Ergonomics Analysis for Vehicle Assembly Using Artificial Intelligence

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Abstract

In this paper we discuss a deployed application at Ford Motor Company that utilizes AI technology for the analysis of potential ergonomic concerns at our assembly plants. The manufacture of motor vehicles is a complex and dynamic problem and the costs related to workplace injuries and lost productivity due to bad ergonomic design can be very significant. We have developed two separate ergonomic analysis systems that have been integrated into the process planning for manufacturing system at Ford known as the Global Study and Process Allocation System (GSPAS). GSPAS has become the global repository for standardized engineering processes and data for assembling all Ford vehicles, including parts, tools and standard labor time. One of the more significant benefits of GSPAS is the use of a controlled language, known as Standard Language, which is used throughout Ford to write the process assembly instructions. AI is already used within GSPAS for Standard Language validation and direct labor management. The work described here shows how we built upon our previous success with AI to expand the technology into the new domain of ergonomics analysis.

Introduction

At the 6th Annual Applied Ergonomics Conference held in Dallas, TX in March of 2003, the Institute of Industrial Engineers (IIE) awarded the "Ergo Cup" in Training & Education to Ford Motor Company for the GSPAS Ergonomics Application (Ergo Solutions 2003). Ford Motor Company has been utilizing an integrated process planning system since 1990 to standardize the process sheet writing, create work allocations for the plant floor and to estimate labor time accurately. This system, formerly known as the Direct Labor Management System (DLMS) (Rychtyckyj 1999) is a knowledge-based system that utilizes a semantic network knowledge representation scheme. DLMS utilizes techniques from natural language processing, description logics and classification-based reasoning to generate detailed plant floor assembly instructions from high-level process descriptions. This system also provides detailed estimates of the labor content that is required from these process descriptions. Techniques such as machine translation and evolutionary computation were integrated into DLMS to support knowledge base maintenance and to deploy DLMS to Ford's assembly plants that do not use English as their main language.

The process sheet is the primary vehicle for conveying vehicle assembly information from the central engineering functions to the assembly plants. It contains specific information about work instructions and describes the parts and tools required for the build process. The work that is required to build the vehicle according to the process sheet instructions is then be allocated among the available personnel. Work allocation requires a precise means of measuring the labor time that is needed for any particular task. The DLMS system interprets these instructions and generates a list of detailed actions that are required to implement these instructions at the assembly plant level. These work instructions, known as "allocatable elements", are associated with MODAPTS (MODular Arrangement of Predetermined Time Standards) codes that are used to calculate the time required to perform these actions. MODAPTS codes are widely utilized as a means of measuring the body movements that are required to perform a physical action and have been accepted as a valid work measurement system (Carey et al. 2001). For example, the MODAPTS code for moving a small object with only a hand is M2; utilizing the arm gives a code of M3. The MODAPTS codes are then combined to describe an entire sequence of actions. MODAPTS codes are then converted into an equivalent time required to perform that action.

Subsequently the ergonomics engineers would manually inspect the process sheets for possible ergonomic problems. Since there may be 1000 or more process sheets for every single type of vehicle that Ford manufactures, this manual type of inspection was very labor intensive and time-consuming. An ergonomics engineer would spend upwards of two weeks in manually inspecting each process build instruction for a vehicle.

In an effort to streamline this process we developed a system that would automate the inspection of process sheets for ergonomics concerns. This work resulted in the development of an artificial intelligence system for ergonomic analysis within GSPAS that checks for two types of potential ergonomics issues: "red" and "warning". Process sheets that are flagged as "red" will not be sent to the assembly plants until those errors are corrected. Process sheets that are flagged with "warning" messages are released to the assembly plants; however, the ergonomic specialists have the opportunity to check and approve these issues through the use of a system that was built specifically for this application.

The Ergonomics system was developed and deployed to production in April of 2002. Since that time, more than 1100 process sheets with ergonomics problems were stopped by the AI system from going into production at the assembly plants. This has already resulted in a savings of over $17,000,000 in injury cost avoidance as the high risk processes never made it to the plant floor. These calculations are based on the type of injuries prevented and the direct cost associated per injury for each type of ergonomic problem.

