2017

Applying Analytic Hierarchy Process (AHP) to Choose a Human Factors Technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry

Alberto Petruni
University of Kragujevac, Serbia

Evanthia Giagloglou
University of Kragujevac, Serbia

Ewan Douglas
Trinity College Dublin

See next page for additional authors

Recommended Citation

Petruni, A., Giagloglou, E. & Douglas, E. (2017). Applying Analytic Hierarchy Process (AHP) to Choose a Human Factors Technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. *Safety Science*, May 2017. doi:10.1016/j.ssci.2017.05.007

Authors

Alberto Petruni, Evanthia Giagloglou, Ewan Douglas, Jie Geng, Maria Chiara Leva, and Micaela Demichela

ARTICLE IN PRESS

Safety Science xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry

Alberto Petruni [a], Evanthia Giagloglou [a,*], Ewan Douglas [b], Jie Geng [c,e], Maria Chiara Leva [d], Micaela Demichela [c]

[a] *University of Kragujevac, Department of Production Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia*
[b] *University Trinity College of Dublin, Department of Psychology, Centre for Innovative Human System, Dublin 2, Eire, Ireland*
[c] *Politecnico di Torino, SAfeR, Dipartimento di Scienza Applicata e Tecnologia, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy*
[d] *Institute of Technology, School of Environmental Health, Cathal Brugha Street, Dublin 1, Ireland*
[e] *ARIA s.r.l., Corso Mediterraneo 140, 10129 Torino, Italy*

ARTICLE INFO

Article history:
Received 3 February 2017
Received in revised form 21 April 2017
Accepted 18 May 2017
Available online xxxx

Keywords:
Analytic Hierarchy Process (AHP)
Human Reliability Analysis (HRA)
Automotive manufacturing industry

ABSTRACT

The Automotive industry has been developed into a complex and highly automated sector. This level of automation and complexity has led to the establishment of a work environment, where human machine interface and human reliability are now critical factors of performance especially for safety critical tasks. Many different methodologies for performing risk assessment considering human factors are already available in the literature, but they were often developed for other domains (aviation, nuclear and process industry). Their purpose is to support the root cause evaluation and estimate the probability of faulty human actions. The present paper introduces a method to support the evaluation and the choice of a suitable Human Reliability Analysis (HRA) technique for the automotive sector considering the ones proposed from other industrial domains. The Analytic Hierarchy Process (AHP) provides a way of assisting safety managers and risk assessors in the HRA technique selection process. This allows the selected HRA techniques to be evaluated based on relevant criteria for an application in an automotive manufacturing environment. An example of selected HRA techniques in this paper will be demonstrated in a case study. The example can also suggest implications to improve existing industry guidelines, international standards and regulations, which are frequently calling for a wide range of ergonomic factors to be considered in the risk assessment process. Further the case study should show potential benefits to organizations coming from the selection and application of the right HRA technique.

1. Introduction

Since the introduction of mass production in the beginning of the twentieth century, the automotive industry has always been a leader in innovation (Ford, 1926). In recent years, the automotive manufacturing industry has been recognised as one of the most dangerous industries with respect to the workers' health and safety (Bureau of Labor Statistics (U.S. Department of Labor), 2011). Like many other technological systems found everywhere in modern society, the automotive industry is becoming more and more complex mainly due to the various phases of final automotive manufacturing product that require different systems and processes (Mirer, 1998). This creates crucial issues to health and safety management because several high risks must be considered at the industrial working place. The risks can be encountered outside the manufacturing and accident avoidance practices within the organization. The Organisational systems of multinational automotive industries have changed considerably and, as a result, complexity of products, workplaces and job operations increased (Michalos et al., 2010). Particularly, in the automotive manufacturing there are technological machines with high level of automation and human-machine interfaces (Hassam and Mahamad, 2012), Rezazadegan et al. (2015) discussed the impact on the risk assessment. Kvarnstrom (1997) also observed that the implementation of high technological assembly lines resulted in more complicated

---

* Corresponding author.
E-mail addresses: a.petruni@hotmail.com (A. Petruni), egiaglo@gmail.com (E. Giagloglou), douglase@tcd.ie (E. Douglas), xiaojie0411@163.com (J. Geng), chiara.leva@dit.ie (M.C. Leva), micaela.demichela@polito.it (M. Demichela).

http://dx.doi.org/10.1016/j.ssci.2017.05.007
0925-7535/

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

manual operations. Edimansyah et al. (2008) and Oleske et al. (2004) evidenced that an automotive assembly line is a workplace environment with physical problems, such as noise, vibrations and dangerous equipment. Moreover, the presence of repetitive task has always been one of the most relevant safety issues in automotive industry (Graves, 1992; Spallek et al., 2010). Ulin and Keyserling (2004) noticed that auto industry had a high incidence of musculoskeletal disorders. Consequently, human machine interface and human reliability are critical factors of product quality, company performances and employers' safety. Risk assessment is the main tool to identify, analyse, evaluate and control all kind of risks. It is generally performed by safety specialists, workplace managers and/or supervisors. The targeted risks are indicated in the specific national laws and standards (Rasmussen, 1997). With the introduction of WCM (World Class Manufacturing) management systems there has been a push toward the participative approach, with the direct involvement of field operators in the risk assessment and control procedures (Gnoni et al., 2013). The influence of human factors in safety issues, at different levels of different types of organizations, included vehicle manufacturing (Hale et al., 2010), has been more increasingly considered. One of human factors related type of risk is that posed by human error, which becomes a more dominant issue as systems increase in complexity. Hence, accidents and occupational diseases in an automotive plant were correlated to the inadequate human factors conditions (Punnett et al., 2004).

Several types of methodologies are used for identifying and evaluating human error and among them Human Reliability Analysis (HRA) techniques. HRA aims to identify and quantify human error (Kirwan, 1994). These methods can help safety specialists to identify and analyse human errors also in the automotive manufacturing industry. Even a simple interactive system requires an examination of the links between every possible cause and every possible consequence, considering a probabilistic analysis (Hollnagel, 1998). According to Evans (1976) human reliability is the probability that a person correctly performs some system-required activities in a required time, and performs no extraneous activity that can degrade the system. Hollnagel (1998) categorised HRA techniques into two categories: task-dominant approaches and cognition-dominant approaches. Task-dominant approaches are primarily focused on possible deviations in the tasks executed by humans; while cognition-dominant approaches are primarily focused on human cognition processes as the cause of human failure. Some of these techniques include classification schemes based on taxonomy to analyse human action impact on system failure.

HRA techniques may be applied in the automotive sector to identify and help manage critical activities where human error may pose a significant risk. However, there are a wide variety of HRA techniques available, and it is not obvious which technique may be the most beneficial in this context. The suitability of any HRA methodology depends on the context that is being assessed (French et al., 2011). The primary aim of this study is therefore to determine how to select the proper HRA method required by applications in the automotive sector from the large number of HRA techniques available. Human and Organizational Factors (HOF) practitioners and researchers have previously reviewed different HRA methods for comparisons (Bell and Holroyd, 2009; Forester et al., 2006; Kirwan, 1997, 1998; Madonna et al., 2009), but up to now it seems that no method is, in an absolute way, better than the other, and most of the times, the HRA selection is case specific, e.g. Leva et al. (2006).

The human factors discipline attempts to improve worker conditions and optimise overall system performance (International Ergonomic Association (IEA), 2000). Generally, application of Human Factors techniques in industrial sectors means combining and solving problems related to several disciplines, in search of answers that satisfy the improvement of Occupational Safety and/or System Performance. The interdisciplinary sector of Human Factors sometimes implies that different professionals should be involved in the selection procedure and this makes the choice even more difficult and sometimes excessively time-consuming. However, decisional support tools have been developed for such difficult decisions, which involve many stakeholders and many factors. One of the most representative methods of Multicriteria Decision Aid (MCDA) is the Analytic Hierarchy Process (AHP).

