PRODUCTION COST CASE GENERATION BY A RECURSIVE MONTE-CARLO METHOD IN ELECTRICAL MACHINE PRODUCTION

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Abstract: Electrical machine production is a multi-disciplinary area, comprising traditional mechanical processes such as sheet metal cutting, chemical processes for insulation and electrical for the working principles. In manufacturing, high throughput automation of coilwinding and sheet-cutting is combined with complex assembly, such as slotting the coils, often performed manually, but with increasing interest in automation. Followed by inherently slow processes such as the curing of resins for insulation, this poses a very difficult challenge for production system designers. Selecting the most efficient combination of low and high cycle time processes, appropriate levels of automation and sufficient buffer levels, while minimizing investments and work in progress costs.

Keywords: Electric machine, Production, Balancing losses, Recursive, Monte-carlo

1 INTRODUCTION

The global generation of electric energy was 21000 TWh in 2010, with 40% of the worlds electric energy production consumed by electrical machines and drives (Birol, 2013). More stringent efficiency regulation of machines and drives, coupled with increasing electric and hybrid vehicle production (Fulton, 2009), leads to a demand for cost effective production methods for new electric machines.

A multitude of technologies for automation of processes that previously have been carried out manually, can now be automated, for example within magnet handling and assembly (Vervaeke, 2013; Schilp et al., 2013; Kuhl & Franke, 2013), and steel sheet lamination, (Lanza et al., 2013; Thelen & Burkert, 2003).

Within coil-winding automation is well established, here technical development is often focused on improving fill factor (Rahman et al., 2004) or allowing for simplified handling of wire-ends for termination within later assembly processes. The use of single slot windings reduces complexity in the production of the machine (Fornasiero et al., 2010).

While these technologies offer possibilities in higher throughput, reduced personnel costs and more consistent cycle times, they also require larger investments, and reduce flexibility in handling multiple product variants.

Production system designers are faced with a multitude of decisions on what processes are best suited for the product or products to be manufactured within the given system. These decisions are affected by a number of factors such as performance, reliability and economics.

Especially within the relatively new market of automotive traction machines, where market demand is highly uncertain and OEMs often require custom solutions to fit their particular needs (Miller et al., 2011), with production volumes ranging from a few thousand units per year for heavy vehicles such as buses to several hundred thousand per year for cars, electric drive production provides an interesting application for the systematic production analysis methodology presented in this work.

In order for the production system to operate at a high utilization factor, careful selection of preceding process cycle-times and buffer sizes are required. If the buffer into stacking operation is consumed during a standstill of the cutting operation, this inevitably causes a standstill of the stacking process, increasing the standstill factor, IV in equation 1. This standstill may also cascade down through the production system, driving up standstill costs.

Conversely, large buffer sizes may itself lead to high costs for products in work, due to large investments in materials to fill the buffers. Especially for handling of critical materials such as rare-earth magnets (Fyhr et al., 2012; Schilp et al., 2013). The widely adopted philosophy of just in time (Sugimori et al., 1977) suggests low stock levels and evenly balanced processes.

1.1 Production processes

Production of an electric machine stator starts with two independent operations. Cutting magnetic steel sheet, which serves as a flux conductor and structural part of the machine and winding several coils, which when fed with alternating current generate a magnetic field to drive the rotor.

Magnetic steel sheet. The most common production method for magnetic steel sheets is blanking, see figure 1, but as high tooling costs may be prohibitive for lower production volumes, alternative technologies such as water-jet, laser-cutting or roll blanking may be used (Tremel et al., 2012). These process alternatives are illustrated on row 1 in figure 5.

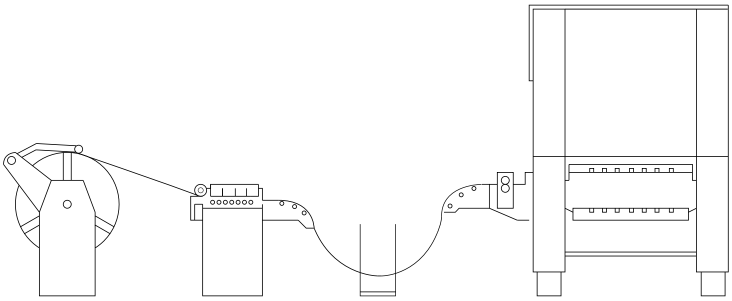

Fig. 1. Components of a press line, the press is fed from a roll of magnetic steel sheet.

