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## Quality-oriented design of rotor assembly strategies for electric drive production systems

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### Abstract

Electric mobility is an emerging industrial sector that requires innovative quality control methods as common manufacturing and testing methods of combustion engines cannot be transferred directly to electric motors. This paper presents new solutions for the quantitative evaluation of quality-oriented rotor assembly strategies in electric drive production systems. The proposed methods assist the analysis of productivity and quality performance of two different assembly strategies namely selective assembly and sequential assembly. The impacts of these approaches are validated within a real industrial context, where state of the art quality and process control technologies show strong limitations. Experimental results have shown that the application of the proposed strategies yield a significant improvement in the production rate of conforming parts of the system. Moreover, the general applicability of these approaches to similar industrial problems encourages their adoption for defect reduction and elimination thus paving the way to zero-defect manufacturing paradigm.

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### 1. Introduction

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 [1]. The transportation sector can increase its energy efficiency by changing the travel behavior and the vehicle fleet, with respect to the amount of cars and the technology used [2]. Substituting the current car fleet by electric vehicles can drastically decrease local and greenhouse gas emissions [3,4]. Current studies show the huge potential of electric drives replacing combustion engines (petrol and diesel), starting with medium-sized cars [2,5]. This trend requires moving from small and medium lot sizes to mass production of electric drives in the automotive sector for hybrid and purely electric vehicles. However, methods and strategies used in production of conventional combustion engines cannot be transferred directly to the production of electric drives. Therefore, new approaches that guarantee output quality of electrical motors

are needed. The project *MuProD*, [6] funded by the European Union, develops methods for increasing the quality of electric drives while decreasing the amount of scrap parts in multi-stage production systems moving towards zero-defect manufacturing.

This paper proposes downstream compensation methods applied to the production of rotors for electrical motors, and evaluates their effect on the overall system level performance taking into account system yield, production rates, and work in progress. The proposed methods are validated in an industrial context using real data obtained from Bosch production system. Section 2 describes the process chain of the production system. Section 3 introduces two new assembly strategies and compares them with the existing practice. In Section 4, the system level analysis is introduced and Section 5 presents the system level performance achieved under these strategies.

## 2. System Description

In this section, Bosch electrical motor production line is considered. The rotor of an electrical motor consists of  $S_p$  stacks. Each stack consists of  $M_p$  magnets radially arranged on a circular steel ring. By piling several stacks together, rotors of different torque can be produced with the same cross-section. The production line is composed of two main branches, namely rotor assembly and stator production (Fig. 1). Light blue squares represent processing stages, red squares inspection stages and circles buffers for temporarily storing in-process inventory. In this paper, the focus of our analysis is the rotor line that is composed of seven main stages:

- $M_1$ : loading of the stacks on the pallet.
- $M_{2,1}, \dots, M_{2,x}$ : assembly of the magnets on the stacks.
- $M_3$ : stack magnetization process and inspection.
- $M_4$ : heating station.
- $M_5$ : rotor assembly machine.
- $M_6$ : rotor balancing station.
- $M_7$ : rotor marking station.

After the motor is assembled, it undergoes a final quality control at the end of line (EOL) inspection station. Two key quality features are inspected. First, the overall magnetic moment of the motor should be within a tolerance limit of 4% from the target value. Secondly, the motor should be free from significant cogging and vibration. The main drawback of the current inspection is that it is performed at the final stage of the manufacturing line, where defects cannot be corrected [7]. Consequently, a defective motor has to be recycled or scrapped. Therefore, feedforward control methods are considered for downstream compensation of deviations generated at previous process stages [7].

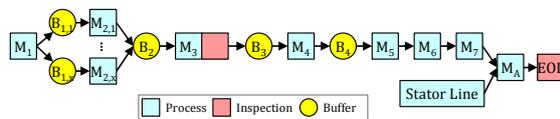


Fig. 1. Multi-stage production system for electric drives.

## 3. Rotor assembly strategies for defect reduction

### 3.1. Current Assembly policy

In the current configuration, there are no inspections before the end of the line. This limits the application of quality-oriented assembly strategies. For this reason assembly process is based on the order in which stacks arrive from the previous stage. Thus, output quality of the assembled rotor can be considered as a process that is only influenced by the quality of 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 individual stacks.