AHP is a method of MCDA developed by Thomas Lorie Saaty in the late 70s (Saaty, 1977, 1980). To date, there are many AHP applications to problems of assessment in various industries and several studies are dedicated on AHP application to occupational safety problems (Caputo et al., 2013; Podgórski, 2015; Zheng et al., 2012). AHP is used to determine the relative importance of a strategy set, which may be made up by different elements as actions, alternatives, criteria, securities. Its greatest characterization is that it structures any problem in a hierarchical way, even if it is complex, multi-person, multi-period or multi-criteria. The AHP can be used to determine the benefit/cost of a project, when this cannot be evaluated exclusively in terms of monetary benefits (Saaty, 1980, 1990; Saaty and Kearns, 1985). Among the most important steps of the AHP decisional analysis and basis of the procedure is the criteria selection.

In this paper, four alternatives HRA techniques have been considered as suitable for the automotive domain and have been compared using AHP decisional analysis on a case study, with the integration of identified requirements (as multi-criteria) from the real automotive manufacturing industry. The selected HRA techniques in this paper are among the most representative ones in the literature. The selected task-dominant approach is the Technique for Human Error Rate Prediction (THERP) (Swain and Guttmann, 1983). This methodology can obtain the human error probability (HEP) in a quantitative way. In addition, we also considered The Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H) (Gertman et al., 2005) as an alternative task-dominant approach, based on a human information processing model of human performance. While the Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998), was chosen as a method representative of the cognition-dominant approaches, which considers interactions between person-related, technology-related, and organization-related factors. Additionally, Human-HAZOP was considered as a qualitative approach, that uses a structured brainstorming technique (with 4–6 people) of experienced personnel to identify human factors and human/error issues affecting the design or operational intent of a system (Whalley, 1988).

2. Review of THERP, CREAM, SPAR-H & human HAZOP

2.1. Technique for human error rate prediction (THERP)

The Technique for Human Error Rate Prediction (THERP) is a methodology for the quantitative assessment for human reliability (or human error) within a control system (Swain and Guttmann, 1983). THERP was originally developed within the nuclear industry in the United States in response to the Three Mile Island incident whereby a poorly designed user interface was a contributory factor in a nuclear meltdown incident (United States. President's Commission on the Accident at Three Mile Island, 1979). Because of its origin, THERP has been used as a popular methodology of assessing human performance and has been cited as currently the most widely implemented technique (Kirwan, 1996).

THERP implements an underlying framework of event trees as the basis of the technique, event trees are commonly implemented

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

in reliability analysis where the probability of the steps that can lead to an undesirable outcome are assessed to develop a numerical probability of failure (Stanton et al., 2013). THERP uses event trees to arrive at a similar figure for a human failure. The event tree contains several human actions each with a possibility of failure or success. Using standard event tree logic, the probability of human failure can be calculated. The key resource to THERP analysis can be found within the THERP manual composed by Swain and Guttmann (1983). The manual contains a range of experimentally calculated HEPs for individual actions ranging from operating valves and switches, to interpreting data from a VDU or an analogue dial. THERP categories Human Error into the following categories:

1) Errors of Omission – Leaving out a step in a task, or leaving out a whole task.
2) Errors of Commission – This is an activity that is carried out, however an error occurred during carrying out this activity there are several different types:
    2.1) Errors of Selection – An error in the Use of controls, or an error in the use of commands.
    2.2) Errors of Sequence – A Required action is carried out in the wrong order.
    2.3) Errors of Timing – task is executed before or after when required.
    2.4) Errors of Quantity – inadequate amount or in excess (too little or too much).

THERP only deals the individual errors, however the approach provides results that have a high level of face validity (Kirwan, 1996). The THERP manual provides many different HEPs pertaining to the usage of different equipment that can be encountered within a nuclear power plant (however a large number are generic and can be found across a variety of different organization) and the possible errors that can emerge during a procedure (e.g. omission error etc.). THERP assumes that operators always take the same basic optimal route through a procedure which may not always occur. THERP is a representative of task-dominant HRA methods (Stanton et al., 2013) and the approach is overly simplistic when compared to Bayesian and modern approaches such as HEART, and JHEDI.

2.2. Simplified plant analysis risk human reliability assessment (SPAR-H)

The Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H) is a quantification method developed as a simple-to-use tool for estimating Human Error Probability (HEP) in nuclear power plants (Gertman et al., 2005). SPAR-H has been applied to approximately 70 U.S. nuclear power plants (Groth and Swiler, 2012) and other research has observed that the underlying principles and HEP data are applicable to other sectors (Bell and Holroyd, 2009; Rivera and Mc Leod, 2012). SPAR-H is easily applied, with a necessary revision, to nominal and emergency situations of aerospace designs (Stamatelatos et al., 2011) and applied in the petroleum context (Øie et al., 2014). The full manual *NUREG/CR- 6883* (Gertman et al., 2005) is available via the U.S. Nuclear Regulatory Commission website. The U.S. Nuclear Regulatory Commission has also released other guidance documents for the performing of the SPAR-H, such as the *SPAR-H Step-by-step Guidance* (Whaley et al., 2011) and the *Simplified Expert Elicitation Guideline for Risk Assessment of Operating Event* (Boring et al., 2005).

SPAR-H is founded on an information-processing model of human performance. The model of SPAR-H is also based on cognitive and behavioural sciences and Human Reliability Analysis (HRA) models. The general procedures of the HEP of a specifically described set of tasks are estimated through the calculation of (1) a nominal error rate, (2) a set of factors that affect performance, (3) the Performance Shaping Factors (PSF), and 4) the error dependency between the tasks. The qualitative description sections of a HRA are dedicated to the data collection; the task identification and the task analysis are not present in the method.

The flow diagram for completing the SPAR-H analysis is described by Whaley et al. (2011): (1) The first step of the method consists of the determination of the plant operation state as "at-power" or "low power/shutdown". (2) Then the previously selected tasks are classified in two system activity types, which are either action task (related to errors of commission - active errors) or diagnosis task (related to errors of omission—latent errors). (3) Different worksheets are employed for quantifying action and diagnosis task related errors. In the worksheets, pre-defined nominal HEP values and PSF weights are combined with action and diagnosis errors. Under normal operating conditions, the nominal probabilities of action errors are one order of magnitude less than the ones of diagnosis errors. The eight PSFs are defined as:

Time Available,	Procedures,
Stress,	Ergonomics,
Complexity,	Fitness-for-Duty,
Experience and Training,	Work Process.

Finally, the overall probability of error is computed by adding together the probabilities of diagnosis and action. As a last step, the dependency is addressed, which is described as the negative influence of a human error on subsequent errors as influenced by crew numbers, time, location and cues.

As advantages, SPAR-H was designed to be a quite fast tool. The worksheets and the checklist approach are standard and easy-to-use. It is not necessary that all users are expert in human performance. The model is also flexible and useful in situations where a highly realistic and detailed analysis is not required. However, as disadvantages, there is not any specific indication about the Human Error Identification in SPAR-H. The users have to understand the operation accurately. Additional guidelines were necessary in order to apply the method in a systematic and consistent way (Laumann and Rasmussen, 2014; Whaley et al., 2012). Another problem observed in SPAR-H was that the reliability assessment results were too optimistic. It was connected to the uncertainty in the evaluation of computer-based tasks (Gould et al., 2012; Hickling and Bowie, 2013; Liu and Li, 2014).

