
SIMULATION MODELING FOR QUALITY AND PRODUCTIVITY IN STEEL CORD MANUFACTURING

Can Hulusi Türkseven

School of Industrial Engineering
Purdue University
315 N. Grant Street
West Lafayette, IN 47907-2023, U.S.A.

Gürdal Ertek

Faculty of Engineering and Natural Sciences
Sabancı University
Orhanli, Tuzla, 34956
Istanbul, TURKEY

ABSTRACT

We describe the application of simulation modeling to estimate and improve quality and productivity performance of a steel cord manufacturing system. We describe the typical steel cord manufacturing plant, emphasize its distinguishing characteristics, identify various production settings and discuss applicability of simulation as a management decision support tool. Besides presenting the general structure of the developed simulation model, we focus on wire fractures, which can be an important source of system disruption.

1 INTRODUCTION

Steel cord is typically used as the main reinforcement material in manufacture of steel radial tires. It strengthens the tire to provide fuel savings, long mileage, safety and comfort. The manufacture of steel cord takes place through continuous processes where wire semi-products are stored on discrete inventory units, namely "spool"s (Figure 1). The steel cord plant is operated with multiple –possibly conflicting- objectives, both quality related (ex: minimizing the number of final spools containing knot defects) and productivity related (ex: increasing throughput). Modeling this type of manufacturing requires special considerations applicable to a narrow scope of industries. One such consideration is the reversal of the wire wound on the spools at each bunching operation. Manufacturing systems with similar operating characteristics include cable manufacturing (electric/energy/fiber-optic), nylon cord manufacturing, copper rod manufacturing.

Literature on steel cord manufacturing is not extensive, since this is a very specialized type of manufacturing, and the systems required are produced and installed by only a handful of companies in the world. We refer the interested readers to the following two studies: Thomas et al. (2002) report improvement of operations in a steel cord manufacturing company using simulation. Mercankaya (2003) develops an optimization-based decision support system for steel cord manufacturing.

We first describe the manufacturing process and outline research objectives. After discussing various modeling approaches for possible configurations and discussing the relevance of simulation modeling, we describe the simulation model, including inputs, decision variables, ouputs and results obtained. We conclude with a discussion of future research areas in production planning for the described systems.

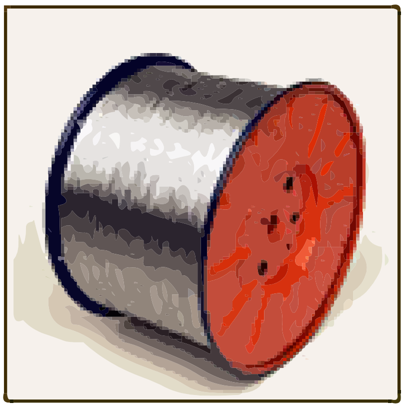

Figure 1. Spool on which Wire is Wound

2 THE MANUFACTURING PROCESS

In steel cord manufacturing incoming raw material, the “steel rod wire”, is thinned into “filament”s which are used in successive bunching operations to construct the “steel cord” final products (Figure 2). Between every bunching operation, the intermediate wire products are wound onto spools of varying capacities (in the scale of thousands of meters). Steel rod wire enters the steel cord plant with a radius of ~2.5mm and passes through dry drawing and wet drawing, accompanied with other operations (including chemical processes such as copper and zinc plating) to produce filaments with a radius of ~0.2mm. Filaments coming out of wet-drawing are wound on spools and are referred to as “payoff”. Payoff becomes the raw material for bunching and spiralling operations. At each bunching operation, bunched wires enter as “core” to be bunched with a new layer of payoff (filaments) to form “take-up”. The “take-up” in turn becomes the “core” for the following bunching operation (Figure 3).