In this paper, we discuss how artificial intelligence technology was used to prevent potential ergonomic problems at our assembly plants with significant benefits in reducing workplace injuries and time lost by workers. Section 2 discusses the problem of ergonomics analysis for manufacturing. Section 3 provides a detailed description of the ergonomics analysis that is being performed by the system. We discuss the application of AI technology in Section 4. An analysis of the benefits provided by our system is given in section 5. The application deployment and maintenance is discussed in Section 6.

Problem Description

The proactive Ergonomics group within Vehicle Operations at Ford Motor Company is responsible for the launch of all future vehicles with ergonomically correct assembly. This team starts working as early as four years before the vehicle is launched to develop standardized ergonomic strategies for vehicle assembly and design. This work includes checking the process build instructions for every vehicle for potential ergonomic issues. A complete ergonomics analysis would include the following:

- Check the assembly work instruction to determine what type of physical action is being described: (ex. LOAD, POSITION, OBTAIN) and what the frequency of the work is.
- Check the assembly work instruction to determine what object is being manipulated (ex. BRACKET ASSEMBLY INNER)
- Check the assembly work instruction in Standard Language to determine what parts and tools are needed for this operation.
- Check the associated parts and determine what part is being used and the weight of that part.
- Check the associated tools and determine the properties of the tool to see how it impacts the operation.

The manufacturing build instructions are written in Standard Language, which is a "controlled language" that was developed specifically at Ford. Standard Language has been in use at Ford since the early 1990s and is used worldwide by Ford engineers to describe the assembly process for virtually all vehicle programs. A controlled language defines a set of explicit restrictions and constraints on the grammar, lexicon and style of the document being produced. The major aim of these constraints is to reduce the ambiguity, redundancy, size and complexity of the language that is being written. A specific type of verb, known as a Standard Language verb, was used as the basis of Standard Language usage. Each Standard Language verb (we currently have 134) was carefully defined to represent a specific action and was used as the main driver for a Standard Language element or sentence. Only one Standard Language verb is valid per element and the resulting actions from a process instruction are based on the interaction between the verb, the object, any modifiers and the tools and parts that are used in the element. The ergonomics engineers identified those verbs that are associated with potential risk factors (force, frequency and posture). Thresholds were assigned to each trigger verb to assess the level of risk based in part on the force and frequency associated with the element. A sample of a process sheet is given in Figure 1.

Process Sheet Written in Standard Language
TITLE: ASSEMBLE IMMERSION HEATER TO ENGINE
10 OBTAIN ENGINE BLOCK HEATER ASSEMBLY FROM STOCK
20 LOOSEN HEATER ASSEMBLY TURNSCREW USING POWER TOOL
30 APPLY GREASE TO RUBBER O-RING AND CORE OPENING
40 INSERT HEATER ASSEMBLY INTO RIGHT REAR CORE PLUG HOSE
50 ALIGN SCREW HEAD TO TOP OF HEATER
TOOL 20 1 P AAPTCA TSEQ RT ANGLE NUTRUNNER
TOOL 30 1 C COMM TSEQ GREASE BRUSH
PART 10 1 01 7499 01 S-011201 B ENGINE BLK HEATER ASSY

Figure 1: Sample GSPAS Process Sheet

In this example, the ergonomics engineer would need to determine if this process sheet has any potential ergonomics concerns. In element 10 the engineer determined that the OBTAIN operation requires an operator to get a "engine block heater assembly" part from the part bin and walk back to his station. This could potentially cause a concern if the part weighed above a certain threshold; therefore the engineer would need to look up the weight of the part. If the part weighed more than a certain threshold (in this case 35 pounds) the engineer would also need to check if a "lift assist" type tool was assigned to this element. If there were no lift assist tool assigned, the engineer would flag this job as having an ergonomic concern due to the excessive weight that the operator would need to carry.

As stated previously, this type of manual analysis was unfeasible due to the sheer volume of data that needed to be analyzed. Potential ergonomics problems that were not flagged before they reached the assembly plant floor would need to be fixed at the plant and this would entail additional delay and expense. Therefore, our challenge in this project was to develop an automated method that could flag potential ergonomics concerns before they reached the assembly plant.

Ergonomics Analysis for Manufacturing

All of the manufacturing process sheet information at Ford is already processed through an AI-based system; therefore we already have a description-logics based knowledge base, an inference engine and a rule base in place. The ergonomic engineers at Ford Motor Company provided us with the details and description of what type of concerns needed be identified and this knowledge was added to the GSPAS knowledge base. The structure of the knowledge included both rules and concepts that provided specific details about potential ergonomics concerns.

