quality/Quantity Modeling and Analysis of Production Lines Subject to Uncertainty. *Final Report Presented to General Motors Research and Development Center*.

[239] Schick. Irvin C, Gershwin. Stanley B (2007) A Taxonomy of Quality/Quantity Issues in Manufacturing Systems. *Proceedings of the 6th Conference on the Analysis of Manufacturing Systems*.

[240] Schmitt R, Isermann M, Wagels C (2001) Integrative Self-Optimizing Process Chains. in Brecher C, (Ed.) *Integrative Production Technology for High-Wage Countries*, Springer, Berlin.

[241] Schmitt R, Beaujean P (2009) The Quality Backward Chain–The Adaptive Controller of Entrepreneurial Quality. *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*, 1133–1143.

[242] Schmitt R, Falk B, Quattelbaum B (2009) Perceived Quality – New Information Data for Production Specifications. *CAT 2009 – 11th CIRP International Conference on Computer Aided Tolerancing: "Geometric Variations within Product Life-Cycle Management"*.

[243] Schmitt R, Falk B, Quattelbaum B, Knispel J (2013) Tolerancing Subjective and Uncertain Customer Requirements Regarding Perceived Product Quality. *Journal of Engineering Manufacture* 227(5):702–708.

[244] Schmitt R, Isermann M, Niggemann C, Laass M, Matuschek N (2010) Cognition-Based Self-Optimisation of an Automotive Rear-Axle-Drive Production Process. *Journal of Machine Engineering* 10(3):68–77.

[245] Schmitt R, Kristes D, Beaujean P (2008) Entrepreneurial Quality Management – A New Definition of Quality. *2008 IEEE International Engineering Management Conference*, 275–280.

[246] Schmitt R, Basse I (2011) A Holistic Approach to Decision Theory-Based Inspection Planning. *Procceedings 14th QMOD Conference on Quality and Service Sciences 2011*, San Sebastian, Spain, August 29–31, 214–224.

[247] Schmitt R, Monostori L, Glöckner H, Viharos Z (2012) Design and Assessment of Quality Control Loops for Stable Business Processes. *CIRP Annals – Manufacturing Technology* 61(1):439–444.

[248] Schmitt R, Niggemann C, Laass M (2012) Cognitive Failure Cluster enhancing the Efficiency and the Precision of the Self-Optimizing Process Modell for Bevel Gear Contact Patterns. *Journal of Machine Engineering* 12(1):55–65.

[249] Schmitt R (2012) Self-Optimizing production systems. in Brecher C, (Ed.) *Integrative Production Technology for High-Wage Countries*, Springer, pp. 698–891.

[250] Schmitt R, Janssen C, Basse I, Schmitt S (2013) Model for a Decision Theory Based Inspection Planning. in Zaeh M, (Ed.) *Enabling Manufacturing Competitiveness and Economic Sustainability – Proceedings of the 5th International Conference on Changeable, Agile, Reconfigurable and Virtual Production CARV2013)*, Springer, Berlin383–388.

[251] Schmitt R, Wagels C (2012) Benchmarking of Methods and Instruments for Self-Optimization in Future Production Systems. *Procedia CIRP of 45th CIRP Conference on Manufacturing Systems*, 161–166.

[252] Schmitt R, Wagels C, Isermann M (2008) Cognitive Tolerance Matching. *Proceedings of the 6th CIRP International Conference on Intelligent Computation in Manufacturing Engineering:*, 289–293.

[253] Scholz-Reiter B, Freitag M, Schmieder A, Pikovsky A, Katzorke I (2006) in Radons G, Neugebaue R, (Eds.) *Nonlinear Dynamics of Production Systems*, Wiley.

[254] Scholz-Reiter B, Görges M, Philipp T (2009) Autonomously Controlled Production Systems – Influence of Autonomous Control Level on Logistic Performance. *CIRP Annals – Manufacturing Technology* 58(1):395–398.

[255] Scholz-Reiter B, Rekersbrink H, Görges M (2010) Dynamic Flexible Flow Shop Problems – Scheduling Heuristics vs. Autonomous Control. *CIRP Annals – Manufacturing Technology* 59(1):465–468.

[256] Scholz-Reiter B, Freitag M (2007) Autonomous Processes in Assembly Systems. *CIRP Annals – Manufacturing Technology* 56(2):712–729.

[257] Seleim A, ElMaraghy HA (2014) Transient Analysis of a Re-entrant Manufacturing System. *Enabling Manufacturing Competitiveness and Economic Sustainability*, 91–95.

[258] Seliger G, Consiglio S, Zettl M (2004) Selling Use Instead of Selling Products: Technological and Educational Enablers for Business in Ecological Product Life Cycles. *Production Engineering and Computers* 6(7):17–21.