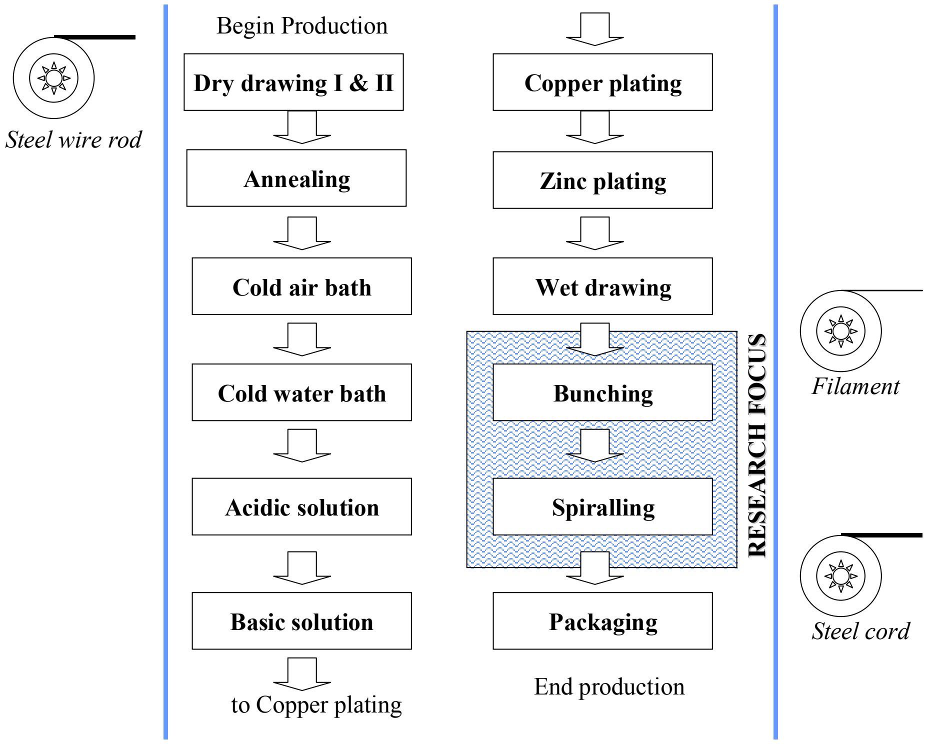

Figure 2. Production Processes in Steel Cord Manufacturing

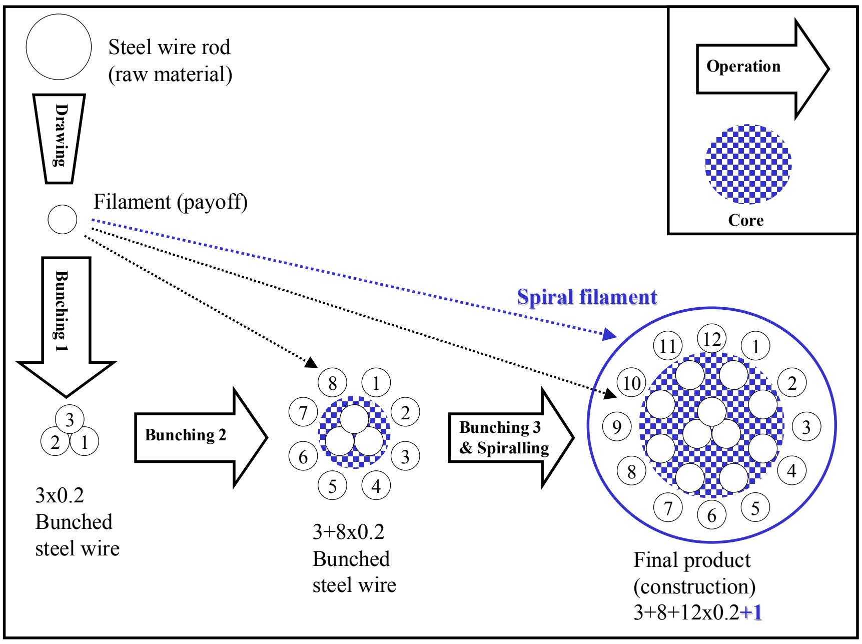

Figure 3. Cross-section of 3+8+12x0.2+1 Construction at Successive Bunching Operations

In each bunching operation the take-up consumes a pay-off longer than its own length, according to a “usage factor”. For example, in a bunching operation with a usage ratio of 0.9, 100000 meters of payoff bunches with 90000 meters of core to produce 90000 meters of take-up. As the product advances along the production line, its thickness increases and thus it takes a longer payoff to cover the take-up; i.e. the usage ratio decreases. Input ratios are discussed with other input parameters in Section 5.