### 3.2. Selective assembly

Selective assembly strategy allows the assembly of high precision products from low precision components at the cost of increasing the complexity of the system management. In

this case the goal is to implement this strategy at the assembly station ( $M_5$ ). Two key quality features are considered under selective assembly. The first applies selective assembly based on the total magnetic flux measurement of stacks. The second approach targets the uniformity of the magnetic profile of the rotor using fuzzy inference system. Both approaches rely on a space-resolved measurement at  $M_3$ .

**Total flux:** Currently, if the measured overall magnetic moment of the motor deviates more than 4% from the target value, the motor is considered defective. This quantity is directly related to the total magnetic flux of the rotor which is again a function of total magnetic flux of individual stacks. Therefore the goal of selective assembly policy is to guarantee a rotor with a total magnetic flux close to the target value by selecting stacks from predefined classes. In this case, space-resolved inspection is used to measure of the total magnetic flux intensity of each stack at  $M_3$ . Measured stacks are sorted into two classes depending on the measured total magnetic flux. The buffer sizes for the two classes are identical and equal to half the size of the original buffer in the current configuration. Then, the assembly machine only couples stacks with high flux with stacks with low flux intensity. This combination allows the sum of the total magnetic flux of the rotor to be close to the specified target value compared to the current configuration.

A discrete event simulation is developed implementing selective assembly strategy based on the total flux of the rotor at the assembly station. For the sake of brevity, we directly discuss the output quality distribution of the rotor from the simulation (Fig. 2). In this analysis an equivalent lower and upper specification limits are defined based on data collected from the current system. Defect rate that is generated under the selective assembly with two classes is reduced to 2%, compared to 10% in the current configuration. These figures are strictly limited to the assembly station in isolation; the system level analysis using these results is treated in section 5.

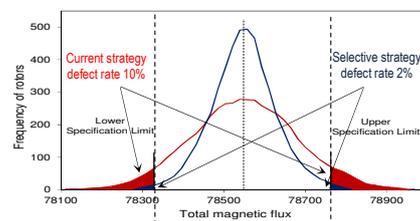


Fig. 2. Comparison of defect rates based on total magnetic flux.

**Fuzzy logic using space-resolved inspection:** In this section, selective assembly based on a fuzzy inference system (FIS) is explained. The goal is to reduce variation of the output field intensity and cogging of the motor. More details can be found in a previous paper [9]. From the space-resolved measurement in  $M_3$ , discrete magnetizations values of the 24 magnets in the laminated stacks are calculated. Efficient compression of the features enhances comprehension of the data set and enables generalizing upon the stack [9,10]. This reduction strategy consists of two steps, feature selection and extraction. First, magnets within a tolerance band are neglected. Second, new features are created based on the

remaining magnets by extracting the two most dominant structures. A structure is defined as a section of the stack containing magnets of the same deviation (positive or negative). The following features characterize the structures:

- sum of deviations  $A_i$
- height of its peak  $P_i$
- number of included magnets  $L_i$
- distance  $D_{12}$  between the balance points.

Feature reduction  $W$  maps the original vector  $v$  containing 24 magnetization values to the feature vector  $w$  (1-3):

$$W: \vec{v} \rightarrow \vec{w}, \quad \vec{v} \in \mathbb{R}^{24}, \vec{w} \in \mathbb{R}^7 \quad (1)$$

$$\vec{v} = (m_1 \ \dots \ m_{24})^T \quad (2)$$

$$\vec{w} = (A_1 \ P_1 \ L_1 \ A_2 \ P_2 \ L_2 \ D_{12})^T \quad (3)$$

Within this feature space, the stacks are grouped into six upper classes.  $PP, NN, PN, NP, N, P$ . Thereby,  $P$  indicates that the feature characterizes a positive deviation and  $N$  a negative one. This results in three pairs of complementary classes that define the matching policy:  $PP-NN, PN-NP, P-N$ . A Mamdani FIS selects the best combination of two stacks from corresponding classes for achieving minimum variation in the magnetic field of the rotor. The main parts of the FIS are fuzzifier, inference block with rule base and defuzzifier (Fig. 3). Knowledge about the mechanism of compensation is introduced into the FIS through the rules. Finally, the FIS calculates a suitability index for two stacks based on the similarity of their features. Compared to the current random assembly, the proposed method can successfully reduce variation in the magnetic fields of the permanent magnet rotors. Preliminary experimental results show that the squared sum of the deviations decreased by 65% compared to the current assembly policy.

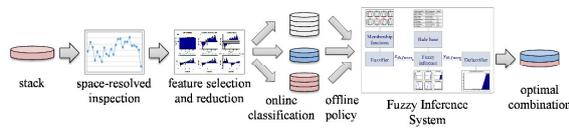


Fig. 3. Selective rotor assembly based on space-resolved inspection using feature reduction and a fuzzy inference system.