[259] Shanoun M, Bassetto S, Bastoini S, Vialletelle P (2011) Optimisation of the Process Control in a Semiconductor Company: Model and Case Study of Defectivity Sampling. *International Journal of Production Research* 49(13):3873–3890.

[260] Shi C, Gershwin S (2012) Part Waiting Time Distribution in a Two-Machine Line. *Information Control Problems in Manufacturing* 14(1):457–462.

[261] Shi J (2006) *Stream of Variation Modeling and Analysis for Multistage Manufacturing Processes*, CRC Press, Taylor & Francis.

[262] Shi J, Zhou S (2009) Quality Control and Improvement for Multistage Systems: A Survey. *IIE Transactions* 41(9):744–753.

[263] Shmukler A, Fischer A (2009) Verification of 3D Freeform Parts by Registration of Multi-Scale Shape Descriptors. *International Journal of Advanced Manufacturing Technology* 49:1093–1106.

[264] Shu MH, Hsu BM, Kapur KC (2010) Dynamic Performance Measures for Tools with Multi-State Wear Processes and their Applications for Tool Design and Selection. *International Journal of Production Research* 48(16):4725–4744.

[265] Siener M, Aurich JC (2011) Quality Oriented Maintenance Scheduling. *CIRP Journal of Manufacturing Science and Technology* 4(1):15–23.

[266] Sila I, Ebrahimpour M, Birkholz C (2006) Quality in Supply Chains: An Empirical Analysis. *Supply Chain Management: An International Journal* 11(6):491–502.

[267] Sloan TW, Shanthikumar GJ (2000) Combined Production and Maintenance Scheduling for a Multiple-Product, Single-Machine Production System. *Production and Operations Management* 9(4):379–399.

[268] Sloan TW, Shanthikumar GJ (2002) Using In-Line Equipment Condition and Yield Information for Maintenance Scheduling and Dispatching in Semiconductor Wafer Fabs. *IIE Transactions* 34:191–209.

[269] Stecke KE, Aronson JE (1985) Review of Operator & Sol: Machine Interference Models. *International Journal of Production Research* 23(1):129–151.

[270] Sterman JD (2000) *Business Dynamics, Systems Thinking and Modeling for a Complex World*, Irwing/McGraw Hill.

[271] Su Q, Liu L, Whitney DE (2010) A Systematic Study of the Prediction Model for Operator-Induced Assembly Defects Based on Assembly Complexity Factors. *IEEE Transactions on Systems Man and Cybernetics Part A: Systems and Humans* 40(1):107–120.

[272] Subbaiah KV, Rao SVUM, Rao KS (2011) An Inventory Model for Perishable Items with Alternating Rate of Production. *International Journal of Advanced Operations Management* 3(1):66–87.

[273] Subramaniam SK, Husin SH, Singh R, Hamidon A (2009) Production Monitoring System for Monitoring the Industrial Shop Floor Performance. *International Journal of Systems Applications Engineering Development* 3(1):28–35.

[274] Takata S, Kirnura F, Van Houten FJAM, Westkamper E, Shpitalni M, Ceglarek D, Lee J (2004) Maintenance: Changing Role in Life Cycle Management. *CIRP Annals – Manufacturing Technology* 53(2):643–655.

[275] Tan B (2013) Modeling and Analysis of Output Variability in Discrete Material Flow Production Systems. *Handbook of Stochastic Models and Analysis of Manufacturing System Operations*, Springer, New York287–311.

[276] Tansky A, Fischer B, Colosimo M, Ben Shabat Y (2013) Multi-Sensor Multi-Resolution Data Fusion Modeling. *CIRP Design International Conference on Smart Product Engineering*, Bochum, Germany.

[277] Teti R, Jemielniak K, O'Donnell G, Dornfeld D (2010) Advanced Monitoring of Machining Operations. *CIRP Annals – Manufacturing Technology* 59(2):717–739.

[278] Tolio T (2009) *Design of Flexible Manufacturing Systems*, Springer.

[279] Tolio T (2013) Interactions Among Production Logistics, Quality and Maintenance in Manufacturing Systems. *Keynote Speech at the SMMSO 2013 Conference on Stochastic Models for Manufacturing and Service Operations*.

[280] Tolio T, Ceglarek D, Elmaraghy HA, Fischer A, Hu SJ, Laperriere L, Newman ST, Vancza J (2010) SPECIES-Co-Evolution of Products, Processes and Production Systems. *CIRP Annals – Manufacturing Technology* 59(2):672–693.