The final steel cord product is obtained by spiralling a single filament after the final bunching operation, and is referred to as “construction”. Figure 3 illustrates the cross-section of the wire semi-products at various bunching stages in manufacturing of construction “3+8+12x0.2+1”. The naming convention for labeling constructions (and semi-product bunched wires) uses a “+” sign to denote each additonal bunching operation. The construction “3+8+12x0.2+1” is obtained by bunching 3 filaments of length 0.2mm in the first bunching operation, then 8 filaments, and then 12 filaments at 0.2mm, followed by a single spiralled filament.

Despite product variety (possibly in the scale of hundreds), we focus in our research on production of a particular construction and analyze quality and productivity issues for that single final product. Our approach can be validly applied in analysis and improvement of steel cord plants where a particular construction constitutes a major share of the production load or is of primary importance for another reason.

As the spool of core and spools of payoff are used in a bunching operation, any of the spools may run out first. The time it takes for this run-out is a function of the spool lengths and production rates of the machines, besides other factors, some of which are discussed below. As run-out takes place, the bunching machine gradually slows down and finally stops. A setup is performed by a skilled operator to feed the next spool with the same kind of wire (core or payoff) into the machine. Payoff or core spool is tied at the wire location where the machine had stopped, and production in that machine restarts. Since the stopping takes place gradually, a certain amount of wire is typically wasted at every “change-over”. This tying of changed spools results in a knot, which is an undesired situation. When the take-up spool (the spool on which the semi-product wire out of a bunching operation is wound) is completely full, a change of take-up is performed. Besides knots due to spool changes, “wire fractures”, seemingly random breaks of the wire due to structural properties, may also result in considerable number of additional knots. By tagging an information card on each spool the locations of knots can be recorded. If the sources of knots (whether they are due to changeovers or fractures) are not recorded, the resulting data would not be perfectly valid from a statistical point of view.

After the spiralling operation the steel cord is cut into specified lengths and wound onto final spools, which are eventually packaged for customers. Tire manufacturers prefer that the spools with the final cuts of steel cords contain no knots at all. Final spools that contain knots, namely "rejected spools", are classified as second quality and are sold at a very low price. Therefore, it is an important management objective to decrease the number of knots and the number of rejected spools.

The motivation of our research has been to identify improved operating policies, specifically "optimal" spool lengths for each bunching operation, such that quality and productivity are improved. Both of these two performance measures can be improved if the number of rejected spools (spools containing knots) is reduced.

3 MODELING APPROACHES

In this section we discuss under what conditions simulation is a suitable modeling approach for steel cord manufacturing and discuss various modeling issues. Typically the steel cord final product is obtained after more than one bunching operation. For example, the construction 3+8+12x0.2+1 goes through 3 successive bunching operations and a final spiralling operation (Figure 3). If machines of all bunching operations had the same cycle times connected serially, and/or if random fractures were negligible, modeling the steel cord manufacturing process would be a fairly simple task. For now, we assume that fracture knots constitute a minor portion of the knots and can be ignored. In Section 4 we provide a detailed discussion of wire fractures and describe approaches to validate data collected on them. We consider three cases that correspond to various manufacturing settings, as illustrated in Figure 4.

In Case 1, we assume that each successive bunching operation is connected serially, and the take-up (output wire) of a bunching operation is directly fed into the next one as core (input wire) without any work-in-process spool inventory. The quality and productivity of this system would be very high, as production takes place continously except the final cuts. The quality output of this hypothetical system is 100% and constitutes an upper bound on quality performance of a real-world plant.