### 3.3. Sequential assembly

**Stage 1 - radial optimization.** The aim of this approach is to impose an angular misalignment  $\alpha$  between the stacks with respect to a reference axis in order to gain uniformity and reduce variability of the output field intensity. The elements of the vector  $\alpha$  have to be computed by an optimization algorithm. The optimization problem is the minimization of a dispersion metrics calculated between the magnetic field intensity of the rotor. According to the representation of the rotor as a matrix, the aim is to change  $\alpha$  in order to compensate the accumulated deviations in the corresponding column. Values of vector  $\alpha$  are integers indicating the counter clockwise shift of a magnet pair, in the same row. After  $M_p/2$  shifting operations the stack reaches its starting position. In order to avoid redundant permutations the first stack is not shifted and can be seen as fixed reference for the shifting operations of the remaining  $S_p-1$  stacks ( $\alpha_1=0$ ).

During the execution phase, the optimization algorithm has to run for each specific batch of  $S_p$  stacks to be assembled in order to compute the specific assembly policy. For evaluating the quality of the rotation vector  $\alpha$ , different cost functions can be applied leading to different optimization results. Two alternative methods for computing the total magnetization deviation  $\Delta B$  are investigated and applied to experimental data. The first cost function sums up the deviation of the current magnet from the reference value (4), which is the mean value in this case. This implies that all deviations are treated in the same way, yielding a smaller total deviation but allowing higher isolated single peaks. Where  $M_p$  is the number of columns (magnets in a stack),  $x$  is the mean value of all column sums,  $x_i$  is the sum of magnetization of one column (all magnets with same polarity), and  $S_p$  is the number of rows (number of stacks in a rotor).

$$\Delta B_m = \sum_{i=1}^{M_p} |x_i - \bar{x}| \quad \text{with } x_i = \sum_{j=1}^{S_p} x_{ji} \quad (4)$$

The second approach uses the variance as the cost function taking into account the square value of the same deviation (5). This results in a more uniform signal as it penalizes high peaks but allowing average deviations yielding a higher value for the total deviation.

$$\Delta B_v = \frac{1}{M_p - 1} \sum_{i=1}^{M_p} (x_i - \bar{x})^2 \quad \text{with } x_i = \sum_{j=1}^{S_p} x_{ji} \quad (5)$$

If both features are present in the stack signals then the optimization algorithm calculates different optimal rotation vectors depending on the underlying cost function. The appropriate cost function is determined by production requirements. For finding the best solution with the underlying cost function, the total magnetization deviation  $\Delta B(\alpha_i)$  is computed for each fixed rotation and stored together with the corresponding rotation vector  $\alpha_i$ . The goal is to find an optimal rotation  $\alpha_{opt}$  for which the magnetization deviation  $\Delta B(\alpha_{opt})$  becomes minimal (6). A brute-force algorithm searches for the global minimum  $\Delta B(\alpha_{opt})$  in the entire solution space  $\Omega$ .

$$\Delta B(\vec{\alpha}_{opt}) = \min \{ \Delta B(x) \mid x \in \Omega \} \quad (6)$$

**Stage 2 - optimal stack order.** Once *Stage 1* solution is determined, *Stage II* aims to find the best axial arrangement of stacks. The axial order of stacks in a rotor is defined by a vector  $\rho$  indicating their vertical order. It starts at 1 for the top stack and increases to the bottom stack position  $S_p$ . The best arrangement  $\rho$  has to be determined such that the variability of the output field intensity of the rotor is minimum. This variability,  $\Delta P$  is defined as a cost function of a rotor whose parameters are derived from experimental observations. Based on experimental observations, two main factors that influence the variability of magnetic field intensity of a rotor have been identified. Thus the cost function is defined as the superimposition of these two individual factors that are discussed here.

The first experiment investigates the impact of stack position  $\rho$  on the variability of the output field intensity of a rotor. A cost parameter  $\Delta P(\rho^{G1})$  as a function of the axial position  $\rho$  and magnetization deviation of stacks is defined. The cumulative variability  $\Delta P_i$  is defined for each stack  $i$ . It is computed as the sum of absolute deviations of each magnet on

a stack from a target reference value or the overall average  $\bar{x}$  as (7). Summarized results from this empirical experiment are reported for an assembled rotor in terms of derived prognosis coefficients  $c_i$  (Table 1). These coefficients are reward vectors defined for each stack position  $i$  on the cost function. It can be assumed that variability on the rotor is minimized if the most variable stack is placed at the central position.

$$\Delta P(\rho^{G1}) = \sum_{i=1}^{S_p} c_i \Delta P_i \text{ where } \Delta P_i = \sum_{j=1}^m |x_{i,j} - \bar{x}|, \forall i=1, \dots, S_p \text{ and } \bar{x} = \frac{\sum_{j=1}^m x_j}{m S_p} \quad (7)$$

Table 1: Structure and parameters of prognosis model.

