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SIMULATION APPLIED TO FINAL ENGINE DROP ASSEMBLY

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ABSTRACT

This study details the synergistic application of ergonomic analysis, discrete-process simulation, and statistical analysis to the problems of determining the optimum design for a final engine drop assembly work station. The study comprised attention to analysis of facilities and tooling systems, material-handling systems, and ergonomic workplace design. The results of the study supported a cost-effective increase in jobs per hour concurrent with implementation of ergonomically sound production processes.

1 INTRODUCTION

Significant improvements to a manufacturing process often require the application of methods and insights of several sources of specialized knowledge within the discipline of industrial engineering. Ergonomic analysis examines the suitability of the process environment to the worker relative to prevention of repetitive strain injuries, delay of the onset of fatigue, and support of the workers' efforts to maintain productivity and quality standards (Martinich 1997); hence, attention to ergonomic improvements not only reduces the number and severity of injuries, but also cuts costs and improves productivity (Auguston 1995), (Feare 1994). Discrete-process simulation analysis supports assessment of the need for and quantity of equipment and personnel, and assessment of operational procedures, via construction and examination of a model relative to system performance evaluation (Law and McComas 1997); understandably, manufacturing is one of the earliest, and yet most perennially popular, areas of simulation application. Relative to both ergonomic and process simulation studies, extensive statistical analyses of both input data (Leemis 1997) and output results (Kelton 1997) are required to achieve thorough, correct understanding of variability inherent in the production system and the manifestations of that variability visible in the context of system performance relative to productivity metrics.

In this study, ergonomic analysis and discrete-process simulation were used concurrently (Miller 1998) to determine the optimum achievable design for a final engine drop assembly work station. Various system design proposals, material-handling methods, operational procedures, and staffing levels required comparative evaluation of their ability to approximate "optimum" design. In this context, "optimum" design entailed attainment of production quotas, avoidance of ergonomic deficiencies, economies of implementation and operational costs, and – very importantly – adaptability of the system to reasonably predictable future modification requirements (Profozich 1998). Similarly broad-based studies of production systems undertaken from a macro viewpoint are those of material flow and layout analysis in production of industrial vehicles (Falcone and De Felice 1996), operations at a bulk-paper terminal (Van Landeghem and Moruanx 1997), and collaborative improvement of layout and scheduling decisions considered collectively in a bulk manufacturing process (Fowler and Lees 1995).

First, this paper presents an overview of the production system. Next, we describe the development of the model (referring both to model design and to data collection), and the verification and validation of it. We then present results of the concurrent discrete-process and ergonomic simulation studies. Last, we summarize our conclusions, including "lessons learned," and describe indicated future work.

2 OVERVIEW OF THE PRODUCTION SYSTEM

In the automotive industry, engines are characteristically assembled at plants dedicated to that purpose ("engine plants") and then shipped to assembly plants, where the engine is installed in an automobile or truck (Ellinger and Halderman 1991). The study described here undertook to improve the final assembly drop work station design at an

