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ARTICLE

CCPE – the use of an analytical method to evaluate safety and ergonomics in maintenance of forest machinery

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ABSTRACT

Many of the hazards in forestry are due to the handling of large trees and large machinery in rough terrain and remote areas. Activities such as maintenance and repair work have been identified as especially hazardous in the highly mechanised cut-to-length method. Accidents are underreported, which emphasises the need for a systematic approach for accident prevention. A possible procedure is the use of an analytical evaluation method to identify presumptive hazardous situations and ergonomic issues before accidents can occur. Safety-critical sectors such as nuclear power and health care have invested many resources in these types of methods. The aim of this paper is to put one of those methods to test in a forestry context in a study evaluating maintenance of forest machinery. A framework for evaluation, Combined Cognitive and Physical Evaluation, known as CCPE, was selected and adapted for the study. The evaluation was successful in systematically predicting what could happen in hazardous situations with regard to use error and ergonomic issues.

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safety; evaluation; forestry; ergonomics; user-centred design; CCPE; analytical evaluation method; accident prevention

Introduction

Many hazards in forestry are due to the handling of large trees and large machines in rough and sometimes steep terrain and remote areas. Activities such as maintenance and repair work have been identified as especially hazardous in the highly mechanised cut-to-length system conducted in the relatively flat conditions of Finland and Sweden (Väyrynen 1984). In contrast to forestry work, where the driving and handling of logs are the major causes of hazards, the design of the forest machine itself causes the major hazards during maintenance work. These design 'errors' are complicated by the remote location of the work, i.e. in the woods where tools and assistance are limited.

Accidents in Swedish forestry are underreported (Pinzke & Lundqvist 2006; Lindroos & Burström 2010), which emphasises the need for a systematic approach to accident prevention. It could be argued that there already is such an approach as the Swedish Work Environment Authority (SWEA) requires that all companies carry out systematic work environment management. However, when SWEA investigated the systematic safety work of forest companies, most of the companies were criticised. The two main issues were a lack of systematic risk assessment and a failure to implement safety measures required by the authority (Hemmingsson et al. 2014). Moreover, 88–120 accidents have been reported annually in the official accident statistics in the last decade and the trend is not in decline (Swedish Forest Agency 2014; Swedish Work Environment Authority 2018). Therefore, it is clear that the requirement for systematic work environment management, on its own, is insufficient in ensuring that risks are identified and necessary safety measures are successfully implemented.

There are several approaches to improve work safety, e.g. reduce mechanical hazards or improve the safety culture. A further approach is to focus on how the design of machines and workplaces directly influences human behaviour, as inadequate design is a common source of human errors (Norman 2002). Well-designed workplaces and machines match the user's expectations of how they respond to input, are consistently designed so that behaviour always results in the same outcome, and are also designed in such a manner that desirable safe behaviours are promoted (Wickens & Hollands 1999). Although it might be possible to perform the actions correctly and safely, the machine can be designed to hide the possibility of safe actions, and may invite a risky behaviour, e.g. by making the risky behaviour perceived to be much faster and easier than the safe alternative. In these situations, the natural human behaviour is to use the less safe option. Ghaffariyan (2016) report that 72% of all accidents in forest harvesting (mostly mechanised) in Australia 2004–2014 were due to personal error such as failure to use personal protection equipment, errors of operation and poor body positions, which suggests that a change in human behaviour can have a large impact.

It is therefore important to investigate how the design of the machine is affecting the human behaviour in a negative way, i.e. how technology invites risky behaviours that can cause accidents. A further positive effect of highlighting the role of the machine in hazardous human behaviour is to reduce the likelihood of the appearance of a blame-culture, i.e. a culture where the causes of accidents are entirely attributed to human actions and behaviour (Dekker 2009). This might emerge if accident prevention work only focuses on internal factors (such as education and training).

To intentionally work with how the machine design affects human behaviour, there is a need for a methodology that systematically reviews the relationship between accidents, machine design and usage. The methods

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can be used in the different stages of the product development process and for finished products on the market. The results should also be in such a format that they can be used as input in a design process by machine manufacturers to improve the ergonomics and safety of future machine models as well as to inform and train operators. This paper presents such a framework for evaluation, Combined Cognitive and Physical Evaluation, known as CCPE (Bligård 2012) and its usage in safety work with forest machinery.