In Case 2, we assume that in-process inventories are stored on spools, and the serial nature of Case 1 is kept. In this type of a system, knots do occur due to spool changes, yet knot locations at the end of bunching processes can be computed easily as multiples of spool lengths. From these locations, the number of spools containing knots can be computed (Figure 5). We can apply search algorithms to find spool lengths that minimize the number of rejected final spools.

Case 3 is much more representitive of how steel cord manufacturing takes place in the real world. Since machine production rates vary for different bunching operations, the numbers of machines at each bunching operation are typically different. Work-in-process wires are stored on spools, which are queued before the next set of bunching machines. For operational simplicity, operators use a FIFO (First In First Out) queueing discipline in selecting the next spool to enter bunching operations. It is extremely difficult to identify mathematically the order in which spools are queued. Operator times, number of knots, knot locations, heuristic operating policies (described in Section 6), the current state of the spools in the system, machine speeds and other factors all affect the time it takes to complete a take-up spool. A linear programming based model that takes these factors as parameters can be questioned with respect to validity, as the constraints to reflect fairly complex nature of operations would require definition of a large number of variables, many of them integer. Therefore, we believe that simulation modeling is the best way to analyze the described system. The existence of wire fractures only strengthens this conclusion.

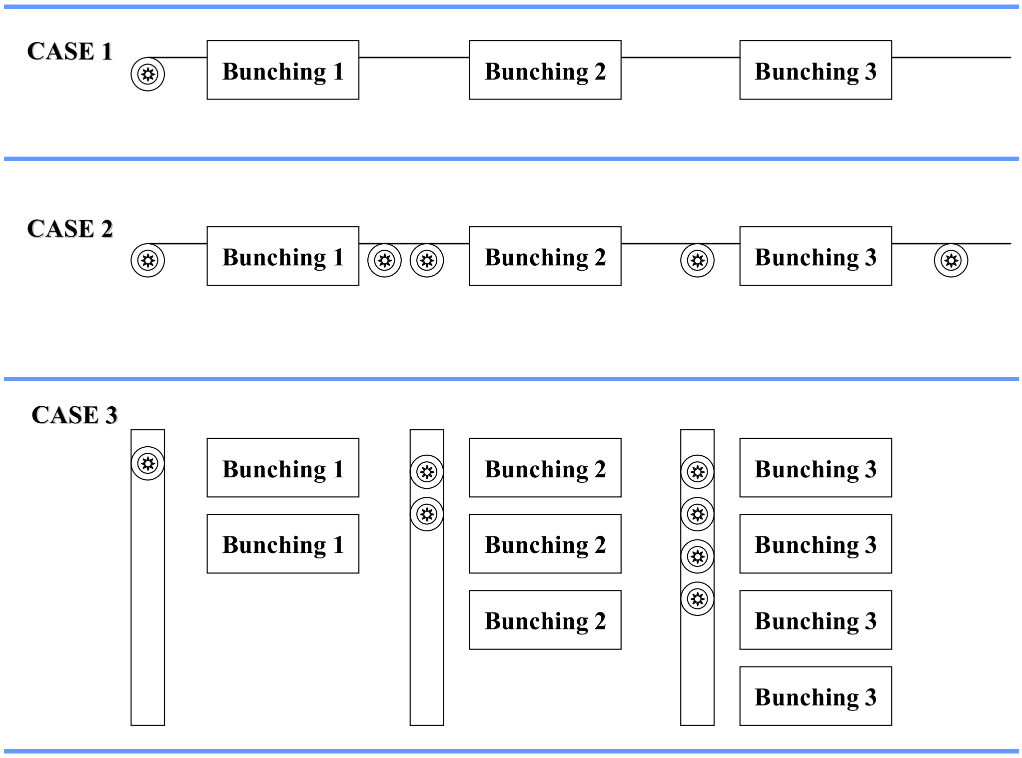

Figure 4. Various Manufacturing Scenarios which Require Different Modeling Approaches