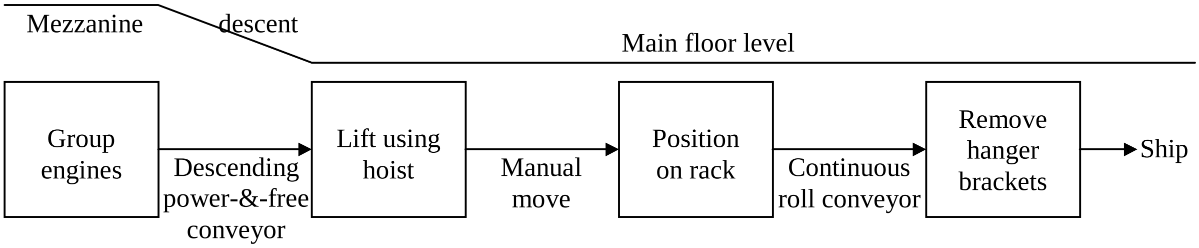

Figure 1: Schematic of Final Assembly Drop Work Station

engine plant. This station is responsible for one of the last steps an engine undergoes prior to shipment to an assembly plant, namely the emplacement of the completed engine into an engine rack which will hold and protect it during transport to an assembly plant. The basic configuration for this work station comprises a combined hoist mechanical operation interfacing with manual operations. The mechanism releases a completed engine assembly from a power-&-free conveyor into an engine rack on a transfer conveyor. On a mezzanine, newly assembled engines are arranged in groups (e.g., by engine type and/or size). The engines then descend to the main floor via a power-&-free conveyor. Using a chain hoist, an operator lifts the engine from the downstream end of this conveyor and positions the engine on a rack. Such a chain hoist, unlike a monorail or jib hoist, serves a fixed spot directly beneath itself, permitting suspension of the workpiece during operations while saving floor space and reducing interference with other operations taking place on the floor (Sule 1988). Often such hoists are installed, as is the case here, to achieve an important ergonomic gain – the elimination of significant strains of repetitive motion (Schwind 1994). The rack, when fully loaded with four engines, travels on a continuous roller conveyor to a station where an operator removes the hanger brackets from each engine. The engines, still mounted in the protective rack, then await shipment to a vehicle assembly plant. Use of these racks not only provides protection, but also achieves economy of space and efficiency of later item retrieval (Kulwiec 1994). The power-&-free conveyor leading to the lift provides relatively high speeds, plus flexibility and precise control of spacing and queuing to deal with temporary blockages due to downtime. By contrast, the continuous roll conveyor used farther downstream provides economy of purchase and operation in a different context wherein the previous advantages are of little consequence (Gunal, Sadakane, and Williams 1996). A schematic of this station and its operations is shown in Figure 1 at the top of this page.

3 MODEL DEFINITION AND DEVELOPMENT

3.1. Project Scope and Model Design

A vital part of any simulation study is setting clear project goals initially (Banks and Gibson, 1996), especially since project scope, model design, and data collection efforts must be defined in the context of those goals. Here, the task of the study was the development of an improved (relative to the desiderata listed in Section 1) system under the following constraints:

- no changes (other than possible chain improvements) to existing power-&-free conveyor
- no changes to the existing rack conveyor
- elimination of the manual hoist operation
- transfer of workers from elevated platform to floor level
- maintenance of workstation throughput without addition of personnel.

A significant portion of effort in this study was devoted to problems with the existing drop. Various authors, such as Radmil and Todor (1996), have identified key factors to examine when seeking workstation improvements. In this system, the operator was overworked even though only one of the two drops was utilized at current line speed. Quality issues arose due to the requirement that the operator control the hoist. From the viewpoints of both Operator “A” and Operator “B,” fatigue and stress became severe during an eight-hour shift, partly due to the rapid work pace. Also, from the viewpoint of Operator “A,” the hoist controls were too high, about 72 inches [1.8 meters]; from the viewpoint of Operator “B,” the height at which the engine hanger was picked up was too low, about 20 inches [0.5 meter] (Kroemer, Kroemer, and Kroemer-Elbert 1994). The modeling team noted that other case studies have identified unduly large reach zones as significant contributors to cumulative trauma disorders (Camarotto et al. 1997).

Plant engineers and managers assembled a cross-functional team comprising plant personnel plus both internal and external consultants in discrete-process, robotic, and ergonomic simulation. The actual models were then built using the computer software packages WITNESS™

(Markt and Mayer 1997) for discrete-process simulation and IGRIP© for robotic and ergonomic simulation (Jackson 1996). These packages combine ease of use, high modeling power, and concurrent construction of model process logic and model animation.

3.2 Data Collection

Well before specific data collection began, a team of plant industrial, process, and controls engineers, simulation consultants (both internal to Ford and external), and engineers from the machine-tool vendor met to specify precisely the scope of the project, as described in section 3.1. The project scope, in turn, spawned understanding of which process data, such as cycle times, transit times, location capacities, and frequency and duration of downtime, would be required. Among these data, only the downtime data were stochastic. However, this simulation study, unlike those devoted solely to process simulation, additionally required detailed, accurate prints or CAD drawings to be integrated into the model. A Gantt chart of critical activities guided group discussions setting appropriate priorities for data collection (Nordgren 1995), since "data quality can make or break a simulation" (Field 1997).