The CCPE framework

CCPE is a methodology for systematic review of shortcomings in machine design which is based on the assumption that the design of the equipment affects human behaviour and how actions are performed (Bligård 2012; Bligård & Osvalder 2014). It builds upon the traditional ergonomics and safety methods Cognitive Walkthrough (Lewis & Wharton 1997) and Predictive Human Error Analysis (Embrey 2004), previously widely used with medical devices. The CCPE methodology has been developed for safety-critical applications, primarily medical technology. The goal is to predict presumptive mismatches in human-machine interaction, such as physical and mental workload, use error, usability problems and ergonomic deficiency, by using a process that supports the evaluators' cognitive processes. The output of CCPE is then used as input to the overall risk management process. The identified mismatches also provide information useful to improve the design of the machine and thus mitigate future accidents.

CCPE has a task-based approach to investigate hazards and errors related to the interaction between operator and machine. It uses the term 'use errors' instead of 'human error' or 'user error', as the latter implies that the error lies with the human, whereas 'use error' recognises that the error is instead a symptom of failure in the interaction between the human user, and the machine, the work task or the environment. Central to the CCPE methodology is the use of a questionnaire process to guide the structured analysis of whether the user is hindered by the technology to carry out their tasks safely and ergonomically well. The CCPE methodology consists of four phases: (1) definition of evaluation, (2) human-machine system description, (3) work load analysis and (4) interaction analysis. The exact content of each phase may vary depending on the purpose of the evaluation. Thus, the CCPE methodology is very adaptable to all types of human-machine systems. The methodology can be performed by a single analyst or by a group of analysts, which can consist of designers, software developers, mechanical engineers, marketing staff, ergonomics and human factors experts, as well as users. Most important is that knowledge about the users and the use of the machine are present among those who perform the analysis. Often, the CCPE methodology requires observations and interviews with users before the analysis phases, so that current and accurate knowledge is available.

The following section will describe the four phases, with the last phase described in more detail as it involves the most novelty. The first three phases create the groundwork for the interaction analysis phase. For ease of illustration, a case study will be used to exemplify CCPE. The case study was part of the larger main study investigating hazards with maintenance and repair work of forest machines, and how the design influences operator behaviour. The example used is harvester saw chain replacement which is a task regularly performed by harvester operators when chains break or become blunt. The data for this the study were collected in April 2017 while interviewing seven forestry machine operators and two company representatives from large forestry companies, as well as observing nine operators during the maintenance of five harvesters (two forwarder operators supported in the maintenance). Two operators helped each other with the maintenance of all but one of the observed harvesters. The semi-structured interviews were made by both authors at the work site in the logger's cabins, and the participant observations of maintenance work were made in connection to the interviews. When hazardous tasks in relation to the machine were observed, the authors asked about this task for further information as the base for CCPE.

Definition of evaluation

The first phase in the CCPE methodology is to establish the framework for the analysis, which then serves as a basis for further analysis. The result of this phase is a description of the purpose of the evaluation, the machine and the usage to be evaluated as well as the intended user and the context in which the use occurs. The choice of machine, use and user made before the analysis begins is decisive for the quality of the subsequent analysis.

Case example: The purpose of the evaluation was to investigate hazards when changing a saw chain on a harvester (Fig. 1), and how the design influences operator behaviour. The user is the harvester operator, the machine a harvester and the use is maintenance work during normal harvesting operations. These boundaries were set in consultation with operators and stakeholders after reading accidents reports and statistics.

System description

The second phase in CCPE methodology is the system description, which illustrates how the human-machine system works. The system description is most important for the workload analysis and for the interaction analysis, because if the system description is deficient, incomplete or wrong, the resulting analysis will suffer. The main parts are describing the operator, the context and the task.