After the cutting process, the sheets are stacked and joined, see figure 2. Welding is common for industrial drives, as it provides a high strength connection with rapid cycle times. Adhesives also provide a strong bond, but require a curing time. Interlocking connections do not offer the strength of a weld, it does however allow even faster cycle times and sufficient structural support when inside a housing. The model presented here includes these joining methods on row 2, group b, in figure 5.

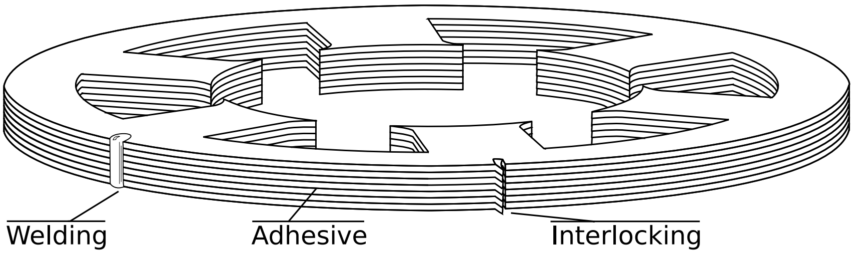

Fig. 2. Magnetic steel sheet stack, with three common joining techniques: welding, adhesives and interlocking.

Coil winding. The manufacture of the field-generating coils recieves attention from both industry and academia. Focus is often placed on maximizing the magnetization $\oint \vec{H}\, d\vec{l} = nI$, simply put higher current (I) or increased number of turns (n). In this work, three winding types have been selected to represent the most common winding types, see figure 3. Distributed coils are the historically most common type of winding for three-phase machines, where a pre-wound hoop-coil is fitted into two stator slots spanning a number of teeth. This requires pulling the loosely wound coil into the slots and handling the end windings. Single tooth coils are pre-wound on a bobbin, which is later placed onto the stator tooth, as the coil shares the slot with its neighbour and both need to be fed over the stator tooth from the center a gap must be left between the two coils unless a segmented stator configuration is used (Brettschneider et al., 2013). Needle wound coils share traits with the single tooth coil, and can be wound in-slot (Mumford, 2003) or as pre-shaped hair-pin coils (Miller et al., 2011). Coil winding processes are included in group a, figure 5.

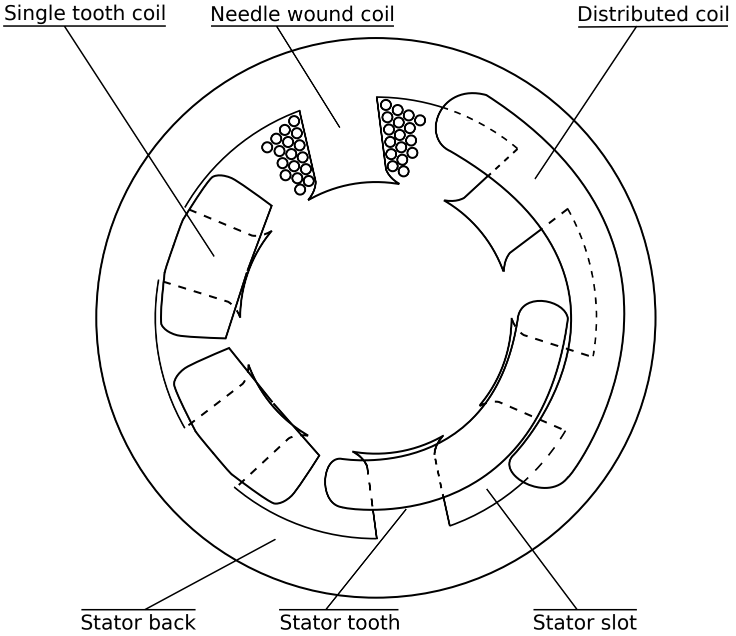

Fig. 3. A schematic stator, illustrating the studied winding types and part naming.

Assembly. The assembly of stator stack and windings are illustrated on row 3 in figure 5, where manual, semi-automated and fully automated processes are included.

Insulation. For increased discharge protection, heat transfer and durability with regards to vibration, the stator and winding package are infiltrated with resin. The infiltration process can be performed by hot-dipping, trickle coating or vacuum infusion. After the infiltration, the resin is cured.

2 SCOPE

This work focuses on analysing the matching and balancing between processes in production of electrical machine stators. Insight into balancing factors, before a physical production system is implemented, allows the production system designer to select the appropriate combination of production processes. The work utilizes and builds upon the methodology described in (Fyhr et al., 2013), where a number of process options are evaluated for each operation, see figure 5. The purpose is to demonstrate an efficient method of generating results for the vast amount of possible process combinations, as described in section 1.1, including balancing costs, not to perform an exacting estimation of costs for one specific product. Functional performance properties, such as fill factor, eddy current losses or electromagnetic overtone spectra that may be affected by the selection of technologies presented in section 1.1, are not considered here.