2.3. Cognitive Reliability and error analysis method (CREAM)

Cognitive Reliability and Error Analysis Method (CREAM) is the representative of cognition-dominant HRA methods, which covers technical, human and organizational factors, and provides a relatively stable HEP output (Chandler et al., 2006). The framework is described as a Method-Classification-Model (MCM). CREAM has not been developed from the underlying model of cognition, but simply uses it as a convenient way to organize some of the categories that describe possible causes and effects in human actions.

CREAM provides two methods that can be used to calculate Human Error Probability (HEP): the basic method and the extended method. Nine Common Performance Conditions (CPCs) was defined as Performance Shaping Factors (PSFs):

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

CPC 1-Adequacy of Organization;
CPC 2-Working Conditions;
CPC 3- Adequacy of MMI and Operational Support;
CPC 4- Availability of Procedures/Plans;
CPC 5- Number of Simultaneous Goals;
CPC 6- Available Time
CPC 7- Time of Day (Circadian Rhythm);
CPC 8- Adequacy of Training and Experience;
CPC9- Crew Collaboration Quality

The basic method uses task analysis to identify human actions, and assesses Common Performance Conditions (CPCs) by judging the expected effects and making a combined score of them with the triplet $[\Sigma_{\text{reduced}}, \Sigma_{\text{not significant}}, \Sigma_{\text{improved}}]$. Final results are interpreted through a control mode matrix defined by the Contextual Control Mode – COCOM. The four COCOM control modes are: (1) Strategic Control, the person considers the global context, thus using a wider time horizon and looking ahead at higher level goals. (2) Tactical Control, performance is based on planning, hence more or less follows a known procedure or rule. (3) Opportunistic Control, the next action is determined by the salient features of the current context rather than on more stable intentions or goals and (4) Scrambled Control, the choice of next action is in practice unpredictable or haphazard.

The extended method aims to produce specific action failure probabilities. The actions may either be those that have been defined by the PSA event tree, or actions that have been noticed during the screening process using the basic method. The extended performance prediction uses a cognitive task analysis to identify the cognitive activities required by the operator. The extended method consists of three steps: (1) Build or develop a profile of the cognitive demands of the task, which can be achieved by using the simplified set of cognitive functions that are part of COCOM. (2) Identify the likely cognitive function failures, which can be achieved by combining the cognitive demands profile with possible error modes. (3) Determine the specific action failure probability, which can be achieved by using a table of nominal probabilities based on the commonly used reference works. With the described calculation of specific adjustment values or weights, finally, the cognitive failure probabilities (CFPs) is obtained (Hollnagel, 1993, 1998).

In the practice point of view during the recent research works, CREAM can be applied in various industries and provides a two-level method to calculate Human Error Probability (HEP): the basic method and the extended method.

The basic method enables safety managers making a fast decision with a macro consideration of HEP. The extended method deals with the specific action failure probability. Thus, safety managers can decide the level of methods for HEP estimation depending on the time limitation or critical tasks' demands. As another advantage, CREAM also provides a good classification for the causes analysis of human errors (Geng et al., 2015). However, CREAM still needs detailed knowledge on human cognition, which requires analysts to understand or be trained to apply CREAM.

2.4. Human HAZOP

HAZOP (Hazard and Operability Analysis) is one of the most widely used techniques for safety and risk assessment procedures. The first basis of this methodology was given at 1963 by the ICI chemical company (Kletz, 2009) and the first guide with the name HAZOP 'A Guide to Hazard and Operability Studies' was published later, in 1977, by ICI and the Chemical Industries Association (Imperial chemical, 1977). Initially, it was developed for analysing chemical process systems but now it has been extended to other types of systems and operations. The HAZOP technique belongs to functional analysis methods and it is a qualitative approach. Its main characteristics are that it is based on guidewords that are applied to parameters and it is carried out by a multidisciplinary team. HAZOP strategy can be human orientated and in this case, we have an investigation for human deviations technique called Human-HAZOP.

Human-HAZOP is an application of the approach focusing on human factors and human/error issues (Whalley, 1988). It can deal with all forms of deviation from the design intent to planned procedures and human actions. Generally, HAZOP is a hazard identification technique, which considers system parts individually and methodically examines the effects of deviations on each part. The human HAZOP keeps the main structure of the method, it keeps guide words but modifies these and applies them to single task procedures and not to process parameters (Shorrock et al., 2003). Basic Guidewords are:

No action
More action
Less action
Wrong action
Part of action
Extra action
Other action
More time
Less time
Out of sequence
More information
Less information
No information
Wrong information

Human-HAZOP studies identify the potential for human failures during safety critical operating or maintenance activities and make recommendations to optimise the factors influencing human performance. The key stages in the Human-HAZOP methodology include: activity with risk of major accident, list key steps in activity, identify credible human failures at each step, assess potential for recover, assess consequences and risk control measures, and optimise performance influencing factors for task. The human HAZOP has to be repeated many times but generally the procedure follows the framework of the process of HAZOP study (Shorrock et al., 2003). Its main advantage is the team work which implies focusing on the method by various experts. There are limitations of the method, such as the difficulty to quantify and predict the human failures, the fact that it does not consider psychological, mental factors and generally does not investigate thoroughly on human and organizational factors, but only the task deviation.

3. Analaytic hierarchy process (AHP)-based method for Human Reliability Analysis (HRA) technique selection

3.1. Experts chosen and experts' judgment

In the present study, the criteria and their weighting were selected by experts with significant experience in automotive domain, safety and Human Factor (HF) knowledge. The experts (Table 1) were divided in two groups:

1) The Group 1 consists of five safety specialists who worked in the automotive industry, when the case study was carried on. Experts in Group 1 aim to provide the HRA selection criteria scheme according to the real application in the automotive industry.
2) The Group 2 consists of four researchers in the HF domain. Experts in Group 2 aim to conduct the AHP expert judgment based on the HRA selection criteria and their HF knowledge.

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

Table 1
Experts chosen and their professional background.

	Experts chosen	Job title	Education background	Knowledge/experience in the safety domain	Knowledge/experience on the human factor (HF) domain
Group 1: criteria selection	Expert A	Safety specialist	Engineer master degree	5.6-years working experience in Occupational Safety	Training knowledge on HF
	Expert B	Safety specialist	Engineer master degree	0.6-years working experience in Occupational Safety	Training knowledge on HF
	Expert C	Safety specialist	Scientific master degree	2.6-year working experience in Occupational Safety	2.6-year PhD candidate in the Ergonomic domain
	Expert D	Safety specialist	Scientific master degree	2-yearsworking experience in Occupational Safety	HF expert
	Expert E	Safety manager	Scientific master degree	8.6-year working experience in Occupational Safety	HF Expert
Group 2: HRA Selection	Expert C	Human factor researcher	PhD Candidate in the Ergonomic domain	2.6-year working experience in Occupational Safety in automotive manufacturing area	2.6-year PhD candidate in the Ergonomic domain
	Expert F	Human factor researcher	PhD Candidate in the Safety domain	2.6-years working experience in the Risk Assessment Domain	2.6-year PhD candidate in the HF integration into the risk assessment domain
	Expert G	Human factor researcher	PhD Candidate in the Ergonomic domain	Training knowledge on Safety	2.6-year PhD candidate in the Ergonomic domain
	Expert H	Human factor researcher	PhD Candidate in the Ergonomic domain	Training knowledge on Safety and 0.6-year working experience in Industrial Safety	2.6-year PhD candidate in the Ergonomic domain and HF majored Master degree

Note that, although Sub-criteria were given by pairwise comparison, the Criteria ranking was given by the expert judgment with consideration of the objectives of the automotive manufacturing industry (Economic 0.15, Usability 0.25, Utility 0.30, Suitability 0.30).