Case example: Relevant factors of the operators were: risk taking and risk behaviour; knowledge and experience of the task; body size and strength, mobility and vision. The factors were elicited from the interviews and observations with the operators. The context that affected performance and safety were the factors weather, light conditions, ground conditions, production targets and working culture. The correct handling sequences for changing the saw chain were described in detail and divided into separate operations. The appearance of the machine during the task and the way the operator interacts with the machine were also described.

Figure 1. A typical position of the saw when changing the saw chain on a harvester head

Workload analysis

The third phase is the workload analysis. The purpose is to map automation levels, task demands, and mental and physical workload, which may affect the interaction between human and machine. The amount of mapping needed is determined by the focus of the subsequent interaction analysis. For example, if the focus of the subsequent analysis is based on cognitive interaction, then the mental workload is described in more detail than the physical workload.

Case example: For the task of changing a harvester saw chain, task demands, mental workload and physical workload were mapped out. The main aspects found to affect performance were time pressure, physical load on neck and back, and snow depth.

Interaction analysis

The fourth and final phase in CCPE methodology is interaction analysis, where the interplay between human and machine is evaluated for potential hazardous action. The interaction analysis is based on the correct handling sequences that were documented in the system description. For every action in the handling sequence, questions are asked to identify possible mismatches between human and machine. The question process tries to simulate how the user interacts with the machine, with the analysts in the evaluation team playing the role of the user. The questions in the interaction analysis are adapted to the purpose of the evaluation. The answers to the questions are then compiled and form the basis for identifying hazards and creating suggestions for improvement.

Case example: For the interaction analysis, the questions in the template (Tables 1–3) were used. Questions 1–4 focused on performing the operations correctly and Questions 5–8 focused on human errors. Tables 1, 2 and 3 show three examples of operator actions from the case example: machine egress, placing the harvester head in position for maintenance, and removal and replacement of the sawbar and saw chain. The template used was specially developed for this evaluation and is a variant of the standard CCPE template for interaction analysis.

Discussion

Analysis: change of saw chain

The evaluation with CCPE showed that saw chain replacement could be a hazardous task. Saw chain replacement is done either with the harvester head standing on the ground, or with it hanging from the crane. There is always a possibility for the operator to get cut on the saw chain, although this caused only minor harm when it occurred. Replacement of the saw chain with the unit on the ground means that the driver must be in an ergonomically bad, forward-leaning position. Some harvester heads can also tip forward and harm the operator. Knowledge and experience of how the harvester head is to be placed securely on the ground, and how to lock the harvester head is important for working safely. Due to the poor ergonomical position that the operators need to work in, the saw chain change often occurs with the harvester head hanging from the crane instead, especially when the ground is wet or snowy so that the driver risks getting dirty, wet and cold. Because the crane is hydraulic, the crane arm slowly sinks during the saw chain exchange, which results in the operator being wedged underneath the harvester head if the task takes too long. For various reasons, such as the prospect of getting wet or dirty from snow and soft soils, drivers often stand on the wheels or band during the task, with the risk that the operator may fall from the machine. A sinking crane altering the harvester head position will consequently alter the operators' position and increase the risk of falling.

Application of CCPE to forest machinery

The goal for the main study was to evaluate how well CCPE worked in a forest machine context. The CCPE assessment resulted in the identification of hazards in repair and

Table 1. Combined cognitive and physical evaluation interaction analysis for operation machine egress

Operation: Machine egress	Y/N	Why?	
1. Can the action be performed in a safe and ergonomically good way?	Yes	Most often, not always. Sometimes the machine is turned so you have to jump down on a band. The machine may be tilted so it is located close to the ground	
2. Does the machine give any information (cues) about how the action can be performed in a safe and ergonomically good way?	Yes	There are stairs, platforms and handles	
3. Does the user know how the action can be performed in a safe and ergonomically good way?	Yes	General knowledge	
4. Will the user try to perform the action in a safe and ergonomically good way?	Maybe	Some were cautious and some were careless	
5. Error	**6. Cause**	**7. Consequence**	**8. Prevention**
How can the action be performed in an unsafe or non-ergonomic way?	Which are the possible causes of the ergonomic error?	Which are the consequences for the user?	Is the machine designed to prevent the ergonomic error?
Jump instead of climbing	Faster way, too close to the ground or the bands. It is faster	Slip trip or fall	No
Climbing forwards on the ladder while not reaching the handle	Faster, don't think it is needed	Slip trip or fall	No hindrance exists to prevent this action
Not holding the handle	Faster, more complicated with platform	Slip trip or fall	Yes, handles exist but not always easily accessible
Not using existing platforms		Slip trip or fall	Yes, platforms exist but are in some cases are not well-placed

