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Analysis of In-line Quality-Oriented Assembly Strategies in the Production of Electric Drives

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Abstract

This paper presents the analysis of quality-oriented rotor assembly strategies in electric drive production systems. These approaches combine quality-oriented system policies and an improved rotor assembly technique. In order to analyze alternative policies, a quantitative method for the integrated evaluation of quality and production logistics performance is developed. The results show improvements in both quality of parts at the rotor assembly station and the overall productivity of the system. Experimental results demonstrate that quality related decisions, supported by the proposed method, bring important performance and quality improvements. Moreover, the benefits of the approaches are validated within a real industrial context.

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Keywords: quality-oriented assembly; electric drives production; Zero Defects Manufacturing.

1. Introduction

Delivering product quality is increasingly becoming an important strategy that determines the success and competitiveness of today's manufacturing companies. In response to this challenge, programs such as Six-Sigma, Just In Time, Continuous Improvement, Total Quality Management, Toyota Production System and World Class Manufacturing have proposed solutions for quality-oriented production strategies [1]. On the other hand, achieving dynamic production targets with appropriate design and operation of manufacturing system also plays a decisive role. Therefore, numerous research and tools have been developed to support an efficient design and operation of manufacturing systems [2][3].

In order to guarantee customers' quality expectations in a highly dynamic market, manufacturing industries need to focus both on their quality and productivity performances. Traditionally most of previous studies on these two topics assume independence of the quality and production logistics performance of manufacturing systems. However, recent works started addressing the problem of studying quality and logistic performance of manufacturing systems into an integrated framework [4]. Although quality is considered as an important issue in real manufacturing systems, most quality-oriented techniques and solutions emphasize process level improvements. Therefore quality has been rarely studied at a system level. In addition, the applications of traditional quality improvement tools are not well adapted for dynamically changing contexts such as small-lot production with respect to mass production manufacturing. Especially, these approaches have shown limitations in addressing quality-oriented production in highly changeable and emerging strategic manufacturing sectors.

New studies have recognized this gap and recent research efforts are being dedicated to address this need. "Zero Defect Manufacturing" is one of the emerging paradigms aiming at going beyond traditional six-sigma approaches in highly technology intensive and emerging strategic manufacturing sectors through knowledge-based approaches. For example, at the European level, the PPP Factories of the Future 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 European projects have been funded boosting cross-sectorial research on this topic and at achieving the largest possible target impact for the developed technologies [5].

One of the emerging industries that can highly benefit from such innovative efforts is the e-mobility manufacturing sector. The global trend towards sustainable mobility is

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promoting the use of electric vehicles [6]. Besides, the growing demand for individual transportation yields an increasing number of cars worldwide. In order to reduce emissions of the current car fleet the trend is going towards zero-emission vehicles using electric drives [7]. Substituting the current car fleet by electric vehicles can drastically decrease local and greenhouse gas emissions [8]. Current studies show the huge potential of electric drives replacing combustion engines (petrol and diesel), starting with medium-sized cars [9]. As a result of the complete different construction technique of electrical motors, the perfected methods of manufacturing and quality control of combustion engines cannot be directly transferred to electrical drives.

In the production of automotive electric drives, the state of the art quality control is the so called “End Of Line” (EOL) testing, as the major final product functional and quality test and as approval test for the customers. This testing method is executed after all manufacturing steps have been completed and can therefore been classified as off-line inspection. If a defect occurs in one of the upstream production stages, it will not be detected in-line. Consequently, value adding processes will still be applied on an already defective product. Following the EOL testing approach, there is no possibility of applying in-process quality control techniques, since process data are not available at the relevant process stages [10].

In order to realize in-line zero-defect manufacturing solutions, information platforms that support data connectivity and computation requirements must be integral part of modern production systems. This need in the digital manufacturing era introduces the concept of Cyber Physical Systems (CPS), which are defined as integrations of computation and physical processes. In CPS, Embedded computers and networks monitor and control physical processes, usually with feedback loops where physical processes affect computations and vice versa. The study has also developed and implemented a simplified data acquisition, transformation and computational platform that support the proposed methodology.