3.2. Identification of overall Goal, Criteria, and alternatives

The overall goal for the AHP-based HRA technique selection is to support the selection of the most suitable HRA technique designated for the automotive manufacturing industry. The HRA techniques preliminarily selected in the review section are considered as alternatives for our Hierarchy. Apart from these HRA techniques, scenario 0 is added. The option of scenario 0 means no HRA documented technique will be applied.

To define the criteria of the HRA technique selection, the requirements were taken from a real automotive manufacturing industry via interview of safety managers, safety specialists, and on-site observations. Since it is difficult to get all people together for a brainstorming session or other free-flowing discussions in a group, semi-structured interviews were conducted which allows more freedom for a conversation. The procedures include:

1) The objectives of the interviews: exploring the HRA selection criteria especially for Automotive Manufactory Industry.
2) A list of interviewees selected from relevant stakeholders: all safety specialists in the automotive manufactory industry were chosen.
3) The major questions include:
    3.1) What types of hazards are considered in your risk assessments?
    3.2) Do you feel there is a need of improvement when human factors are included in risk assessments?
    3.3) Have you heard of Human Reliability Analysis techniques?
    3.4) What criteria do you concern when you want to select a Human Reliability Analysis technique? Why important? What aspects (or sub-criteria) do you concern for this criterion?

After summarizing answers from interviewed safety specialists, the following issues are the most concerning (for selecting HRA):

1) _Background consideration:_ Usually, users of HRA techniques are Environment Health and Safety (EHS) groups including safety specialists, ergonomics specialists, and environmental analysts. EHS Team Managers should generally have high level education (e.g. Master Degree).
2) _HRA technique demand:_ The preferred HRA techniques should be able to guide EHS group to conduct the human reliability analysis (procedures, good application historical records, etc.).
3) _Time and financial limitation:_ There is not an optimum method, but a manager will choose the one that will give efficient results within acceptable time and financial consideration. Inside a single industrial plant, different HRA techniques or methods may be applied to different areas.
4) _Complexity of the HRA application:_ The complexity of HRA techniques may increase the difficulty of use, e.g. even high-level safety specialists or supervisors cannot use the HRA technique in a correct way if it is too complex.
5) _Accuracy of the outputs:_ The accuracy and reliability of the HRA techniques should also be considered to prohibit different results coming from the same method.

According to the safety specialists concerned issues and on-site observations, four criteria were finally determined, which describe the preferences in a general way. Each criterion has six sub-criteria that describe in a way and complement each criterion (see Table 2). The sub-criteria are exstracted from interviews as well.

The first criterion **SUITABILITY** was set in terms of the requirement: *2) HRA technique demand*. The criterion covers the application scope of the HRA techniques. The preferred HRA techniques can be applied in the automotive manufacturing industry. The preferred analysis can support all process phases analysis, such as normal operation, maintenance, or non-routine situations. Good applied historical records are preferred that can provide a reliable information for the application. Support for the critical tasks or areas analysis and less interference are preferred as the efficiency consideration. Finally, the results of applying such HRA technique should satisfy the relevant national regulations.

The second criterion **ECONOMIC** was set because of *Time and financial limitation* consideration. Direct costs, time for data

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

Table 2
Criteria for the AHP-based HRA technique selection method.

Selected criteria Criteria		Sub-criteria	
Suitability	Applicability in Automotive Industry	1S	**Applicability in the whole automotive industry domain** *Note: e.g. original domain of application, common domain of application, and whether it is already applied in the automotive domain*
		2S	**Applicability in all process phases of the automotive industry** *Note: e.g. normal operation phase, maintenance phase, and non-routine situation*
		3S	**Good applied historical records**
		4S	**Prioritization Support for the critical areas or tasks analysis**
		5S	**Interference with production** *Note: e.g. interviews with operators while working*
		6S	**Results include support for Risk Assessment requests from national regulators** *Note: e.g. stress/ergonomic*
Economic	Describes the extent to which time, effort or cost is well used for the intended task or purpose	1E	**Direct costs** *Note: e.g. license, material, development of new software of tool*
		2E	**Time for data collection**
		3E	**Time for data analysis**
		4E	**Frequency of required application**
		5E	**Possible use of existing databas**es *Note: e.g. Incident Events Record, Medical Examination Records,* etc.
		6E	**Hierarchical levels of people involved** *Note: e.g. the number of managers, supervisors, operators, or technicians who will be engaged in during the method application*
Usability	Ease to use and learnability of a human-made object	1Us	**Need for training for the users to use the method**
		2Us	**Number of users involved**
		3Us	**Necessity of pre-knowledge of users** *Note: e.g. education, skills, experience*
		4Us	**Necessity of external consultant** *Note: e.g. specialized in the method or in human factors*
		5Us	**Type of material support** *Note: e.g. standard datasheet, or software for analysis*
		6Us	**Complexity of the method** *Note: e.g. possibility to be used in a wrong way*
Utility	Did the modelling methodology provide a useful output	1Ut	**Qualitative or semi-quantitative Output**
		2Ut	**Quantitative Output**
		3Ut	**Clearness of results for understanding and making a decision** *Note: e.g. tables, graphics*
		4Ut	**Level of details of output and their usefulness** *Note: levels of details useful for the needs of the automotive industry*
		5Ut	**Output related to the production quality**
		6Ut	**Output related to workers' health** *Note: psychological and physical aspects*

collection, time for data analysis, hierarchical levels of people involved can directly influence the cost and time consumption. Meanwhile, the frequency of required application and possible use of existing databases are the other indirect influential factors that can influence the time and costs.

The third criterion **USABILITY** was set with the aim to fulfill the consideration of *the knowledge background* and *the complexity of the HRA application*. The preferred HRA techniques are not required long-time or complicated training to understand. The necessity of pre-knowledge should match the users' knowledge background. If it is not necessary, internal experts are preferred other than external consultants to apply the HRA techniques. Less users involved and less material support are better to conduct more efficient analysis without disturbing so many people and/or even the production process itself. The complexity of the HRA techniques should be considered. More complexity, more difficult to use, even cause the fault to use.

The fourth criterion **UTILITY** was set with the consideration of the *accuracy of the outputs*. The qualitative, semi-quantitative, or quantitative outputs are identified, so that the decision makers or safety managers can choose depending on their demands. Clearness of results for understanding and making a decision is required. Level of output details should be balanced. Neither a quite summary nor complicated report are preferred. That information is difficult to support making a decision. If the outputs relevant to the production quality and workers' health, that could be better.

3.3. Hierarchy structure of the AHP-based HRA technique selection method

The hierarchy structure is the main characterization of the AHP. Each level may represent a different cut at the problem. Elements that have a global character can be represented at the higher levels of the hierarchy, others that specifically characterize the problem at hand can be developed in greater depth (Saaty, 1990). According to the identified overall goal, criteria, and alternatives, the structure of AHP-based HRA selection is constructed (Fig. 1).

3.4. Pairwise comparison judgment for criteria

To compute the priorities for different criteria, the AHP first constructs *pairwise comparison matrixes*. A pairwise comparison matrix A is a $m \times m$ real matrix, where m is the number of selected criteria. Each entry a_{jk} of the matrix A represents the importance of the *jth* criterion relative to the *kth* criterion, where a_{jk} denotes the entry in the *jth* row and the *kth* column of A (Saaty, 1980). The relative importance between two criteria is measured according to the fundamental scale of Saaty (1990) in Table 3.