4 MODELING WIRE FRACTURES

Wire fractures may constitute a significant percentage of all the knots, depending on the quality of incoming steel rod wire, heterogeneity caused by dry drawing processes, the plant environment, machine characteristics, and other factors. As opposed to knots from change-overs, which may be controlled –at least to some degree- through scheduling, wire fractures are uncontrollable. Since the frequency and locations of knots have great impact on quality and productivity, one would ask the essential question of whether any patterns exist in wire fracture locations. As part of our study, we collected this data from bunching machines in a particular steel cord plant and carried out basic statistical analysis. The data collected gives the locations of wire fractures in spools entering the final bunching operation.

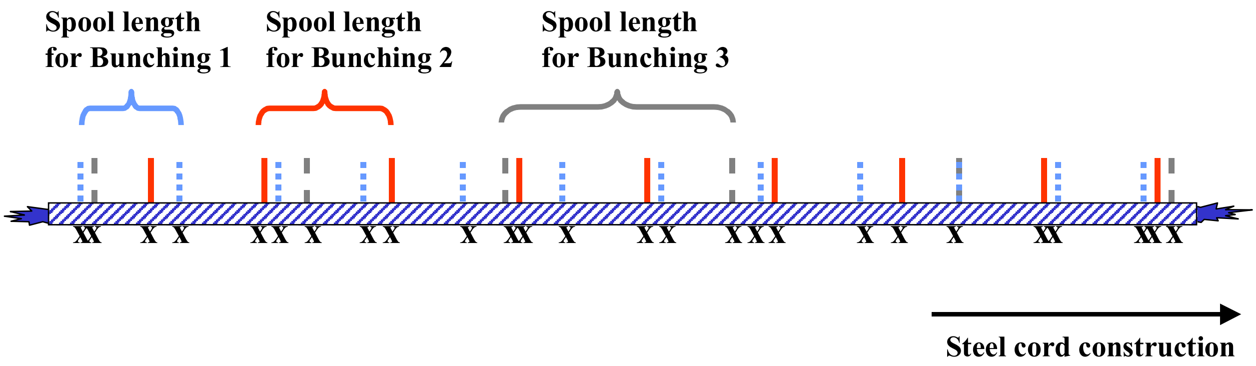

Figure 5. Locations of Knots in Case 2. The x Signs Denote the Knots Due to Change-overs. The Intervals Shown in Brackets Correspond to Lengths of Work-in-Process Spools, and Are Decision Variables in the Simulation Model.

Fracture locations have been thought to be related to the location of previous fractures, the locations of previous knots, core and payoff lengths. Production specialists suggested that these issues do not affect the fractures. It was tested if fracture locations and frequency followed any distribution. However, statistical analysis of the data did not suggest any patterns. Fracture locations have been assumed random (uniform distribution) in the simulation model. Thus, inter-fracture distances are assumed to follow exponential distribution and the number of fractures on unit length of wire is assumed to follow poisson distribution. In addition to a known historical average value for the percentage of fractures, an estimate can also be obtained from a sample collected during a particular time interval. One important question is whether the collected data agrees with the patterns observed historically. This can be formulated as a statistical null-hypothesis and tested using statistical techniques.

5 SIMULATION MODEL

5.1 Description

In the simulation, the number of rejected spools (a measure of both quality and productivity) is computed given a set of spool lengths. Through grid-search on spool lengths, the optimal spool lengths can be determined.

The optimal spool lengths are constrained to be within a certain percentage of the current spool lengths. This constraint is imposed by plant managers as a result of the strategy of making gradual changes over time, as opposed to rushing in radical changes in short time periods. One other reason for such constraints is the impact on other operational measures. For example, selecting the spool lengths that are too short would lead to prohibitively frequent payoff or core changes, and increased operator costs.

Some production issues are almost unique to this particular type of manufacturing: An example is that the locations of knots are reversed at every spool change. When a wound spool of length h with knot locations $(k_1, k_2, \ldots, k_n)$ is fed into the bunching operation, the unwinding results in knot locations $(h-k_n, \ldots, h-k_2, h-k_1)$.