[281] Toshniwal V, Duffie N, Jagalski T, Rekersbrink H, Scholz-Reiter B (2011) Assessment of Fidelity of Control-Theoretic Models of WIP Regulation in Networks of Autonomous Work Systems. *CIRP Annals – Manufacturing Technology* 60(1):485–488.

[282] Tseng MM, Jiao RJ, Wang C (2010) Design for Mass Personalization. *CIRP Annals – Manufacturing Technology* 59(1):175–178.

[283] Tsung F, Li Y, Jin M (2008) Statistical Process Control for Multistage Manufacturing and Service Operations: A Review and Some Extensions. *International Journal of Services Operations and Informatics* 3(2):191–204.

[284] Tubilla F, Gershwin S (2009) The Hedging Zone Policy for Real-Time Scheduling of Sequence-Dependent Setups. *Information Control Problems in Manufacturing* 13(1):1487–1491.

[285] Urban TL (1998) Analysis of Production Systems When Run Length Influences Product Quality. *International Journal of Production Research* 36(11):3085–3094.

[286] Van der Duyn Schouten FA, Vanneste SG (1995) Maintenance Optimization of a Production System with Buffer Capacity. *European Journal of Operational Research* 85:323–338.

[287] Van Volsem S, Dullaert W, Van Landeghem H (2007) An Evolutionary Algorithm and Discrete Event Simulation for Optimizing Inspection Strategies for Multi-Stage Processes. *European Journal of Operational Research* 179(3):621–633.

[288] Váncza J, Egri P (2006) Coordinating Supply Networks in Customized Mass Production – A Contract-Based Approach. *CIRP Annals – Manufacturing Technology* 55(1):489–492.

[289] Váncza J, Egri P, Monostori L (2008) A Coordination Mechanism for Rolling Horizon Planning in Supply Networks. *CIRP Annals – Manufacturing Technology* 57(1):455–458.

[290] Váncza J, Monostori L, Lutters D, Kumara SR, Tseng M, Valckenaers P, Van Brussel H (2011) Cooperative and Responsive Manufacturing Enterprises. *CIRP Annals – Manufacturing Technology* 60(2):797–820.

[291] Venkatasubramanian V (2005) Prognostic and Diagnostic Monitoring of Complex Systems for Product Lifecycle Management: Challenges and Opportunities. *Computers & Chemical Engineering* 29(6):1253–1263.

[292] Vijayaraghavan A, Sobel W, Fox A, Dornfeld D, Warndorf P (2008) Improving Machine Tool Interoperability Using Standardized Interface Protocols: MTConnect. *International Symposium on Flexible Automation*, ASME, pp. 23–26.

[293] Waiyagan K, Bohez EL (2009) Intelligent Feature Based Process Planning for Five-Axis Mill-Turn Parts. *Computers in Industry* 60(5):296–316.

[294] Wang H (2002) A Survey of Maintenance Policies of Deteriorating Systems. *European Journal of Operational Research* 132:469–489.

[295] Wang J, Hu Y, Li J (2010) Transient Analysis to Design Buffer Capacity in Dairy Filling and Packing Production Lines. *Journal of Food Engineering* 98(1):1–12.

[296] Wang J, Li J, Arinez J, Biller S (2013) Quality Bottleneck Transitions in Flexible Manufacturing Systems with Batch Productions. *IIE Transactions* 45(2):190–205.

[297] Wang J, Li J, Arinez J, Biller S (2010) Product Sequencing with Respect to Quality in Flexible Manufacturing Systems with Batch Operations. *Automation Science and Engineering IEEE Transactions on* 7(4):776–790.

[298] Wang J, Li J, Arinez J, Biller S, Huang N (2010) Quality Analysis in Flexible Manufacturing Systems with Batch Productions: Performance Evaluation and Non-Monotonic Properties. *Automation Science and Engineering IEEE Transactions on* 7(3):671–676.

[299] Wang J, Li J, Arinez J, Biller S (2012) Indicators for Quality Improvability and Bottleneck Sequence in Flexible Manufacturing Systems with Batch Productions. *International Journal of Production Research* 50(22):6388–6402.

[300] Wang KH, Chen WL, Yang DY (2009) Optimal Management of the Machine Repair Problem with Working Vacation: Newton's Method. *Journal of Computational and Applied Mathematics* 233(2):449–458.

[301] Wang K, Han K (2013) A Batch-Based Run-To-Run Process Control Scheme for Semiconductor Manufacturing. *IIE Transactions* 45(6):658–669.

[302] Wang YM, Nagarkar SR (1999) Locator and Sensor Placement for Automated Coordinate Checking Fixtures. *Journal of Manufacturing Science and Engineering* 121(4):709–719.

[303] Weber A (2004) Is Flexibility a Myth? *Assembly* 47(5):50–59.