4 MODEL VERIFICATION AND VALIDATION

The models were verified and validated largely by comparison of their predictions with known deficiencies of the current system (Sargent 1996). For example, the analysis team compared ergonomic sensitivities, equipment utilizations, and throughput predicted by the model with those observed in practice. Additionally, the animations helped verification and validation by supporting ready identification and correction of modeling errors relative to material flow, conveyor operational details, and precise time-and-motion details pertinent to the manual operations (Sokhan-Sanj and Mackulak 1997). Walkthroughs of the model, conducted by the modeling team, exposed errors for early correction, as did examination of model traces, some run with no downtime to establish baseline values and ease the task of desk checking (Robinson 1997).

Presentation of the model and its results to the plant engineers and managers was made easier because they all were acquainted with simulation and its benefits from participation in previous projects. Since these engineers and managers already constituted an "open-kimono" team, the results presented dispassionately and quantitatively by the simulation could revise or replace strongly held intuitive opinions when appropriate. The modeling team presented the animation and the results of statistical analyses to management within an agenda of restating the project objectives and the problems addressed, reviewing the project methodology, and comparing the benefits versus costs of proposed solutions (Gogg and Mott 1995).

5 RESULTS OF THE STUDY

5.1 Early Results Pertaining to the Discrete Process Study

In the first phase of the study, the plant engineers and modeling team members compared five alternatives involving single- versus double-engine drop, two or four engine-drop workers, and 24-inch versus 40-inch dog spacing on the power-and-free conveyor which transports engines from the mezzanine to the main floor. Extensive experimentation with the validated model produced the results summarized in Table 1.

Table 1: Relative Production Capacity of Alternatives

Alternative	Relative Capacity
Double drop, 4 workers, and 40-inch dog spacing	1.58
Double drop, 2 workers, and 40-inch dog spacing	1.44
Single drop, 2 workers, and 40-inch dog spacing	1.00
Single drop, 2 workers, and 24-inch dog spacing	1.03
Single drop, 4 workers, and 24-inch dog spacing	1.16

These comparisons of relative production capacities were next used as guidance to modifying and enhancing the design of the workstation relative to ergonomic and interface concerns.

5.2 Results Pertaining to the Ergonomic Study

The three-dimensional kinematic simulations unearthed two significant ergonomic concerns within the initial design of the workstation. These simulations, since they analyzed work content in the ergonomic sense, not system output, needed no "warm-up" period to bypass an initial transient. This station comprised two separate jobs: (1) hoist operation and (2) reach and place engine hanger bracket. The hoist operation was satisfactory with respect to lifting, absence of back strain, and absence of problems relative to the arms and shoulders. However, the reach-and-place operation as initially designed was at high risk for back injury, and, for females, was at high risk for shoulder injury. These ergonomic assessments were performed using the University of Michigan three-dimensional static strength prediction program [3DSSPP] (Chaffin and Erig 1991), which identified the most serious problem as lower back compression (index of 787, where

770 is a threshold value for risk). Since the 3DSSPP uses a double linear optimization technique to compute spinal compression forces from net reaction moments about the lumbar spine, it is amenable to field use without laboratory collection of surface electromyography data measuring muscle activation (Hughes 1995). Since the actual task is inherently frequent and repetitive, engineers deemed the actual risk higher, and hence more urgently meriting correction, than the risk index derived by this static model. Metabolic stress of both jobs was analyzed using a method of estimating metabolic rate using qualitative job descriptors accounting for hand motion, walking and carrying, lifting, and pushing and pulling (Bernard and Joseph 1994); these researchers' development of the method was based on eighty typical jobs in automotive manufacturing. This model unequivocally indicated absence of significant metabolic stress.

Redesign of the workstation to obviate these high risks for back and shoulder injury entailed revamping the hook-release operation required of the operator (primarily by improving its work envelope), lowering the platform to improve postural configuration relative to removing the engine hanger bracket, and modifying the interface between the workstation and the power-&-free conveyor to eliminate the task of replacing a "bar, chain, & hook" apparatus on the conveyor. After reexamination of the revamped workstation with the ergonomic model confirmed achievement of throughput, the analysis team returned to the process study to integrate the redesigned workstation into the overall process.