This paper proposes a direct selective assembly strategy with in-line inspection as a proactive downstream compensation technique at the rotor assembly station. Additional system level management policies are investigated for improving the overall system performance. Changes in system level management policies impact the quality and production logistics performance differently. In order to investigate these impacts a method for the evaluation of their effect on the overall system level performance taking into account system yield, production rates, and work in progress is developed. The proposed methods are validated in an industrial context using real data obtained from Bosch production system.

The paper is organized as follows: Section 2 describes the process chain of the electric drive production system. Section 3 introduces the direct selective assembly technique and required system adjustments for the implementation of measurement and estimation of key quality features of the rotor. Section 4 describes system level management policies based on the direct selective assembly. Section 5 presents a modeling and evaluation method for the system level analysis of the production line. Section 6 reports the numerical results obtained from the quantitative evaluation of the proposed policies and configurations. Section 7 concludes highlighting the benefits and implications of the proposed approach.

2. Production system description

This section presents the current Bosch production system for electric drives that is considered in the study. The schematic representation of the processing stages is shown in Fig. 1., where squares represent processing and inspection stages (M_i) and circles represent buffers ($B_{i,j}$) for storing inventory between M_i and M_j. The line produces a number P of different rotor models, $p=1,..,P$. A rotor type p is composed of S_p laminated stacks, which can be seen as the size of the batch of stacks to be assembled. Each stack has M_p magnets. The line is composed of two main branches, respectively dedicated to the production of the rotor and to the production of the stator. The focus of this study is the rotor line.

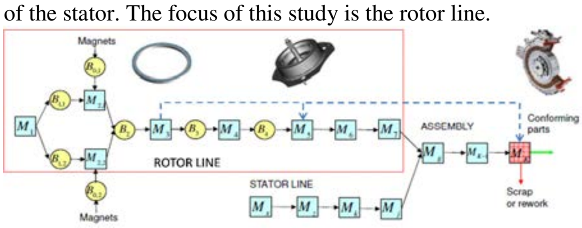

Fig. 1. Current production line of the electric drive with EOL inspection

This line is composed of seven main stages, dedicated to the following operations:

- M_1: loading of the stacks on the pallet.
- $M_{2,1}$,$M_{2,2}$: assembly of the magnets on the stacks. The station is composed of a pick and place system for positioning the magnets in their locations.
- M_3: stack magnetization process and total flux measurement.
- M_4: heating station. A rotating table moves the stacks into a heating chamber.
- M_5: assembly machine. The required number of stacks is taken and a pile of stacks in the z direction of the machine is formed by mounting each stack on the central shaft.
- M_6: rotor balancing station.
- M_7: rotor marking station.

After assembling the rotor and the stator, the completed motor undergoes the EOL inspection. At this stage, motor characteristics as well as customer requirements such as torque, speed, etc. are tested. Since defects in the magnetic circle have a considerable effect on the performance of the whole electric car, 100% EOL testing is needed.

Two main factors that affect the operational performance of the rotor have been identified and accordingly two key quality features (*KQC*) are considered. The first key quality characteristic is the *total integral magnetic flux* (KQC_1) of the rotor, while the second quality feature is the *uniformity of magnetic field intensity* (KQC_2). Both quality features influence the operational performance of the final assembled electric motor. The *total integral magnetic flux* of a rotor guarantees the motor’s capability to generate a torque equal to the design target, while the *uniformity of magnetic field intensity* allows the motor to run without cogging, excessive vibration and noise.

In the current configuration there are no inspections performed before the end of the line (EOL). This limits the application of proactive quality-oriented assembly strategies before final assembly operation. Therefore the current assembly process is based on the order in which stacks arrive to the assembly station. Thus, output quality of the assembled rotor can be considered as a process that is only influenced by the quality of the input stacks. Experiments under this policy show that the output quality of a rotor is a function of the cumulative randomness that arises from the magnetization process M_3 of individual stacks.

Each stage in the production system is subject to breakdowns, characterized by a failure rate p, which is the inverse of the mean time to failure, and a repair rate r, which is the inverse of the mean time to repair. The company collects estimates of these parameters. These values are not provided for confidentiality reasons. Moreover, each stage is characterized by a specific processing rate (parts/time) that is also omitted.