[304] Weckenmann A, Jiang X, Sommer KD, Neuschaefer-Rube U, Seewig J, Shaw L, Estler T (2009) Multisensor Data Fusion in Dimensional Metrology. *CIRP Annals – Manufacturing Technology* 58(2):701–721.

[305] Wegener K, Hoffmeister HW, Karpuschewski B, Kuster F, Hahmann WC, Rabiey M (2011) Conditioning and Monitoring of Grinding Wheels. *CIRP Annals – Manufacturing Technology* 60(2):757–777.

[306] Wiendahl HP, Andersson P, Berggre C, Nehler C (2004) Manufacturing Firms and Integrated Solutions: Characteristics and Implications. *European Journal of Innovation Management* 7(1):218–228.

[307] Wiendahl HP, Kuprat T (1991) Logistic Analysis of Production Processes by Operating Curves. *CIRP Annals – Manufacturing Technology* 40(1):475–478.

[308] Wiendahl HP, von Cieminski G, Begemann C, Nickel R (2005) Human Factors in Production Planning and Control. *Integrating Human Aspects in Production Management*, vol. 160. 113–125.

[309] Wiendahl H-P, ElMaraghy H, Nyhuis P, Zäh M, Wiendahl H-H, Duffie N, Brieke M (2007) Changeable Manufacturing – Classification, Design and Operation. *CIRP Annals – Manufacturing Technology* 56(2):783–809.

[310] Wright CM, Mehrez A (1998) An Overview of Representative Research of the Relationships Between Quality and Inventory. *Omega* 26(1):29–47.

[311] Wu Z, Shamsuzzaman M, Wang Q (2007) The Cost Minimization and Manpower Deployment to SPC in a Multistage Manufacturing System. *International Journal of Production Economics* 106(1):275–287.

[312] Xiang L, Tsung F (2008) Statistical Monitoring of Multistage Processes Based on Engineering Models. *IIE Transactions* 40(10):957–970.

[313] Xu X, Wang L, Newman ST (2011) Computer-Aided Process Planning – A Critical Review of Recent Developments and Future Trends. *International Journal of Computer Integrated Manufacturing* 24(1):1–31.

[314] Yan CB, Hassoun M, Meerkov SM (2012) Equilibria, Stability, and Transients in Re-entrant Lines Under FBFS and LBFS Dispatch and Constant Release. *Semiconductor Manufacturing IEEE Transactions on* 25(2):211–229.

[315] Yang L, Lee J (2012) Bayesian Belief Network-Based Approach for Diagnostics and Prognostics of Semiconductor Manufacturing Systems. *Robotics and Computer-Integrated Manufacturing* 28(1):66–74.

[316] Yang ZM, Djurdjanovic D, Ni J (2008) Maintenance Scheduling in Manufacturing Systems Based on Predicted Machine Degradation. *Journal of Intelligent Manufacturing* 19(1):87–98.

[317] Yang Z, Djurdjanovic D, Ni J (2007) Maintenance Scheduling for a Manufacturing System of Machines with Adjustable Throughput. *IIE Transactions* 39(12):1111–1125.

[318] Yano CA, Lee HL (1995) Lot Sizing and Random Yields: A Review. *Operations Research* 43:311–334.

[319] Yao X, Xie X, Fu MC, Marcus SI (2005) Optimal Joint Preventive Maintenance and Production Policies. *Naval Research Logistics* 52(7):668–681.

[320] Yeh RH (1997) State-Age-Dependent Maintenance Policies for Deteriorating Systems with Erlang Sojourn Time Distributions. *Reliability Engineering System Safety* 58:55–60.

[321] Yeung TG, Cassady CR, Schneider K (2008) Simultaneous Optimization of Control Chart and Age-Based Preventive Maintenance Policies Under an Economic Objective. *IIE Transactions* 40:147–159.

[322] Zaideman O, Fischer A (2010) Geometric Bone Modeling: From Macro to Micro-Structures. *Journal of Computer Science and Technology* 25(3):614–622.

[323] Zero WIN – Towards Zero-Waste in Industrial Networks, European Community, FP7/2007-2013. Grant agreement n° 226752.

[324] Zhou J, Djurdjanovic D, Ivy J, Ni J (2007) Integrated Reconfiguration and Age-Based Preventive Maintenance Decision Making. *IIE Transactions* 39(12):1085–1102.

[325] Zhu X, Hu SJ, Koren Y, Marin SP (2008) Modeling of Manufacturing Complexity in Mixed-Model Assembly Lines. *Journal of Manufacturing Science and Engineering* 130(5):51013.

[326] Zou C, Tsung F, Liu Y (2008) A Change Point Approach for Phase I Analysis in Multistage Processes. *Technometrics* 50(3):344–356.