Position	Formula	Parameters
Top stack	$\hat{m}_{1,j} = m_{1,j} + c_b \cdot m_{2,j}$	$c_b = 0.071$
Center stacks	$\hat{m}_{i,j} = m_{i,j} + c_c \cdot m_{i-1,j} + c_c \cdot m_{i+1,j}$	$c_c = 0.045$
Bottom stack	$\hat{m}_{n,j} = m_{n,j} + c_b \cdot m_{n-1,j}$	$c_b = 0.071$

A second experiment shows that the variability on the rotor is reduced by placing oppositely deviating magnets next to each other. This reduction in variability is achieved because the close proximity creates a neutralization of interfacing deviations. In this experiment also a cost parameter  $\Delta P(\rho^{G2})$  is defined corresponding to each axial position  $\rho$ . The adjacent compensation has to be evaluated for  $(S_p-1)$  interfaces for a rotor of  $S_p$  stacks. The resultant deviation at a given interface between stack  $i$  and stack  $i+1$  ( $\Delta P_{i,i+1}$ ), is computed as (8). The cumulative cost function  $\Delta P(\rho^{G2})$  is evaluated as a sum of all interface deviations.

$$\Delta P(\rho^{G2}) = \sum_{i=1}^{S_p-1} \Delta P_{i,i+1} \text{ where } \Delta P_{i,i+1} = \sum_{j=1}^m |x_{i,j} + x_{i+1,j} - 2\bar{x}|, \forall i=1, \dots, S_p \quad (8)$$

The optimal axial arrangement is chosen as the one that minimizes both of the above two goals. Similarly as in *Stage I* this problem can be formulated as pair  $(\Omega, \Delta P)$ , where  $\Omega$  i.e., the set of all feasible axial positions and  $\Delta P$  is a mapping  $\Delta P: \Omega \rightarrow R$ . Therefore, the algorithm chooses the optimal arrangement  $\rho^{opt}$  that results the minimum of both sums (9). A simulation result for a rotor with five stacks is shown in Fig. 4.  $\Delta P(\rho^{opt}) = \min\{\Delta P(\rho^{G1}) + \Delta P(\rho^{G2}) \mid \rho \in \Omega\}$  (9)

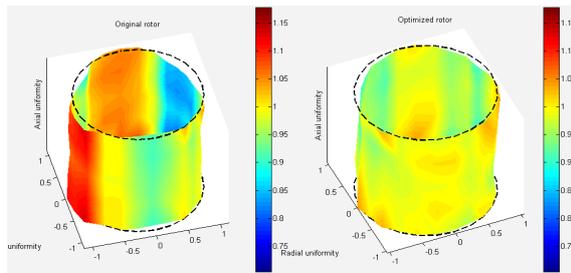


Fig. 4. 3D visualization of a rotor profile before and after optimization.

**Combined approach.** Instead of performing *Stage I* and *Stage II* optimization consecutively, it is possible to implement a combined approach. The algorithm finds the best axial order for each possible radial permutation. This approach guarantees finding the global optimum at the cost of higher calculation time. For experimental data, the combined approach is able to reduce the deviation by more than 9%

compared to the consecutive optimization for  $S_p=5$ . However, the computation time increases from 0.2s to 40s by the factor 200 affecting the overall system level performance.

#### 4. System level performance evaluation model

A decomposition based performance evaluation method is adopted to analyze the system level quality and production logistic performance of the two assembly strategies. This model analyzes a general manufacturing system that is composed of multiple processing stages (blue squares) and inspection stages (red squares) defined as  $M_k, k=1, \dots, K$ , (Fig. 5). Buffers (circles) have the role of decoupling the consecutive stages in the system. They can be either inventory storages or automated material handling systems that transport semi-finished parts between machines.

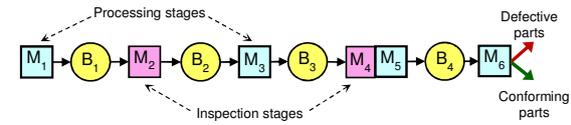


Fig. 5. Modelling formalism for a generic multi-stage production line.