3. Direct selective assembly strategy for rotor assembly

This section describes the proposed direct selective assembly strategy. In addition, it presents the required changes that must be introduced into the existing system configuration and the current assembly strategy. Selective assembly is a quality oriented assembly strategy in order to address the problem of matching P components of each type into an assembled product with an improved output quality. There are two main variants of selective assembly strategy, namely direct selective assembly (DSA) and fixed bin selective assembly (FBSA) strategies. FBSA relies on the measurement and sorting of components into predefined fixed quality classes (bins) [12]. On the other hand, in DSA components matching does not involve classes, but it is directly based on the individual measurements of components' quality characteristics. Therefore, the choice of P components under DSA considers each component's measurement to determine the best combinations from the available set of components. Thus, this paper applies DSA in all of the assembly policies investigated in the study.

In order to apply the (DSA) strategy to the current production system there are two main changes needed to be introduced into the existing configuration. The first requirements is the development and introduction of inspection stage equipped with sensors for the space resolved measurement of the magnetic flux of individual stacks after the stack magnetization stage M_3 Fig. 2. This inspection station has been developed in Bosch in the MuProD project [10]. The second requirement is the change in the management of buffers B_3 and B_4 in the line which are currently separated by the heating station M_4. The two buffers are managed as a combined buffer $B_{3,4}$ Fig. 2. Such a configuration allows generating higher number of stack combinations for the assembly station, thus increasing the output quality of the assembled rotor. The inspection station provides the in-line computer with the stacks magnetization profile. These measurements are used by the DSA strategy to compute the deviations of stacks from target values and the information is used to minimize the cumulative deviation on the output rotor.

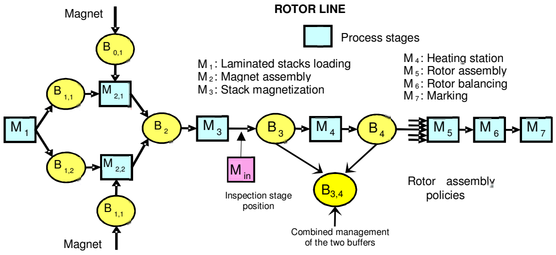

Fig. 2. Modified processing stages of the rotor production line

For optimizing the *total integral magnetic flux* (KQC_1) of the rotor, a stack selection algorithm is used to choose the best combination of stacks from the buffer. The flow chart for this algorithm is shown in Fig. 3.

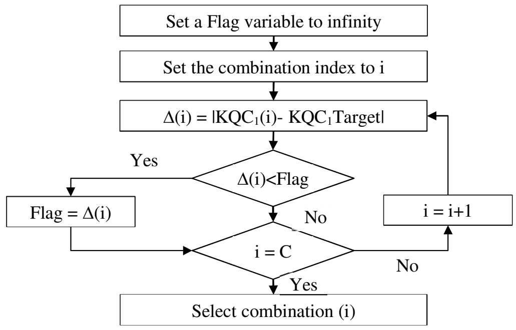

Fig. 3. Stack selection algorithm for DSA

After the set of stacks that are chosen to assemble the rotor are defined a second set of optimization algorithms are used improve *uniformity of magnetic field intensity* (KQC_2). Based on the inspection measurements mathematical modelling and computation techniques for the minimization of magnetic intensity deviation of the rotor has been developed. Full exposition of the optimization algorithms for the two key quality characteristics of the rotor are presented in [11]. The algorithm uses matrix based representation of the individual stacks and the rotors after the measurement of the magnetic field intensity using the space resolve inspection. The stacks are manipulated with respect to their angular alignment and their vertical position until the optimal arrangement is obtained by the algorithm.

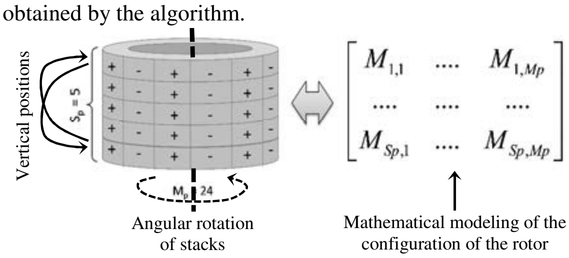

Fig. 4. Stack and rotor representation for the optimization of KQC

The two aforementioned optimization algorithms are the kernel enabling the DSA during the in-line implementation. In this way, the in-line computer has all the relevant information about the stacks in the buffer and can communicate to M_5. The information includes; the best stacks to be assembled according to KQC_1, and then their vertical and rotational coordinates according to KQC_2. The schematic implementation of DSA representing information and material flow between M_3 and M_5 is shown below Fig. 5.