Ergonomic analysis of process sheets in Standard Language is done at two different levels. The artificial intelligence system in GSPAS checks each process sheet for elements that violate certain "red" ergonomic conditions as identified by the ergonomics engineers. Any such violation requires the process engineer to rewrite the element(s) that have Ergonomics errors and resubmit the sheet for AI validation. The process sheet does not validate correctly and cannot be released to the assembly plant until all of the ergonomics errors are corrected.

There are three classes of ergonomics errors that the AI system checks for: frequency errors, tooling torque violations and heavy part violations. A frequency violation is triggered when the element describes repetitive actions for a particular operation that exceed a predetermined threshold. The "ergonomics frequency" error is based on the Standard Language verb that is used in the element and the number of times that a particular operation needs to be done. The information about each verb and its associated frequency condition is stored in the knowledge base and can be easily updated. For example, the following element will trigger an ergonomics error.

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HANDSTART 10 BOLTS will return an error:
The number of times <TEN> verb <HANDSTART>
is performed exceeds the ergonomic limit
<8>.
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The processor must rewrite this element so that the number of bolts is changed from 10 to 8 or less and then revalidate the process sheet. This will usually require that the element be split into two or more separate elements that do not violate this ergonomics condition. Splitting the offending element into two separate elements (each containing 5 "Hand-start" operations) does not change the amount of work that needs to be done. However, since the work is now split up it will probably be assigned to two separate operators.

A tool torque violation is triggered when a power tool with a torque above a certain threshold is assigned to an element using a particular Standard Language verb and a tool to mitigate the additional torque is not assigned to that element. The Ergonomics Analysis system reads and verifies that the tool assigned to the element belongs to the class of tools that can handle the high installation torque. This analysis is based on several factors: a comparison of the tool description, checking the tool description with the information that is available inside the AI knowledge base and checking the tool number.

A part weight violation is triggered when the operator is assigned a part that weighs more than a maximum weight and a lift assist is not assigned to that element. The processor must assign a lift assist tool to this element in order to validate it. The ergonomics analysis must consider several factors in determining if this element is in violation of the ergonomics constraints. First, the system must analyze the Standard Language sentence to determine what part description in the sentence is actually being lifted by the operator as a sentence may contain multiple parts. For example, the following Standard Language sentence contains three potential part descriptions:

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LOAD THE FRONT BUMPER INTO STATION WITH
PALLET TRANSFER SYSTEM
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The AI parser must recognize the fact that the "front bumper" is the only part that is actually being loaded and that the weight of the other two items is irrelevant. Each element in Standard Language has a number of parts assigned to it; these parts are loaded into GSPAS from the Worldwide Engineering Releasing System (WERS). Each part in WERS contains a prefix and suffix as well as a part description. There may be upwards of 100 parts and their various revisions assigned to a single Standard Language element. The ergonomics analysis system selects the most up-to-date part from the list of available parts and tries to match the WERS part description to the part description that is specified in Standard Language. This part matching is based on the following rules:

- Match the head noun in the Standard Language description with the same term in the part description from WERS. The "head noun" is the last and main noun in a sequence of terms. For example, the description "STATION WAGON LOAD FLOOR LOCK CYLINDER" has a head noun of "CYLINDER". This is the noun that is searched for in the WERS part description.

- Standard Language allows for the use of size adjectives that modify a part description at the end of the description. The term "front bumper large" signifies to the system that the process engineer needs to override the existing size of the "bumper assembly" with a "large" size. In this case, the head noun is "large" and the Ergo Analysis tool will ignore this size when finding the head noun search term. In this example, the head noun will be "bumper".
- The ergonomic analysis tool will also ignore generic terms such as "assembly", "front", and "rear" in determining what the head noun should be.
- The WERS part descriptions often contain extra punctuation & abbreviations that will cause the part matching to fail. The ergo analysis tool filters out the punctuation and special characters before making any comparisons. Abbreviations are checked against the GSPAS knowledge base, and substitutions are made before the comparison takes place. For example, the term "brkt" is converted to "bracket" before any comparisons are made.