Continuous time-discrete state Markov chain model is used to characterize the behavior of each stage. A transition rate matrix  $\lambda$  is defined to model each machine with multiple operational and failure states by means of arbitrarily complex Markovian structures. When the machine is in an operational state  $o$ , it processes parts at a rate of  $\mu_o$  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  $\mu$ . 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  $Y$ . The total fraction of defects generated by the stage is denoted as  $\gamma$ . 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.

Having derived the characteristic parameters  $(\lambda_i, \mu_i, Y_i)$  for each stage, the steady-state probability vector  $\pi$  of the Markov chain and the performance of the stage in isolation, i.e. not integrated in the production line, can be computed:

$$\pi \cdot \lambda_i = 0 \quad E_i^{Tot} = \pi_i \cdot \mu_i^T \quad E_i^{Eff} = \pi_i \cdot \text{diag}(\mu_i) \cdot Y_i^T \quad Y^M = \frac{E_i^{Eff}}{E_i^{Tot}} \quad (10)$$

Full exposition of this methodology is presented in [11-13]. However, the formalism does not consider the application of the typical assembly strategies proposed here. Since these strategies affect the material flow and the behavior of stages, this impact has to be included in the stage models.

5. System level performance analysis of assembly strategy

A system level model of the rotor production line is developed by introducing specific considerations for each of the assembly strategies discussed in Section 3. The process chain model allows the joint analysis of quality and production logistics performances. Three process chain models are developed each one representing each assembly strategy. The first is for the current configuration, while additional two models are developed for the proposed two assembly strategies. The two models for the new strategies are adaptations of the current configuration at two specific areas that are affected by the application of the assembly strategies. Firstly, an inspection station for the measurement of magnetized stacks is introduced in (Fig. 6)  $M_3$ . The location of this inspection station depends on the assembly strategy. It is placed next to  $M_3$  (position (a) in Fig. 6) for selective assembly and before  $M_5$  (position (b) in Fig. 6) for sequential assembly. Secondly, times affecting the assembly station and inspection station are considered under each strategy.

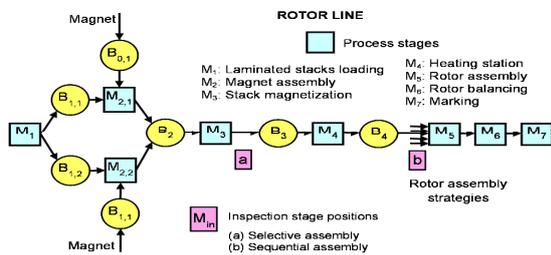


Fig. 6. Current rotor production line and required changes for new strategies.

5.1. Current Configuration

The process chain model for the current configuration aims to replicate the results that are obtained from actual production system. This enables to test the validity of the model and the underlying assumptions. Accordingly this process chain integrates adaptations and approximations required to characterize the existing production line. The model that approximates the rotor production line into the process chain is shown in Fig. 7.

Once the necessary approximation for each processing station is done then the decomposition method is called to evaluate this process chain. Quality and productivity performance of the configuration are computed and the results are reported in Table 2. These values are satisfactorily close with the actual production system (these figures are transformed for confidentiality reasons).

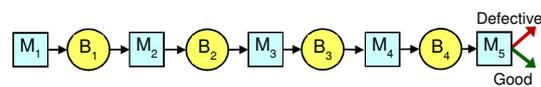


Fig. 7. Approximated process chain of the current production line.

5.2. Selective assembly

After the performance of this strategy is evaluated at the assembly station, a system level analysis is performed considering the entire process chain shown in Fig. 8. The strategy requires introduces some changes to the management and layout of the line.  $B_3$  and  $B_4$  in the original line are combined and split into a parallel configuration to store measured classes of stacks. The multiple paths for the flow of materials and the policies for assembling stacks only from matching classes create a complex system. Due to this complexity in the system management, modeling selective assembly requires more technical mathematical derivations. For the sake of space limitations, we omit this derivation that can be found in [14]. The new cycle time of the integrated magnetization and inspection machine is also modified using the additional times that must be introduced for measuring individual stacks before classifying them. Finally, the performances of the system in terms of rotor quality and production rate are reported in Table 2.