3.5. Priorities calculation and consistency checking

Once the matrix A is built, it is possible to compute priority vector, which is the normalized eigenvector of the matrix. The priority vector shows relative weights among criteria or sub-criteria. Aside

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

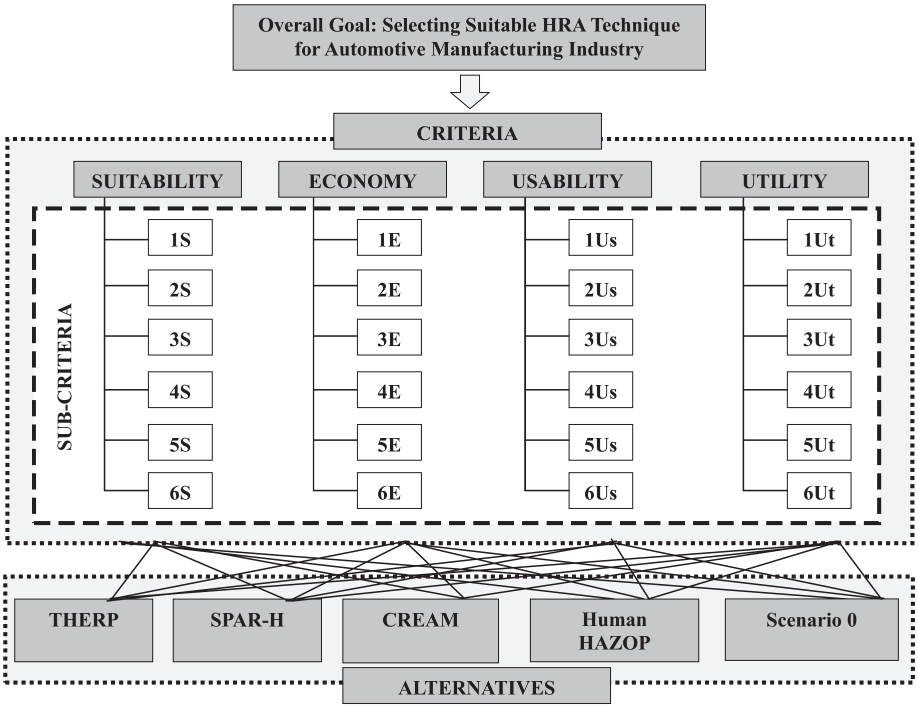

Fig. 1. Framework for the AHP-based HRA technique selection method.

from priorities calculation of criteria or sub-criteria, AHP measures also the consistency of the comparison by using the Consistency Index CI, Random Consistency Index RI, Consistency Ratio CR, see Eqs. (1) and (2). Perfect consistence means zero value of CI (CI = 0), while accepted consistence ratio CR is less than 10% (CR < 0.1), which means the subjective judgment can be accepted.

$$CI = (\lambda max - n)/(n - 1) \tag{1}$$

where

CI is the consistency index;
λ_{max} is the maximum eigenvalue;
n is the size of the measured matrix.

$$CR = CI/RI \tag{2}$$

where

CR is the consistency ratio;
CI is the consistency index;
RI is the random consistency index.

3.6. Ranking of alternatives

Once we calculate the priority vectors of Criteria and Sub-criteria, we continue with the calculation of priority vectors of alternatives based on each sub-criterion. Finally, the matrix combined with the alternatives and the weighted criteria will be established for the last ranking and decision making.

4. Application

4.1. Pairwise comparison matrixes and priorities for criteria and sub-criteria

Many application tools are available for automatically performing the AHP. In this case study, the free online BPMSG AHP online system® (Goepel, 2014) was applied. Given each of the four Criteria consisting of six Sub-criteria, four matrixes for priorities of each Criterion were established (see in Table 4). Note that, although Sub-criteria were given by pairwise comparison, the Criteria ranking was given by the experts' judgment and objectives for the automotive manufactory industry. The comparison required the Human Factor (HF) knowledge and the on-site working experience in the automotive manufacturing industry. The priorities of Criteria were assigned:

4.2. Priority vectors of alternatives and results

In the case of 24 Sub-criteria, 24 matrixes were established and combined with the alternatives and the weighted sub-criteria. Table 5 provides the final results of alternatives ranking in terms of each Criterion. The labelled weights of Sub-criteria were referred

Table 3
The fundamental scale according to Saaty (1990).

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or Strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

Table 4
Comparison matrixes and priorities for each criterion.

Suitability	1S	2S	3S	4S	5S	6S	Priority Vector	Economic	1E	2E	3E	4E	5E	6E	Priority vector
1S	1	7	3	1	3	8	37.90%	1E	1	1	0.5	0.5	1	3	12.70%
2S	0.14	1	1	0.33	0.33	2	7.20%	2E	1	1	2	0.25	0.33	3	12.20%
3S	0.33	1	1	0.33	0.25	1	7.20%	3E	2	0.5	1	0.25	0.5	5	13.00%
4S	1	3	3	1	1	3	22.50%	4E	2	4	4	1	3	5	37.80%
5S	0.33	3	4	1	1	3	19.60%	5E	1	3	2	0.33	1	6	20.40%
6S	0.12	0.5	1	0.33	0.33	1	5.60%	6E	0.33	0.33	0.2	0.2	0.17	1	4.00%
λ_{max} = 6.243, CR = 3.9%								λ_{max} = 6.485, CR = 7.7%							
Usability	1Us	2Us	3Us	4Us	5Us	6Us	Priority Vector	Utility	1Ut	2Ut	3Ut	4Ut	5Ut	6Ut	Priority Vector
1Us	1	4	3	4	1	0.33	19.90%	1Ut	1	0.5	0.14	0.14	0.17	0.11	2.70%
2Us	0.25	1	4	3	1	0.2	11.20%	2Ut	2	1	0.33	0.2	0.17	0.11	4.10%
3Us	0.33	0.25	1	0.33	0.17	0.14	3.70%	3Ut	7	3	1	0.33	0.33	0.33	10.90%
4Us	0.25	0.33	3	1	0.33	0.2	6.10%	4Ut	7	5	3	1	4	1	32.20%
5Us	1	1	6	3	1	0.2	14.60%	5Ut	6	6	3	0.25	1	0.33	17.20%
6Us	3	5	7	5	5	1	44.50%	6Ut	9	9	3	1	3	1	32.90%
λ_{max} = 6.501, CR = 8.0%								λ_{max} = 6.396, CR = 6.3%							

to the priority vector of each sub-criterion shown in Table 4. The final ranking result is obtained (Table 6 and Fig. 2).

5. Discussion

5.1. Preferred HRA technique selection results

5.1.1. Human-HAZOP as a qualitative approach is the most preferred

Our decisional analysis shows Human-HAZOP as the most preferred HRA technique for the automotive manufacturing industry. Indeed, Human-HAZOP can deal with all forms of deviation, from the design intent to planned procedures and human actions. Its high score can be explained from the Usability, Utility and Economic criteria.

Advantages of Usability: Human-HAZOP is quite flexible in terms of application of procedures, moreover does not require demanding supporting material. In the Usability criterion, Human-HAZOP was ranked high thanks to the sub criteria: *complexity of the method* (6Us) and the *necessity of users' pre-knowledge* (3Us), which means Human-HAZOP is easy to use and its team-work feature can guarantee the necessary learnability.

Advantages of Utility: Human-HAZOP gained its highest level of 1Ut and 3Ut. Results demonstrated that *qualitative output* (1Ut) and the *clearness of results for understanding and making a decision* (3Ut) are the major contributions to the Utility score. This probably relies on the method's core: the guidewords.

Economic Advantages: Generally Human-HAZOP is an economic HRA method, in almost all the economic sub criteria was high ranked except the *possible use of the database* (5E).

Although Human-HAZOP is ranked as the most preferable, for the Suitability criterion ranked as the last one, because of the low score of the sub criteria 1S, 4S and 3S. The ranking results showed that Human-HAZOP does not provide *a prioritization support for the critical areas or tasks analysis* (4S), moreover the method does not *include applied historical records* (3S) and it is based on guidewords that do not allow the analyst to predict an error. Since it is a procedural method, is not *suitable for the whole automotive industry* (1S) globally, but it can be applied individually to all subdomains and procedures of the industrial plant.