Nevertheless, the matching of the part description from Standard Language with the part descriptions from WERS still misses some matches and potential ergonomics violations for lifting. These misses are caused by the ambiguity that is inherently present in natural language. The following list shows some of the cases where part matching still has problems and our proposed solutions:

- The part description in Standard Language and the part description in WERS refer to the same part, but they use a synonym rather than the exact part match. For example, "glass" & "windshield" may refer to the same part, but they do not use the same terminology. A straight comparison will not match these as describing the same part. Our solution to this is two-fold: we can make one term a synonym of the other as we already check for synonyms or we can modify our knowledge base so that both "glass" & "windshield" belong to the same class of parts and have the same properties.
- There is no direct correlation between the terms in Standard Language and WERS. We have analyzed all the terminology in WERS and have found that about 13% of these terms are not found in Standard Language. This list contains some misspellings as well as terms, acronyms and abbreviations that are not in Standard Language and will not match up properly. The correct terms will need to be added into Standard Language, and it may be necessary to use a spellchecker to correct the misspelled terms that can be fixed.
- We are currently just checking the head noun from Standard Language against the list of terms in the part description without doing any analysis on the part description itself. For example, the following Standard Language element "ROUTE THE WIRE THROUGH THE HARNESS" is matched up against the part description "PART WIRE HARNESS". In this case the part "WIRE" in Standard Language matches up with the term "WIRE" in the part description even though they don't represent the same part. We will need to parse the WERS part descriptions in order to analyze the phrase and find the appropriate head noun for comparison. This will require us to add additional Standard Language terminology and modify the parser to handle the types of phrases that are used in the WERS part descriptions.

Ergonomics "WARNING" Processing

The ergonomics "red" conditions that were discussed in the previous section prevent the process instructions from being released to the assembly plants. We also developed a system to check for ergonomic conditions of less severity that are known as "warning" messages. A process sheet that has "warnings" can get released to the assembly plant; however, the warning messages are reviewed by the ergonomics engineers and either approved as being acceptable or flagged as "requiring action". Those that require action will be sent back to the process engineers for correction.

There are also three classes of ergonomics warnings that the AI System checks for: frequency warnings, force warnings and "always flagged" warnings. These warning conditions differ from the error conditions in the thresholds that are assigned to trigger each condition. For example, a frequency violation may trigger a warning at a level of 6, but an error is not triggered until it reaches a level of 12.

A frequency warning is triggered when the element describes repetitive actions for a particular operation that exceed a predetermined threshold. The "ergonomics frequency" warning is based on the Standard Language verb that is used in the element and the number of times that a particular operation needs to be done. A force warning is triggered when the operator is assigned a part that weights more than a maximum weight and a lift assist is not assigned to that element.

An "always flagged" warning is triggered whenever a particular Standard Language verb is used, regardless of the tools or parts that are assigned to this element. In Standard Language a verb may be defined in terms of another verb; for example, the POSITION verb also includes a GRASP in it. Therefore trying to position a part that weighs more then 10 pounds will also trigger an ergonomics warning because the part must be grasped before it can be positioned.

Uses of AI Technology

The ergonomics analysis tool in use at Ford makes use of the following AI technologies: description logics, natural language processing and rule-based processing. The heart of our AI system is the knowledge base that utilizes a semantic network model to represent all of the automobile assembly planning information. The use of a semantic network as part of knowledge representation system is also known as "Description Logics". A Description Logic implementation known as CLASSIC has been successfully used at AT&T to develop telecommunication equipment configurators (McGuiness and Patel-Schneider 1998). The DLMS implementation of Description Logic is based on the KL-ONE knowledge representation language (Brachman & Schmolze 1985). There are over 10,000 concepts represented and each concept may have up to 45 properties or attributes depending on the context of the object being represented. This knowledge base contains information about the parts, tools, ergonomics triggers, work descriptions and all the other knowledge that is relevant to building a car at Ford. Description logics enable us to maintain and modify the knowledge base despite the dynamic changes that are present in the automobile industry. In an average year about 8% of our knowledge base is updated in order to keep current with changes in the manufacturing processes.

Natural language processing techniques are integrated with the knowledge base to represent the technical language of manufacturing process planning in the automobile industry. As discussed in the previous section, we need to be able to match part descriptions that are have multiple written representations, but represent one single part. This includes dealing with acronyms, synonyms, abbreviations, misspellings, misplaced punctuation and other problems inherent in natural language. The rule-based component of our application consists of modeling the knowledge about potential ergonomics concerns into rules and interact with the knowledge base.