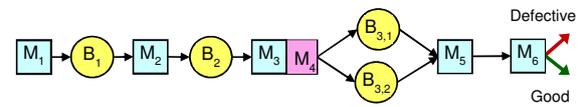


Fig. 8. Process chain model of the selective assembly strategy.

5.3. Sequential assembly

The adoption of the sequential assembly strategy and introduction of the inspection machine modifies the behavior of the assembly machine. Since it performs measurement, optimization and assembly of stacks it requires additional time. These times are different depending on the type of rotor to be assembled. However, in this case we consider a typical rotor assembled from five stacks and the production logistics behavior of this machine is adjusted accordingly. The new assembly machine is an integrated machine composed of  $M_5$  (the current assembly machine) and  $M_6$  (the proposed inspection and optimization station) Fig. 9. Under this strategy, this machine can be modeled into an equivalent machine  $M_{sq}$  by using the state transition diagram in Fig. 9.

The set of transition rates of the equivalent machine  $M_{sq}$  ( $M_5$ ) and corresponding processing rates are computed in (11). Estimated times are obtained as follows:

- Assembly ( $T_{asbl}$ ) equal to the current process
- Inspection ( $T_{insp}$ ) time required by inspection
- Optimization ( $T_{opt}$ ) algorithm time, section (3.3)
- Additional ( $T_{add}$ ) time for positioning stacks is considered

$$p_{sq} = \mu_U \cdot \gamma$$

$$r_{sq} = \mu_U \cdot (1 - \gamma)$$

$$\frac{1}{\mu_U} = T_{asbl} + T_{insp}; \quad \frac{1}{\mu_{sq}} = T_{asbl} + T_{insp} + T_{add} + T_{opt} \tag{11}$$

Once model adaptation of the assembly machine is performed then the decomposition approach described in Section 4 can be used to evaluate the system level performance of this strategy.

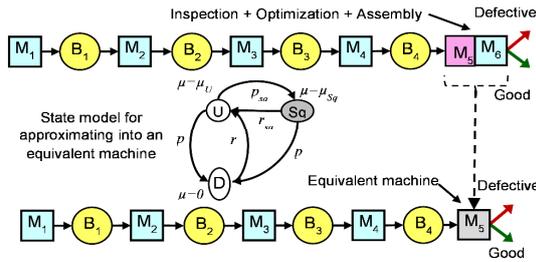


Fig. 9. Process chain and state approximation of the assembly machine.

5.4. Numerical results and comparison of strategies

The quantitative models for each of the assembly strategies are evaluated and the summary of the performance results are reported in Table 2. The results show that both assembly strategies improve the effective throughput of the current system. Comparatively, the sequential assembly performs better (16.55%) than the selective assembly (8.85%) on the effective throughput ( $E^{Eff}$ ). This difference can be explained through the impact of the two new strategies on  $E^{Tot}$  and  $\gamma^{system}$ .  $E^{Tot}$  is slightly lower for the selective assembly due to the system complexity and related deadlocks, but it improves the yield to 0.93. Similarly,  $E^{Tot}$  is lower under sequential assembly due to the required additional inspection time before the assembly operation. However the intelligent optimization techniques integrated into the sequential assembly greatly improve the quality of rotors giving a system yield ( $\gamma^{system}$ ) equal to 1. Therefore, the quality and production logistics trade-off is optimal under the sequential assembly strategy for the considered system.

Table 2: Comparison of the assembly strategies by system performance.

Strategy	$E^{Eff}$ [parts/t.u]	$E^{Tot}$ [parts/t.u]	$\gamma^{system}$	$\Delta\% E^{Eff}$ vs. Baseline
Current line	0.5752	0.6729	0.85	-
Sequential	0.6704	0.6704	1.00	+16.55%
Selective	0.6261	0.6726	0.93	+8.85%

6. Conclusion

In this paper, two different assembly strategies for the reduction of defect propagation in multi-stage production lines are proposed. A quantitative methodology to support the design of the best possible strategy by estimating their impact on the overall system performance is developed. The benefits of the strategies are demonstrated within a real industrial process-chain, dedicated to the production of electric drives. In addition, by using an intelligent and adaptive assembly policy, the conformity of output rotor to specifications can be maximized. Furthermore, alternative algorithms for solving the sequential assembly optimization problems in real-time are proposed. The corresponding computational times are also

different, which in some cases must be provided by adequate computers or machine controls. These implications should be considered before implementation. A generalization and extension of the proposed methodologies can be applied to systems in several industrial contexts. Such tools help to facilitate the achievement of defect reduction and elimination goals such as zero-defect manufacturing.

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