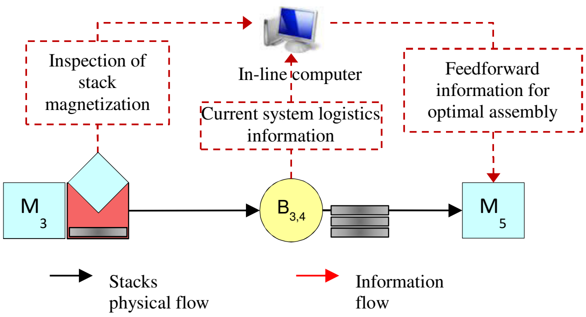

Fig. 5. Direct selective assembly implementation schema

In order to compare the impact of DSA on the two different quality characteristics, the rotor magnetic flux and field uniformity are studied independently. First, the rotor magnetic flux is identified as the only cause for all the 10% of non-conforming engines in the current system configuration. Then, the same is done as far as the rotor magnetic field uniformity is concerned.

4. System management policies based on DSA strategy

In this section, three system management policies based on DSA are presented. These policies apply the optimization techniques proposed for the two key quality characteristics (KQC). The definition of the policies is based on two parameters. The first parameter is the buffer threshold (x) defined between the stack magnetization station (M_3) and the assembly station (M_5). This parameter can range from S_p to the total buffer capacity (N). The second parameter is the choice of stack sets that are included in the optimization process. For the sake of simplicity the policies are named as policy A, B, C, and are described as follows.

4.1. Policy A

Policy A introduces the buffer threshold (x) parameter and it can range between S_p and N. According to Policy A, the assembly station M_5 is governed by the following conditions with respect to the buffer level (n):

- If $n < x$, then wait until x stacks are available in the buffer before beginning the assembly of a rotor;
- If $n = x$, select the best combination of S_p stacks out of x and assemble a rotor;
- If $n > x$, select the best combination of S_p stacks out of the first x available in the buffer.

By setting x greater than S_p, the number of stacks combinations to analyse increases. This in turn increases the probability to assemble high quality rotors. However, high values of x increase the average buffer level and decrease the total throughput of the line. The number of stack combinations to analyse each time a rotor has to be assembled is a function of parameters x and S_p, and calculated as follows:

$$\binom{x}{S_p} = \frac{x!}{(x-S_p)!S_p!} \quad (1)$$

4.2. Policy B

Policy B always fixes the buffer threshold equal to S_p. The assembly station M_5 is governed as follows:

- If $n < S_p$, then wait for S_p stacks to be in the buffer before assembling a rotor;
- If $n = S_p$, then pick the S_p stacks available in the buffer;
- If $n > S_p$, then select the best combination of S_p stacks out of n.

4.3. Policy C

Policy C combines both the previous Policies A and B. According to Policy C, the assembly station M_5 is governed by the following conditions:

- If $n < x$, then wait for x stacks to be in the buffer before assembling a rotor;
- If $n = x$, then select the best combination of S_p stacks out of x;
- If $n > x$, select the best combination of S_p stacks out of n.

The number of stack combinations to analyze each time a rotor has to be assembled is calculated as follows:

$$\binom{n}{S_p} = \frac{n!}{(n-S_p)!S_p!} \quad (2)$$

The schema illustrating the optimization space of Policy A, B and C is shown in Fig. 6.

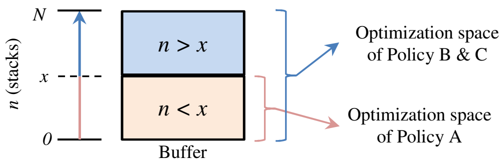

Fig. 6. Optimization spaces of policies relative to the buffer threshold (x)

5. System level performance evaluation method

A generalized production system model for the joint analysis of quality and production logistics performance under application of the proposed policies is developed to study their influence at system level. The proposed model analyzes a general manufacturing system that is composed of multiple processing stages (blue squares) and inspection stages (red squares) defined as M_k, $k=1,..,K$, (Fig. 7).