We have found that the combination of using a controlled language, such as Standard Language, in conjunction with a description logics based knowledge structure has allowed us to maintain the knowledge base without requiring any wholesale rewriting of rules. This basic architecture has been proven to be an excellent choice for the long-term maintenance of knowledge bases that represent a very dynamic problem domain such as auto manufacturing (Rychtyckyj and Reynolds 2000).

Application Use and Payoff

The ergonomics analysis tool has been deployed at Ford for approximately two years. The impact of this system can be summarized as follows:

- The automation of the ergonomics “red” processing stopped over 1100 process sheets with potential ergonomics problems from reaching the assembly plants.
- The automation of the ergonomics “warning” processing reduced the workload of the ergonomics engineers by 20% due to the fact that they did not have to review as many potential concerns as before.
- The engineers that wrote the process sheets became aware of ergonomics concerns and started writing their process sheets to address these concerns before they were flagged by the system.
- Ergonomics is a vital concern to both Ford and the UAW. All of the process improvements that have been described in this paper, including the use of MODAPTS, Standard Language and ergonomics analysis have been supported by both management and the UAW.
- The use of ergonomics triggers for manufacturing assembly would not be limited to Ford Motor Company. Most manufacturing companies have their own systems for dealing with process build instructions and some utilize controlled languages for this task including Boeing (Wojcik, Halmback and Hoard 1998) and Caterpillar (Kamrath and Adolphson 1998).

The quantifiable benefits of the system include cost savings of over $17 million dollars in terms of avoiding injury costs associated with the “red” triggers as well as reducing the number of “warning” triggers that need to be manually inspected by 20%. However, the benefits of this application to Ford Motor Company are much more significant than those numbers. The avoidance of health and injury problems makes the workplace safer for our employees and improves the morale of our workforce. In addition, this system has convinced our ergonomics engineers that the application of AI can help make their job easier and improve their efficiency. The hardware and software was already in place and our main investment was the time spent by the developers and the ergonomics engineers. The benefits of this system, both quantifiable and indirect, were significantly higher than the development costs and this system has been a very successful industrial application of AI.

Application Development and Deployment

The artificial intelligence development for our applications here at Ford Manufacturing Engineering Systems is based on the Hewlett-Packard UNIX (HP-UX) platform utilizing the Lispworks and Knowledgeworks tool from Xanalys Corporation (Xanalys 1998). We have found that this tool provides a flexible and powerful development environment while providing access to our

Oracle database through an SQL interface. In addition, this tool provides the capability to create a Graphical User Interface (GUI) through the CLIM (Common Lisp Interface Manager) package and easy communication to other systems and platforms. The integration of Lispworks and Knowledgeworks with our existing Oracle databases has been very successful in terms of throughput and accuracy. Our AI system makes thousands of database transactions every day and this is all accomplished with an average response time of about 8 seconds for each AI process sheet validation.

The development of the ergonomics analysis system for process validation took about 2 months with a team of 2 developers as well as additional time provided by the ergonomics specialists. We added the additional functionality and rules needed to represent the ergonomic analysis through a combination of KnowledgeWorks rules, LISP code, concepts and their associated properties into our knowledge base. The Ergonomic "hard" constraints (e.g. lifting thresholds, verbs to check, etc) are all contained in our knowledge base and can easily be modified. The AI system reads the required information from an Oracle database, does the required processing and writes the results back into the Oracle database.

Maintenance of this system is made much simpler by the use of a knowledge base that uses a Description Logics framework. Any changes that need to be made to the knowledge base can be quickly made through a graphical Knowledge Base Manager (KBM) and then migrated to the production environment. We have also developed a suite of regression tests that are run and validated before any changes are moved to production. In addition, the knowledge base contains built-in edit checking functionality that validates the entries that are being added to specific slots and attributes for different classes of concepts.

Conclusions

In this paper we discussed two applications of ergonomics analysis that are being used at Ford. There is no question that ergonomics is a critical factor in manufacturing and needs to be addressed at the earliest point possible. Our ergonomics analysis tool has made it possible to analyze the assembly work before it reaches the assembly floor for potential ergonomics violations. This ergonomics analysis of process sheets identifies problem concerns in the area of frequency and repetitive issues, excessive tool torque and the lifting of heavy parts without some form of mechanized lift assists. In the future, we plan to increase the performance of the existing systems with additional part matching capabilities and expand the ergonomics analysis to catch other types of potential problems.

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