Table 2. Combined cognitive and physical evaluation interaction analysis for operation placing the harvester head in a position for maintenance

Operation: Position of the harvester head	Y/N	Why?	
1. Can the action be performed in a safe and ergonomically good way?	Maybe	If the harvester head is placed on the ground in a position where the risk of tilting is minimised. Locks are used to secure the harvester head	
2. Does the machine give any information (cues) about how the action can be performed in a safe and ergonomically good way?	Maybe	Nothing implies that it is safer to replace the saw chain with the harvester head on the ground or how to place the harvester head on the ground	
3. Does the user know how the action can be performed in a safe and ergonomically good way?	Yes	The majority of operators know that it is safer to place the harvester head on the ground	
4. Will the user try to perform the action in a safe and ergonomically good way?	Maybe	Some will work with caution and some carelessly	
5. Error	**6. Cause**	**7. Consequence**	**8. Prevention**
How can the action be performed in an unsafe or non-ergonomic way?	Which are the possible causes of the ergonomic error?	Which are the consequences for the user?	Is the machine designed to prevent the ergonomic error?
Stand on the band or steps while doing the change	Faster, avoiding the snow, feels smoother, more upright working position, easier access to tools	Slip trip or fall	No
Crawl under the harvester head	Better access and reach, faster	Can get stuck and clamped	No
Use a bad working position	Better access, harvester head in wrong position	Musculoskeletal damage if repeated	No

maintenance of machinery; identification of hazardous situations; and the elicitation of proposals for improvement, aimed at machine owners and manufacturers. The improvement proposals were divided into proposals for machine owners/machine operators, proposals for purchasing companies and proposals for manufacturers.

Many of the hazardous situations identified with CCPE were explained by the fact that operators were not physically enabled to perform their duties in a safer manner, i.e. the machine is not designed to fit human anthropometry. Measures taken by machine owners and the professional knowledge of operators can increase safety a great deal, but it is the machine manufacturers that have the best opportunities to permanently increase safety by redesigning the machines. From a safety point of view, it is more important to eliminate hazards before they occur, rather than to introduce additional protection mechanisms to protect the operators against existing hazards.

CCPE's main contribution is the structure of the analysis. None of the identified situations were totally unknown, but the use of the methodology clarified the circumstances under which they occur. This structured way of working is especially important to counter the biases of the analysts, i.e. preventing them from taking shortcuts when a field seems familiar enough, resulting in only the most obvious actions being documented. When all knowledge is documented,

Table 3. Combined cognitive and physical evaluation interaction analysis for operation remove and replace sawbar and saw chain

Operation: Remove and replace sawbar and saw chain	Y/N	Why?	
1. Can the action be performed in a safe and ergonomically good way?	Yes	It can be performed in a safe and ergonomic good position	
2. Does the machine give any information (cues) about how the action can be performed in a safe and ergonomically good way?	No	No information in the machine or at harvester head	
3. Does the user know how the action can be performed in a safe and ergonomically good way?	Yes	Almost all operators know which hazards to avoid	
4. Will the user try to perform the action in a safe and ergonomically good way?	Yes	They use a standard way of working	
5. Error	**6. Cause**	**7. Consequence**	**8. Prevention**
How can the action be performed in an unsafe or non-ergonomic way?	Which are the possible causes of the ergonomic error?	Which are the consequences for the user?	Is the machine designed to prevent the ergonomic error?
Not using protection gloves	Faster and easier, forget the gloves	Can be cut by sharp parts (links and knives)	No

there is a solid foundation to prioritise and create countermeasures.