5.1.2. CREAM as a semi-quantitative approach goes to the second place

CREAM is the second preferred HRA technique under this decisional analysis. It owes its second place to Economic, Suitability and Utility criteria. A CREAM method needs only a few days of training and the supporting material is open source; this gives privilege in terms of economic criteria. Its suitability and utility second rank may result from its easy application, its clear inclusion of psychological characteristics and the workplace organization requirements. To be noticed that CREAM is first for two subcriteria: *a prioritization support for the critical areas or tasks analysis* (4S) and *level of details of output and their usefulness* (4Ut). The ranking results showed its advantages of two-level methods. The basic method (as a semi-quantitative way) supports the macro risk evaluation (output) of a task. CREAM enables analysts or managers to make a fast decision, whether it is a critical task and the in-depth probability analysis of human failure is required.

5.1.3. Scenario 0 is surprisingly placed at the third place: no HRA documented technique will be applied

The most surprising result is that Scenario 0 was selected as the third preferred choice. This is paradoxically logical, because many

Table 5
Results of alternatives ranking for each criterion.

Suitability %	1S 37.9%	2S 7.2%	3S 7.2%	4S 22.5%	5S 19.6%	6S 5.60%	Result	Economic%	1E 12.7%	2E 12.2%	3E 13%	4E 37.8%	5E 20.4%	6E 4%	Result
THERP	43.5	7.8	28.5	19.8	6.0	33.7	2.66	THERP	4.2	4.2	3.1	8.5	21.4	8.3	0.94
HUMAN HAZOP	9.5	55.1	7.2	8.1	15.6	8.0	1.34	HUMAN HAZOP	32.7	26.1	32.4	47.2	6.4	48.0	3.26
CREAM	28.5	22.8	15.7	46.9	6.0	20.9	2.65	CREAM	7.0	13.8	8.4	31.5	39.2	26.7	2.46
SPAR-H	15.7	11.4	45.7	19.8	6.0	33.7	1.76	SPAR-H	5.6	5.0	6.6	9.1	30.0	12.8	1.23
Scenario 0	2.7	2.9	2.8	5.3	66.4	3.6	1.58	Scenario 0	50.4	51.0	49.5	3.8	3.0	4.1	2.13
Usability%	1Us 19.9%	2Us 11.2%	3Us 3.7%	4Us 6.1%	5Us 14.6%	6Us 44.5%	Result	Utility%	1Ut 2.7%	2Ut 4.1%	3Ut 10.9%	4Ut 32.2%	5Ut 17.2%	6Ut 32.9%	Result
THERP	11.8	7.7	4.6	6.2	7.9	22.2	1.48	THERP	7.2	41.5	23.0	19.9	23.9	26.4	0.98
HUMAN HAZOP	3.1	7.7	17.6	3.9	3.6	55.3	2.75	HUMAN HAZOP	46.3	8.8	39.8	9.9	11.6	10.4	3.76
CREAM	8.1	7.7	7.6	18.2	14.3	12.9	1.17	CREAM	33.8	8.8	9.5	37.9	28.8	29.2	2.73
SPAR-H	9.8	7.7	4.8	6.7	8.4	6.5	0.75	SPAR-H	9.7	38.3	24.3	29.1	32.1	31.0	1.34
Scenario 0	67.3	69.2	65.5	65.0	65.8	3.1	3.85	Scenario 0	2.9	2.6	3.3	3.2	3.6	3.0	1.19

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

Table 6
The final priority vectors of alternatives and criteria.

	Economic 0.15	Usability 0.25	Utility 0.30	Suitability 0.30	Result
THERP	0.9359	1.4791	0.9772	2.6618	1.6019
HUMAN HAZOP	3.2616	2.7502	3.7576	1.3414	2.7065
CREAM	2.4636	1.1694	2.7340	2.6472	2.2763
SPAR-H	1.2251	0.7518	1.3377	1.7580	1.3004
Scenario 0	2.1270	3.8518	1.1936	1.5842	2.1153

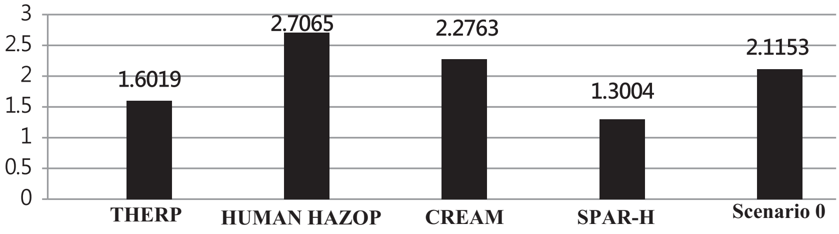

Fig. 2. Results of AHP-based HRA Technique Selection.

companies avoid using known methods and create their own methodologies for HRA.

Advantages of Usability: The Scenario 0 has placed at third position in consequence of its high ranking in Usability and the sub criterion *no training is needed*. Companies that use their own methodologies, or try to improve HRA without applying any of the known HRA techniques may rely on historical reports, experts' support and organization.

Economic Advantages: since no HRA documented technique are applied, *the direct costs* (1E), *time for data collection* (2E), and *time for data analysis* (3E) of the Scenario 0 are free to define.

The major disadvantage of Scenario 0 that contributes the low ranking of the Utility criterion is an unknown output. The uncertainty and the lack of accuracy of Scenario 0 effect all sub criteria of the Utility: unknown *output format (qualitative, quantitative, or semi-quantitative outputs' support*, 1Ut and 2Ut), unknown *clearness of results for understanding and making a decision* (3Ut), unknown *output details and their usefulness* (4Ut), and unknown of *other supports for the production quality and worker' health* (5Ut and 6Ut).

As a result, although Scenario 0 finally goes to the third place, safety managers should pay more attention to the output control. The uncertainty analysis should be conducted if the Scenario 0 is strongly suggested.

5.1.4. THERP & SPAR-H as quantitative analysis approaches are the last two preferred HRA techniques

THERP ranked at the fourth place. THERP was developed for the nuclear industry, to be easily understandable to engineers who may have a limited understanding of human factors and may not have the time or resources to commission a full human factors safety audit on site. However, THERP was still placed as the last one of the Economic criteria, because of its resource intensive activity which requires considerable time and resources from the assessors, and such resources may be difficult to achieve within an organization, in time and budget limits (Humphreys, 1988). With only the Suitability criterion that was placed as the first, this fact does not seem in accordance with THERP suitability since it has been developed for nuclear plants. But, THERP wins the first position for the Suitability criteria thanks to the S1 sub criterion and its big impact on the decision, 37.9% of importance. Indeed, THERP can be used throughout the whole lifecycle of a plant, it is not tied to the design HRA. The fault tree approach used within THERP allows the approach to be integrated with engineering reliability assessment techniques, which can assist designers in providing a numerical probability of failure, which is frequently required by regulatory bodies.

SPAR-H is the last preferred HRA technique as the ranking result, mainly because SPAR-H was designed for nuclear plants and can be applied to other industrial sectors only after corrections. Although the method was considered fast and simple, the corrections to be done for automotive application may compromise time and add cost for making it suitable and advantageous. Consequently, SPAR-H was ranked as the least usable method. Each PSF level is associated with an HEP multiplier value. Therefore, the weighting factor depends on how the analyst or the group of analysts judges the PSF and at which extent it improves or reduce reliability. Moreover, the PSF are quite old in relation to the technology currently available in industries (Boring and Blackman, 2007; Laumann and Rasmussen, 2014). To notice that SPAR-H was still ranked first for the sub criteria 2Ut, 5Ut, 6Ut and 3S, because it may consider human's individual characteristics, environment, organization, or task that specifically decrements or improves human performance, thus respectively increasing or decreasing the likelihood of human error (Blackman et al., 2008). This fact is very important, since different factors that contribute to human error can be re-evaluated and especially positive factors to human performance can be used for historical records and for relation to production quality and to the operators' health. Overall, SPAR-H was considered a low resource-demanding, because the total resources required are not elevated compared to the detailed level of the results (Gould et al., 2012); Forester et al. (2006) considered SPAR-H a method with a proven track record due to its extensive use.