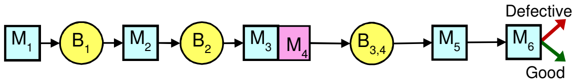

Fig. 7. Approximate modelling formalism of the rotor line

This process chain model is an approximate transformation of the rotor line given in Fig. 2. Individual stages are connected by material transportation systems or inter-operational buffers (yellow circles), $B_{i,j}$ storing work in progress between stage M_i and M_j. For example, in Fig. 7, processing stages M_1, M_2, M_3 and M_5 perform manufacturing transformation processes on the incoming workpieces. Inspection station M_4 measures key quality features of parts processed at upstream manufacturing stages. Based on the information collected by inspection stations, the assembly policies can be applied at the rotor assembly station.

The behaviour of each stage is modelled as a continuous time-discrete state Markov chain of general complexity. The underlying transition rate matrix is λ. This framework allows to model machines having multiple operational and failure states, connected by means of an arbitrarily complex Markovian structures. When the machine is in an operational state *o,* it processes parts at a rate of μ_o parts per minute. A breakdown state is simply characterized by $\mu=0$. These processing rates [parts/t.u.] are collected in the quantity reward vector μ. For each operational state a statistical distribution of the processed quality characteristic *y* is assumed, namely $f_o(y)$. According to the Specification Limits imposed by design on the processed feature, the yield is defined for every state *o*, namely Y_o; these elements are collected in the quality reward vector *Y*. Monte Carlo Simulation is used to forecast the expected yield at the assembly station. The total fraction of defects generated by the stage is denoted as γ. The performance measures of interest are the following:

- Average total production rate of the system, E^{Tot}, including both conforming and defective parts, observed in output.
- Average effective production rate, E^{Eff}, of conforming parts, observed in output.
- System yield, Y^{system}, that is the fraction of conforming parts produced by the system (E^{Eff} / E^{Tot}).
- *WIP*, which is the total average inventory of the system.

After deriving the characteristic parameters (λ_i, μ_i Y_i) for each stage, the steady-state probability vector π_i of the Markov chain and the performance of the stage in isolation can be computed:

$$\pi_i \lambda_i = 0$$
$$E_i^{Tot} = \pi_i \cdot \mu_i^T \qquad E_i^{Eff} = \pi_i \cdot diag(\mu_i) \cdot Y_i^T \qquad Y^{M_i} = \frac{E_i^{Eff}}{E_i^{Tot}} \tag{3}$$

The system level performance of the production line is evaluated using analytical method based on a recent idea of decomposition approach that applies to Markovian machines that was recently proposed in [13]. The machines are characterized by transition rate matrix λ and processing rate vector μ_i. Therefore, it applies to the stage models described in this section. The idea of the decomposition approach is to decompose the *K*-machine system into a set of *K-1* two-machine one-buffer sub-systems *l(k)*, i.e. one for each buffer in the original system. The decomposition equations for such general system settings are provided in [13]. This method proved to be accurate in estimating the system performance, showing a percentage difference below 3% against simulation.

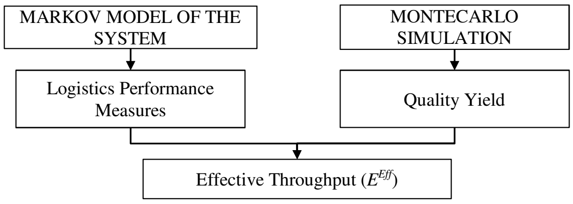

Fig. 8. Schema of the performance evaluation process

6. Numerical results and system behavior

This section presents the analysis results obtained under each system management policy, i.e. for Policy A, B, C and current policy. These policies are studied for different rotor types however for the sake of simplicity the results are reported only for a rotor type S_p = 5. Each system level management policy has different production logistics and quality implications. Therefore, separate results obtained on production logistics performance and quality performances are given. Finally, their integrated impact on the joint production logistics and quality performance of the overall production system is reported.

6.1. Production logistics and quality performance

Production logistics performances including total throughput (E^{Tot}) of the line and the average buffer level (*WIP*) between M_3 and M_5 are evaluated. For the Current policy and Policy B the buffer threshold can be assumed fixed i.e., *x* = 5. The total throughput under these policies is 17.26 rotors per hour and the average buffer level 3.25 stacks. In Fig. 9 (a) the corresponding values are indicated on the left side of the graph when *x* = 5.