3 METHODOLOGY

Production system performance and resulting production costs, for a multitude of production process combinations, are analyzed using self developed software. The software implements a multi-state production process model, see figure 4, based on eq. 1 first published by (Jönsson et al., 2008).

$$\begin{aligned} k_i = {} & \frac{K_A}{N_0}\left[\frac{1}{n_{pA}}\right]_I + \frac{K_B}{N_0}\left[\frac{N_0}{1-q_{Qi}}\right]_{II} + \\ & \frac{K_{CP}}{60N_0}\left[\frac{t_{0i}N_0}{1-q_{Qi}}\right]_{III} + \frac{K_{CS}}{60N_0}\left[\frac{t_{0i}N_0 q_{si}}{(1-q_{Qi})(1-q_{si})}\right]_{IV} + \\ & \frac{K_D}{60N_0}\left[\frac{t_{0i}N_0 q_{si}}{(1-q_{Qi})(1-q_{si})}\right]_V + \left[\frac{K_B \bar{n}_q p}{N_0}\right]_{VI} \end{aligned} \tag{1}$$

3.1 Production costs

The production cost equation, eq 1, describes the cost $k_i(N_0)$ of a part on row i in the production system as a sum of costs from different sources, where:

I investment costs.
II material costs.
III machine costs in production.
IV machine costs at standstill.
V wage costs
VI work in process costs

In the production system model, expanded on in section 3.2, contributing costs from sources $II - V$ will vary depending on the time spent in each process state and its input queue size, see figure 4. A notable difference in the implementation described here as compared to the original works by (Jönsson et al., 2008) is the handling of queue costs in VI, see eq. 1, where K_B is the value of the input material, $\bar{n}_q$ is the average queue size and p is the interest rate.

In the stacking, insulation and assembly processes, illustrated on rows $2-4$ in figure 5. The material costs K_B, are described by the calculated costs from preceeding processes, see equation 2, when the results of multiple processes are assembled (row 3 in figure 5) the sum of the costs from those processes are used as material cost, see equation 3.

$$K_B(i) := \begin{cases} k_{i-1}(x) & x = a \quad a = \{1,2,3\} \\ k_{i-1}(x) & x = b \quad b = \{4,5,6,7\} \end{cases} \tag{2}$$

$$K_B(i) := \sum_{x=a}^{b} k_{i-1}(x) \tag{3}$$

3.2 Production system model

Each process option for a given operation consumes a queue of input material, and proceeds to either place the result on the output queue or reject it as out of specification. In case the input queue is empty, the process requests input material waits for it to be filled, see figure 4.

In this stator production case the two top level processes, magnetic steel sheet cutting and coilwinding, consume a spool of magnetic steel sheet and a drum of copper wire, see figure 5 and figure 1.

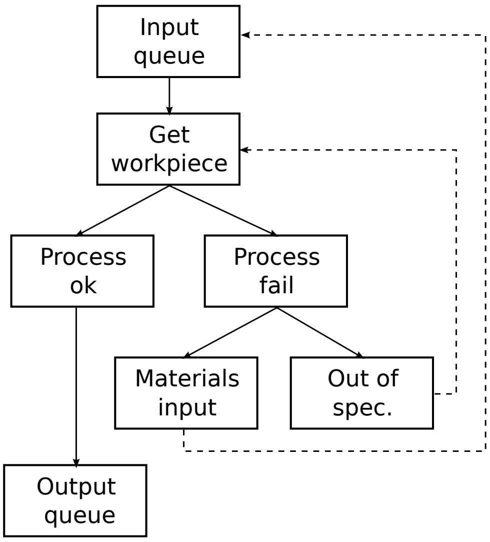

Fig. 4. Process states represented in each process option.

Subsequent processes options consume the output generated by the preceeding step. All compatible combinations are considered, thus generating twelve cases for the initial two rows of stator cutting operations and six for the initial two coil winding rows. This gives 61 cases at row 3, for a total of 183 combinations at row 4.