A question may occur: "why those two quantitative analysis approaches go to the last places?" During the on-site observation and interview, it can be realized that unless some critical industries (e.g. aviation & space domain, military safety domain) requiring the human error probability to control the critical tasks, the automotive manufacturing industry itself, similar like other process industries, the consequences originated by human error may not reach to the critical level that should conduct the probabilistic analysis. Safety managers prefer a general idea of human error classifications, to identify human errors and adopt mitigation measures. Only for some critical tasks is required in-depth analysis of the human error probability; for example, working tasks in the painting mixing room, in which the human error can potentially cause the fire or explosive hazards. This situation may also explain why safety managers preferred Scenario 0 instead of quantitative

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

analysis approaches; it would be an exhausted workload if for the whole plant are applied such quantitative approaches frequently in terms of time-consuming and cost increasing because of the occupied human resources.

5.2. Performance of applying AHP to support the HRA technique selection

5.2.1. Advantages of the AHP application to support the HRA technique selection

With the number of available HRA techniques increasing, the difficulty on their selection and implementation acts as an increasingly common obstacle to the industrial companies in the application of the correct one for their domain. AHP can assist safety managers in selecting the right methodologies for their job and therefore improving the level of safety within their organization, thus reducing economic losses such as lost time incidents, absences due to injury, and less scope for error. AHP structures any decision in a Hierarchy and this helps the stakeholders to understand the priorities of their selection. Another characteristic that shows the AHP flexibility is that allows more people to be involved within the decision. This multi-person approach is very useful in large organizations, where managers from different departments may face conflicting interests. In terms of the best HRA tool selection, the AHP initially structures the demands of the automotive manufacturing industry and then individuates the most suitable option.

The decisional results also demonstrated that the AHP model is in accordance with the characteristics of the HRA techniques, therefore, utile for this kind of decisions. The present study can be useful to health and safety management as a decisional support. AHP can improve the HRA selection in terms of time and organization. Thanks to the hierarchical structure adds priorities to main aims of the company.

5.2.2. Limitation of the AHP application

The present decisional analysis is focused on a HRA technique to be adopted for the whole plant. It cannot be used for HRA techniques in separated industrial subdomains. Another important limitation is related on the core of the AHP method, which is the consistency matrix. The AHP can be used only for consistent decisions, and it is an important advantage if we want to avoid contradictions, but not all decisional problems can be consistent.

Additionally, it is important to mention that the HRA decision is made by experts, who carefully evaluated and scored the criteria. The experts' choices are subjective; nevertheless, the AHP structure provides an important support for minimising biased decisions.

6. Conclusion

The experts involved in this study were 9 divided in two groups. One group of five safety professionals, and on group of 4 HF doctoral students that worked as interns in the same safety department of the international automotive company, which occupies about 4000 employees at the production site. The educational qualification of all the components was the Master's degree: two in mechanical engineering, four in environmental sciences, one in natural sciences, one in food technology and processing and one in HF. The evaluation of each component of the group was considered at the same level.

The Automotive industry has been developed into a complex and highly automated industry. Additionally, it is influential in terms of income and number of workers; it employed 2.2 million people within the European Union in 2011 (European Automobile Manufacturers Association (ACEA), 2014) and 0.9 million people within the United States in 2014 (Bureau of Labor Statistics (U.S. Department of Labor), 2014). In the last decade, it has seen a worldwide continuous increase due to the development of this business in emergent economies (Organisation Internationale des Constructeurs d'Automobiles (OICA), 2016).

The level of automation and complexity along with the parallel increase of workers' number worldwide, has led to the establishment of an intensive human working environment, where HRA techniques can better support the risk assessment for human activities. The AHP process was used to evaluate which HRA techniques can be more purposefully be applied.

The approach allowed the selected techniques to be evaluated based on specific criteria, and the case study illustrated the example of a real automotive manufacturing industry, in order to verify that the needs of the organization are met. The AHP analysis may also help stakeholders to understand the priorities of the preferred selection. This can be provided beneficial to the industry allowing the provision of the right balance between complexity and accuracy for the level of analysis and output required.

The basic aim of the present analysis was to select the best choice as a general method. Not surprisingly Human-HAZOP is the best HRA choice, since it can deal with all forms of deviation from the design intent to planned procedures and human actions.

Acknowledgement

This work forms part of the EU FP7 funded Marie Curie Actions Initial Training Networks research project titled Innovation through Human Factors in Risk Analysis and Management (InnHF-FP7-PEOPLE-2011-ITN: Project ID 289837; for further information on the project please visit - www.innhf.eu).

The authors want to thank Dr Nora Balfe for her support, assistance and useful suggestions.

References

Bell, J., Holroyd, J., 2009. Review of Human Reliability Assessment Methods Research Report RR679. Health and Safety Executive (HSE), Buxton, UK.

Blackman, H.S., Gertman, D.I., Boring, R.L., 2008. Human error quantification using performance shaping factors in the SPAR-H method. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting. SAGE Publications, New York City, USA, pp. 1733–1737.

Boring, R.L., Blackman, H.S., 2007. The origins of the SPAR-H method's performance shaping factor multipliers. In: Proceedings of IEEE 8th Human Factors and Power Plants and HPRCT 13th Annual Meeting. IEEE, Monterey, USA, pp. 177–184.

Boring, R.L., Gertman, D., Joe, J., Marble, J., Galyean, W., Blackwood, L., Blackman, H., 2005. Simplified Expert Elicitation Guideline for Risk Assessment of Operating Events. US Nuclear Regulatory Commission, Washington, USA.

Bureau of Labor Statistics (U.S. Department of Labor), 2011. Automobiles. <https://www.bls.gov/spotlight/2011/auto/> (Jan. 13, 2017).

Bureau of Labor Statistics (U.S. Department of Labor), 2014. Databases, Tables & Calculators by Subject. <http://data.bls.gov/pdq/SurveyOutputServlet> (May 13, 2015).

Caputo, A.C., Pelagagge, P.M., Salini, P., 2013. AHP-based methodology for selecting safety devices of industrial machinery. Saf. Sci. 53, 202–218.

Chandler, F., Chang, Y.H.J., Mosleh, A., Marble, J., Boring, R., Gertman, D., 2006. Human Reliability Analysis Methods: Selection Guidance for NASA. National Aeronautics and Space Administration NASA, Washington, USA.

Edimansyah, B.A., Rusli, B.N., Naing, L., Mohamed Rusli, B.A., Winn, T., Tengku Mohamed Ariff, B.R.H., 2008. Self-perceived depression, anxiety, stress and their relationships with psychosocial job factors in male automotive assembly workers. Ind. Health 46, 90–100.

European Automobile Manufacturers Association (ACEA), 2014. Employment Trends. <http://www.acea.be/statistics/tag/category/employment-trends> (Jan. 13, 2017).

Evans, R.A., 1976. Reliability Optimization. Generic Techniques in Systems Reliability Assessment. Noordhoff International Publishing, Leyden, The Netherlands, pp. 117–131.

Ford, H., 1926. Mass production. In: L, G.J. (Ed.), The Encyclopedia Britannica; a Dictionary of Arts, Sciences, Literature & General Information, 13th ed. The Encyclopædia britannica company, ltd, London, UK, pp. 821–823.