The logistics performance for Policy A and C depends on the buffer threshold *x* corresponding to the policy. Fig. 9 (a) shows the E^{Tot} and the *WIP* with respect to *x* for these policies. Due to the higher speed of M_5 relative to M_3, the average buffer level is low with respect to the total buffer capacity. When the buffer threshold increases that the average buffer level also increases linearly. The increase in the buffer threshold *x* also negatively impacts the total throughput, however this is strongly visible for buffer thresholds *x* > 35 Fig. 9 (a).

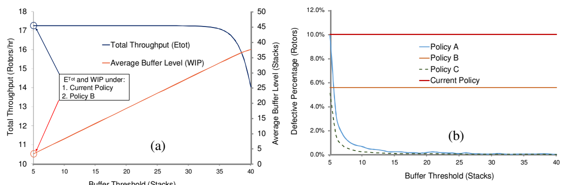

Fig. 9. Total throughput and average buffer level (a) and Average defect percentage of rotors under different policies (b)

The quality performance of the policies is also investigated. From historical data, the percentage of rotors with quality problems is estimated 10% Fig. 9 (b) under the current policy. Policy B implements the optimization algorithms thus reducing the non-conformity to 5.57%, but with similar system management to the current policy. In addition to the optimization algorithm, Policies A and C impose buffer thresholds in order to allow the accumulation of stacks in the buffer before assembly begins. Increasing the accumulation by raising the buffer thresholds increases the possible combinations of stacks. This further decreases the percentage or non-conformity of the rotors. From Fig. 9 (b), when the buffer threshold increases from 5 to 6 and then to 10 stacks, the corresponding fraction of non-conforming rotors for policy A reduces as 10%, 3.09% and 0.66% respectively, and 5.57%, 1.48% and 0.22% for policy C. However when the buffer threshold is further increased, the difference between the two policies becomes insignificant. In comparison, Policy C performs better on the first few thresholds increases than policy A by making scrap percentages to decrease faster.

6.2. Joint quality and production logistics performance

The joint system level quality and production logistics performance of the policies is measured using the average effective throughput E^{Eff}. It indicates both the gains in the quality and production logistics by each policy. Both policies demonstrate the same behavior on the logistics performance indicators for any buffer thresholds. The system quality performance of Policy C is slightly higher for all buffer threshold values, but for buffer thresholds $x > 20$, scraps tend to zero for both policies. The flatness characterizing the average effective throughput of policy A and C is an interesting feature to notice. Since the *WIP* minimization is an important goal in manufacturing systems management, the threshold maximizing the effective throughput has to be the lowest possible. Thus, thresholds in the flat part of the effective throughput curves cannot be considered the same as higher thresholds mean higher *WIP* and, as consequence, high lead times. Therefore subsequent decision must take this into account.

From Fig. 10 it can be seen that the combined application of the optimization algorithm and the appropriate choice of policy configuration increase the effective throughput of the system by 11.5%. The sole application of the optimal assembly algorithm provides 6.3% of this increase on the effective throughput while the additional 5.2% increase is the result of the system level management policy using buffer threshold configuration. This highlights the importance of supporting process level quality improvement techniques with the appropriate system configuration and management.

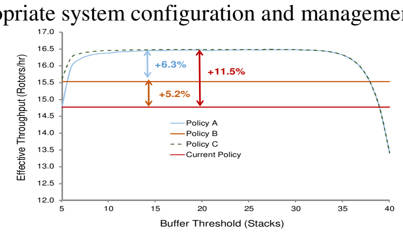

Fig. 10. Average effective throughput under proposed policies

7. Conclusion

This paper investigated three system level strategies for the quality-oriented assembly of rotors in an electric drive production system. A quantitative methodology supporting the analysis of integrated system level quality and production logistics performance of the system under different policies governing the system has been presented. The method supports decision making on the choice of the best policy and the system configuration. Significant benefits of these policies are demonstrated within a real industrial case, dedicated to the production of electric drives. The overall solution combines process level quality improvement techniques together with system level configurations solution for an improved performance of production systems. Future research will be aimed at extending this approach for quality-oriented system level analysis in several manufacturing contexts to support their design and operational phases.

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