5.2 Implementation

The simulation was programmed in C++ language, and takes ~1 minute running time to compute performance measures for a 10 ton production schedule (10 simulation experiments are performed). We preferred programming with a general-purpose language, as there are complexities (ex: reversing of knot locations at bunching operations) that would be next to impossible to reflect using spreadsheets and would have to be custom-programmed if a simulation language or modeling software were used.

5.3 Model Inputs, Decision Variables and Outputs

Input Parameters:

- Usage ratios: Ratio of take-up length to incoming payoff length at bunching and sprialling operations. As the diameter of the wire increases, usage ratios decrease.
- Wire densities: Linear density of wires on spools. These density values are used to convert meter based calculations to tones, as calculations in the plant are carried out on a weight basis.
- Fracture ratios: Expected number of fractures per ton at each bunching operation.
- Machine characteristics and quantities: Primarily the production rates, the rate at which bunching machines bunch payoff filament on core to produce take-up.
- Knotting time: The time it takes to restart the bunching process following a changeover or fracture. This time is very dependent on the source of the knot and is in the scale of 1-20 minutes.
- Final spool length: The length of final cuts that are wound on spools to be packaged and sent to tire manufacturers. These final cuts should be free of any knots.

Decision variables:

- Spool lengths: The length of wires on the take up and payoff spools.

Outputs:

- Number of accepted spools: The number of final spools that contain no knots.
- Number of rejected spools: The number of final spools that contain knots.
- Rejected wire length: The length of total rejected wire between knots, with a length smaller than final cut length.

- Throughput time: Total time required to convert a given tonnage of payoff to steel cord.

6 RESULTS

The simulation program provides an accurate estimation of the system performance measures given a particular setting. The results were validated with historical data from an existing steel cord plant and the simulation model was observed to be valid. The program was used to determine optimal spool lengths within a constrained search space. The accuracy of the simulation can be increased through increasing simulation run lengths and number of simulations and applying experimental design and output analysis techniques.

If there is inaccuracy in implementing any type of policy, the simulation can be used only as a strategic testing tool to evaluate operating policies. Conclusions/suggestions obtained through the simulation analysis of the analyzed manufacturing plant are as follows:

- Some of the current operational rules used by operators are proven to be useful. One such heuristic rule is performing a take-up change-over if only a few hundred meters have remained on the bunching operation. This is a reasonable approach: If the final spool length is greater than the remaining distance, winding the take-up completely would result in a rejected final spool further down the production line. The simulation model suggested that this indeed is a very helpful rule and should be implemented by all the operators.

- Feasibility of implementing dynamic control policies can be investigated. For example, current FIFO rule for selecting among queued spools for bunching can be replaced by a more sophisticated approach. The simulation model can be used to evaluate such changes in operational policies. However, this would also require that measurements be very accurate and that computers be placed at the plant floor.

7 FUTURE RESEARCH

Even though the developed simulation model accurately reflects the characteristics of the analyzed plant, the model can be extended to include new features (such as compensating for machine break-downs) and operational rules (such as dynamic spool selection). Meanwhile, it can also be used to test the economic feasibility of investing in new manufacturing technology, including better machines. A long term project could be developing the current tool into a generic modeling environment to analyze systems with similar manufacturing characteristics.

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AUTHOR BIOGRAPHIES

CAN H. TÜRKSEVEN is a graduate student at Purdue University. He received his B.S. from Manufacturing Systems Engineering Program from Sabancı University, Istanbul, Turkey, in 2003.

GÜRDAL ERTEK is an assistant professor at Sabancı University. He received his B.S. from Industrial Engineering Department of Boğaziçi University, Istanbul, Turkey in 1994 and his Ph.D. from School of Industrial and Systems Engineering at Georgia Institute of Technology, Atlanta, GA, in 2001. His research areas include supply chain planning, material handling, production planning and simulation analysis.