5.3 Union of Ergonomic and Process Study Results

Since the redesign of the workstation inevitably created "ripples" affecting the overall process, the team next returned to the discrete process model armed with new information and system constraints learned from study of the ergonomic model. Process model alternatives were newly constrained to a pair of single-engine drops with two operators stationed at each drop, additional conveyor stops, and an upstream conveyor capacity of either four or five racks (24-inch dog spacing required) to accommodate installation of larger electrical panels. Furthermore, the conveyor speed was now limited to approximately thirty feet per minute to avoid long-term damage to the conveyor stops. The project team selected six alternatives for re-evaluation using the process model. Since the process model had been designed with ease of modification in mind (by use of sound modeling practices such as modular development, mnemonic attribute and variable names, and extensive internal comments), revision, re-verification, and re-validation of the model required less than 10% of the time devoted to these tasks for the base model. The project team chose six alternatives for comparative assessment; results are shown in Table 2.

Table 2: Relative Production Capacity of Ergonomically Revised Alternatives

Alternative	Relative Capacity
5 racks on conveyor @ 30 feet/minute	1.25
4 racks on conveyor @ 30 feet/minute	1.14
5 racks on conveyor @ 16 feet/minute	1.11
4 racks on conveyor @ 16 feet/minute	1.00
5 racks on conveyor @ 17 feet/minute*	1.12
5 racks on conveyor @ 20 feet/minute	1.16

* alternative chosen

After extensive discussion, the project team and its management chose the fifth alternative above due to its ability to meet production quotas, use of a relatively low conveyor speed (implying relatively low operational and maintenance costs for the conveyor), and adaptability to potential increases in the amount of production demanded. After subsequent implementation and actual operation, predictions of the model were confirmed to within 2½%.

The modeling team also investigated the consequences of prolonged (and stochastic) downtime at either of the two single engine drops under the proposed operational policy of "reassign the two operators there to the other drop for the duration of repairs." The simulation model indicated that the nominally expected "50% of normal production" would increase to 58% of normal under this contingency policy. These analyses, due to the randomness associated with them, required much longer warm-up times (measured in weeks, so that downtimes could occur repeatedly) than did the earlier analyses (whose warm-up period was a few minutes, representing typical station load times).

6 CONCLUSIONS AND INDICATED FURTHER WORK

This study confirmed the value of 3-D kinematic simulation in working on a conceptual project. Use of a three-dimensional representation instead of two-dimensional drawings enhances both intuitive and analytical understanding of the processes. Additionally, the combination of ergonomic assessment and three-dimensional simulation provided an excellent format for simultaneous engineering. Significant "lessons learned or confirmed" during this combined-simulation study were (a) the importance of including engineers with extensive intuitive knowledge and understanding of the workstation on the project team, and (b) the necessity of interviewing the operators of the workstation to understand their perceptions and concerns for accurate inclusion within *both* the ergonomic model and the process model (*Materials Handling Engineering* Editors 1994). Thenceforth, ergonomic (re)-assessment has proved sufficient for revamping of an existing workstation. The animation inherent in this kinematic simulation helped in training both production and maintenance workers, thereby tightening the coupling between process engineers and production managers (Krieg, Völker, and Geipel 1996). The quantitative results of the concurrent kinematic and discrete-process simulations helped development of the controls logic just prior to installation. Specifically, improvement of the cycle time during the simulation study had required inclusion of various stop, switch, and control positions, plus control logic sequences, within the simulation model. Those details of the controls logic yielding the best cycle times were passed on to the build engineers for production system implementation.

Future plans call for benchmarking a complete 3-D ergonomic simulation package against one of the recognized ergonomic software tools. The availability and power of such tools is increasing rapidly (Johnson 1998). Success in this endeavor requires not only identical inputs to the package and tool being compared, but also a controlled environment in which engineers explicitly define a job suitable for these analyses. Such a controlled environment is best achieved in the context of an established ergonomics team (Ousnamer 1997). Explicit definition of testing criteria, such as the National Institute of Occupational Safety & Health [NIOSH] lifting equation (United States Department of Health and Human Services 1994) to analyze the two-handed lifting activities of workers, will likewise be required.

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APPENDIX: TRADEMARK

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