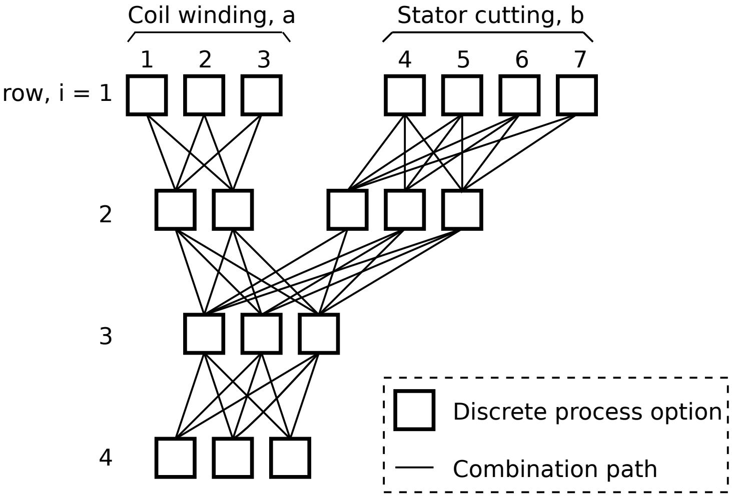

Fig. 5. Production process flowchart, illustrating the process options and notation.

The standstill rate (q_{si}) is caused by input material shortage, buffer underruns or reject occurrence (q_{qi}). Standstills caused by lack of input material in the initial refinement step, prompts replacement of the input material, before the process is restarted. In subsequent refinement steps a buffer underruns causes the current process to wait for additional workpieces to be added to its input queue, see figure 4.

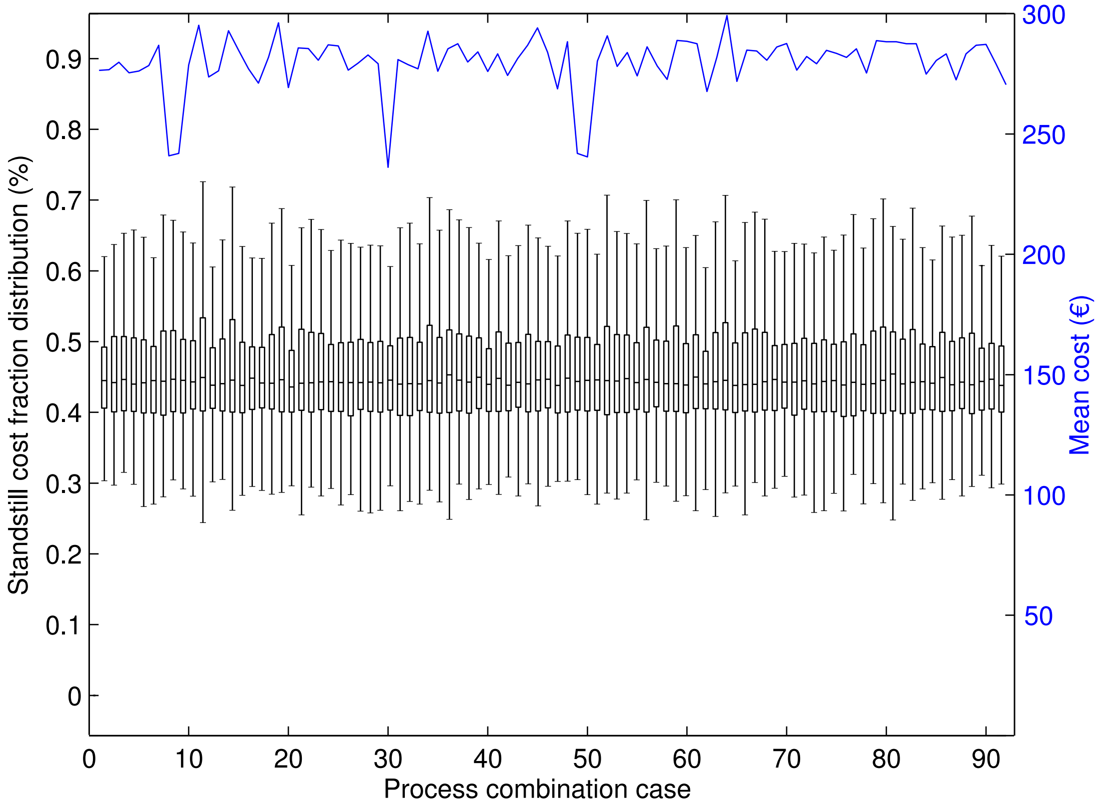

Fig. 6. Average part cost and standstill cost fraction distribution for 92 of the resulting cases.

4 RESULTS

As mentioned in section 3.2, 186 cases are generated. Results for 92 of these are included in figure 6, where average product cost and standstill cost fraction distributions are presented. Case 6, 13, 21, and 30 show low variance in standstill fraction, case 30 also shows the lowest average product cost, see figure 7.