CCPE was originally developed to evaluate usability, ergonomics and safety in the operation of medical devices (Bligård 2007; Bligård & Osvalder 2007). It has also been used to evaluate non-safety-critical products like office chairs and vacuum cleaners (Bligård & Osvalder 2017). The major difference between the previous evaluations and this study is that in the former the focus was on evaluating purpose-built user interfaces, i.e. the part of the machinery purposely designed to interact with the human user, rather than maintenance work. Furthermore, there was often a detailed set of instructions from the manufacturer on how to best interact with the equipment, which was used in the analyses. However, even without explicit operating instructions for the repair and maintenance of forest machines, it was shown that CCPE provided insights into why events may occur, as the analysis requires the use to be viewed from different perspectives. This is useful input for an overall risk management process that combines hazards identified from several sources.

CCPE in forest machine risk management

In many industries, technology plays an important role for the outcome and it is therefore important to develop machines with high ease-of-use in order for the operation to be simple, safe and efficient. The CCPE methodology has several components that make it useful in this type of evaluation. The first strength of the CCPE methodology is that it can detect mismatches in the interaction between humans and machines without requiring empirical tests with users. The second strength is that CCPE can also identify events that do not usually occur but can have serious consequences (not limited to analysis of past accidents). The third strength is the integrated analysis of both physical and cognitive aspects, and physical and cognitive ergonomics. CCPE analysis thus becomes coherent and demonstrates a holistic perspective because it spotlights many aspects that work together during human-machine interactions, often influencing each other. These properties make the CCPE methodology useful for industries with limited resources for risk analysis and with relatively few reported incidents and accidents.

Based on the results, it can be concluded that the methodology worked well by providing a good structure for the analysis of machine design and usage. However, CCPE is not designed to be the only method used in identification of hazards in the workplace, as it has a narrow focus on human-machine interaction. The CCPE methodology has an analytical, task-based, low-level (granular) perspective in evaluation, and aims to obtain a more comprehensive approach for ergonomics and safety. Supplementary methods that are task-independent provide a high-level perspective and are therefore needed for a complete risk management process. These methods should also involve users if possible. The higher-level methods also need to include an organisational perspective on safety, as that scope is not covered by CCPE. Some examples of higher-level methods previously applied in forestry are provided by Safetree (2017), that presented three practical procedures for forestry safety work: (1) a 'bow tie' risk assessment method, (2) a conventional risk management process (with a dual risk assessment) and (3) a conventional risk management process using an assessment matrix (with a single assessment). In each of these procedures, CCPE can be useful as a supporting tool to enhance the risk assessment and management related to interactions between operators and machines. Furthermore, CCPE can also be used as input for evaluating occupational health and safety performance, for example, in the tool for small and medium-sized enterprises developed by Tremblay and Badri (2018).

Similar task-based approaches to CCPE have been used earlier in safety work in the forest industry. Bentley et al. (2005) used the 'Task and Job safety analyses', which based on operations in the work task investigates three issues: (1) physical hazards, (2) possible errors and violations and (3) possible consequences. However, this method does not directly consider how the design of the machine affects human behaviour.

Another useful approach for improving the design of forest machines is by using ergonomic and safety guidelines (Almqvist et al. 2006; Gellerstedt 2006). Nevertheless, these types of general guidelines do not apply to all machines and have to be revised to meet new standards when new innovations enter the market. One example when guidelines for the design of forestry machines provide inappropriate advice (based on rigid assumptions of how forest machines are built) is that the guidelines demand that there has to be a step or a platform, regardless of machine size. Such a platform may be required in large machines, but the type of work enabled by smaller machines can be conducted from the ground, essentially eliminating the need for a platform. These differences are captured by the CCPE methodology and CCPE can thus be used in conjunction with the ergonomic guidelines to help adjust for the shortcomings of a fixed reference point and faulty assumptions about the design.

Conclusions

The CCPE methodology worked well and generated an overview of hazards with maintenance and repair work of forest machinery by giving a good structure to the investigation. The main issue was that operators could not physically perform their duties in a safer manner, i.e. the machine is not designed to fit human anthropometry. The results from CCPE can be used to find countermeasures and to write instructions for safer use. CPPE has consequently shown that it can be used as input to risk management work in forest industry, and complements existing methods as it covers human behaviour from both a physical and a cognitive perspective.

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