Conversely, the result for case 65 from figure 6 shows the impact of a higher stop frequency and larger stop variance, which results in a higher average product cost, see figure 8.

5 DISCUSSION AND CONCLUSIONS

As demonstrated above in section 4, the benefits of implementing a simple and re-useable statespace model as described in 3.2 are clear. As balancing losses clearly affect product cost and therefore should be considered.

The modeling of standstills as random events and the inclusion of queues as input, does affect decision-making, as there no longer exists a continously decreasing function as in (Fyhr et al., 2013) on which to simply select the combination with the lowest cost in any given volume segment.

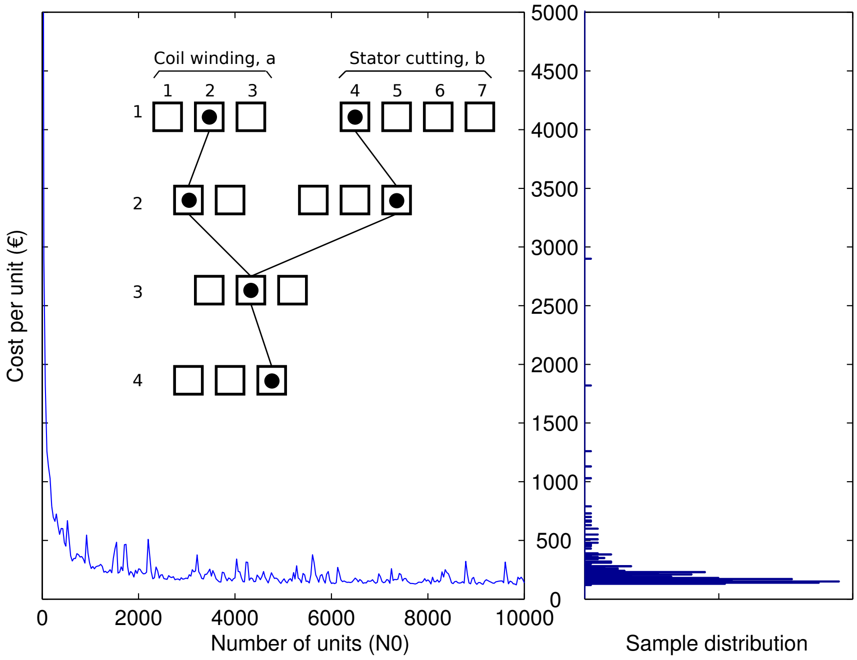

Fig. 7. Resulting cost per unit and cost distribution, for case 30 (see figure 6), with a stamped and interlocked stator and single tooth coil.

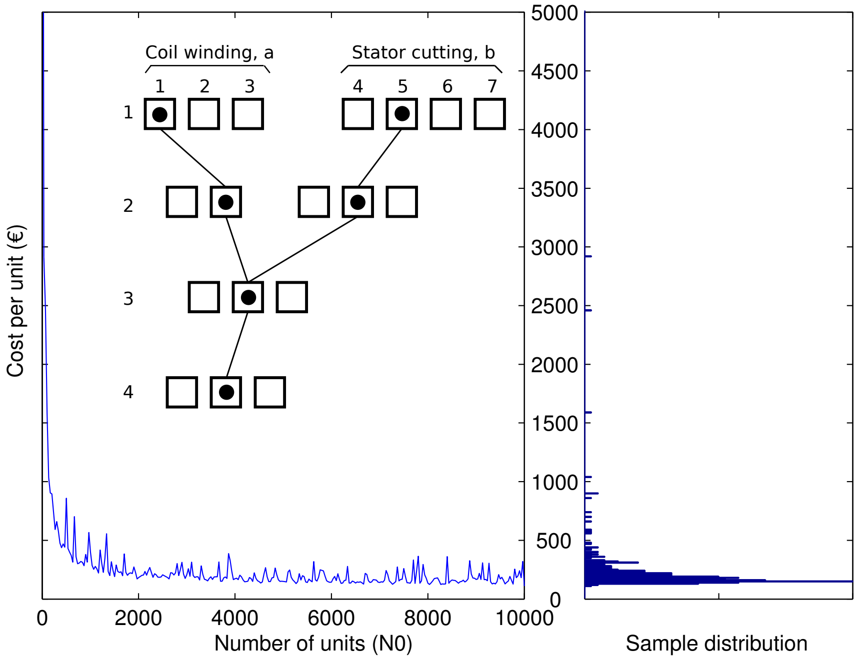

Fig. 8. Resulting cost per unit and cost distribution, for case 65 (see figure 6), with a rotation-blanked and bonded stator and distributed coil.

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