Forester, J., Kelly, D., Kolaczkowski, A., Lois, E., 2006. Evaluation of Human Reliability Analysis Methods Against Good Practices Final Report. U.S. Nuclear Regulatory Commission, Washington, USA.

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007

French, S., Bedford, T., Pollard, S.J., Soane, E., 2011. Human reliability analysis: a critique and review for managers. Saf. Sci. 49, 753–763.

Geng, J., Murè, S., Baldissone, G., Camuncoli, G., Demichela, M., 2015. Human error probability estimation in ATEX-HMI area classification: From THERP to FUZZY CREAM. In: Proceedings of International Conference on Chemical & Process Engineering (ICheaP12), Milan (Italy).

Gertman, D., Blackman, H., Marble, J., Byers, J., Smith, C., 2005. The SPAR-H Human Reliability Analysis Method. US Nuclear Regulatory Commission, Washington, USA.

Gnoni, M., Andriulo, S., Maggio, G., Nardone, P., 2013. "Lean occupational" safety: an application for a Near-miss Management System design. Saf. Sci. 53, 96–104.

Goepel, K.D., 2014. BPMSG AHP Online System: Multi-Criteria Decision Making Using the Analytic Hierarchy Process. <http://bpmsg.com/academic/ahp.php> (Jan. 13, 2017).

Gould, K.S., Ringstad, A.J., van de Merwe, K., 2012. Human reliability analysis in major accident risk analyses in the Norwegian petroleum industry. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting. Sage Publications, Boston, USA, pp. 2016–2020.

Graves, R.J., 1992. Using ergonomics in engineering design to improve health and safety. Saf. Sci. 15, 327–349.

Groth, K.M., Swiler, L.P., 2012. Use of a SPAR-H Bayesian network for predicting human error probabilities with missing observations. In: Proceedings of PSAM 11: The International Conference on Probabilistic Safety Assessment and Management, Helsinki, Finland.

Hale, A.R., Guldenmund, F.W., Van Loenhout, P., Oh, J., 2010. Evaluating safety management and culture interventions to improve safety: effective intervention strategies. Saf. Sci. 48, 1026–1035.

Hassam, S.F., Mahamad, K.A.K., 2012. A study of occupational safety hazards: Safety and health issues in automotive industry. In: Proceedings of International Conference on Statistics in Science, Business, and Engineering (ICSSBE). IEEE, Langkawi, Malaysia pp. 1–6.

Hickling, E.M., Bowie, J.E., 2013. Applicability of human reliability assessment methods to human–computer interfaces. Cogn. Technol. Work 15, 19–27.

Hollnagel, E., 1993. Human Reliability Analysis: Context and Control. Academic press, London, UK.

Hollnagel, E., 1998. Cognitive Reliability and Error Analysis Method (CREAM). Elsevier Science, Amsterdam, The Netherlands.

Humphreys, P., 1988. Human reliability assessors guide: an overview. In: Sayers, B. A. (Ed.), Human Factors and Decision Making: Their Influence on Safety and Reliabilitym. Elsevier applied science, Amsterdam, The Netherlands.

Imperial Chemical Industries, 1977. A Guide to Hazard and Operability Studies. Chemical Industry Safety and Health Council of the Chemical Industries Association, London, UK.

International Ergonomic Association (IEA), 2000. Retrieved from Ph.D. course in Ergonomics and Workplace Design 2013–2014. Polytechnic University of Turin, Turin, Italy.

Kirwan, B., 1994. A Guide to Practical Human Reliability Assessment. CRC Press, Boca Raton, USA.

Kirwan, B., 1996. The validation of three human reliability quantification techniques—THERP, HEART and JHEDI: Part 1—technique descriptions and validation issues. Appl. Ergon. 27, 359–373.

Kirwan, B., 1997. Validation of human reliability assessment techniques: Part 1-validation issues. Saf. Sci. 27, 25–41.

Kirwan, B., 1998. Human error identification techniques for risk assessment of high risk systems—Part 1: review and evaluation of techniques. Appl. Ergon. 29, 157–177.

Kletz, T., 2009. ICI's contribution to process safety. In: Proceedings of 12th International Symposium on Loss Prevention and Safety Promotion in the Process Industries. IchemE Symp, Edinburgh, UK, p. 846.

Kvarnstrom, S., 1997. Stress Prevention for Blue-Collar Workers in Assembly-Line Production, Stress Prevention for Blue-Collar Workers in Assembly-Line Production. OIT, Klamath Falls, USA.

Laumann, K., Rasmussen, M., 2014. Suggestions for improvements to the definitions of SPAR-H performance shaping factors, to the definitions of the levels, and suggestions for changes in the multipliers. In: Proceedings of PSAM 14: The International Conference on Probabilistic Safety Assessment and Management, Honolulu, Hawaii.

Leva, M.C., Friis-Hansen, P., Ravn, E.S., Lepsoe, A., 2006. SAFEDOR: A practical approach to model the action of an officer of the watch in collision scenarios. In: Proceedings of European Safety and Reliability Conference, Safety and Reliability for Managing Risk, ESREL, Estoril, Portugal, pp. 2795–2804.

Liu, P., Li, Z., 2014. Human error data collection and comparison with predictions by SPAR-H. Risk Anal. 34, 1706–1719.

Madonna, M., Martella, G., Monica, L., Maini, E.P., Tomassini, L., 2009. The human factor in risk assessment: methodological comparison between human reliability analysis techniques. Prevent. Today 5, 67–83.

Michalos, G., Makris, S., Papakostas, N., Mourtzis, D., Chryssolouris, G., 2010. Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach. CIRP J. Manuf. Sci. Technol. 2, 81–91.

Mirer, F.E., 1998. Automobile and transportation equipment industry. In: Stellman, J.M. (Ed.), Encyclopaedia of Occupational Health and Safety. fourth ed. International Labour Organization, Geneva, Switzerland.

Øie, S., van de Merwe, K., Hogenboom, S., Laumann, K., Gould, K., 2014. Human reliability assessment of blowdown in a gas leakage scenario on offshore production platforms: methodological and practical experiences. In: Proceedings of Probabilistic Safety Assessment and Management Conference, Honolulu, Hawaii.

Oleske, D.M., Neelakantan, J., Andersson, G.B., Hinrichs, B.G., Lavender, S.A., Morrissey, M.J., Zold-Kilbourn, P., Taylor, E., 2004. Factors affecting recovery from work-related, low back disorders in autoworkers. Arch. Phys. Med. Rehabil. 85, 1362–1364.

Organisation Internationale des Constructeurs d'Automobiles (OICA), 2016. Production Statistics. <http://www.oica.net/category/production-statistics/> (Jan. 13, 2017).

Podgórski, D., 2015. Measuring operational performance of OSH management system – a demonstration of AHP-based selection of leading key performance indicators. Saf. Sci. 73, 146–166.

Punnett, L., Gold, J., Katz, J.N., Gore, R., Wegman, D.H., 2004. Ergonomic stressors and upper extremity musculoskeletal disorders in automobile manufacturing: a one year follow up study. Occup. Environ. Med. 61, 668–674.

Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Saf. Sci. 27, 183–213.

Rezazadegan, F., Geng, J., Ghirardi, M., Menga, G., Murè, S., Camuncoli, G., Demichela, M., 2015. Risk-based design for the physical human-robot interaction (pHRI): an overview. In: Proceedings of International Conference on Chemical & Process Engineering (ICheaP 12), Milan, Italy.

Rivera, S.S., Mc Leod, J.E.N., 2012. Recommendations generated about human reliability analysis on biodiesel plants. In: Proceedings of the World Congress on Engineering, London, UK.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15, 234–281.

Saaty, T.L., 1980. Ahp: The Analytic Hierarchy Process. McGraw-Hill, New York, USA.

Saaty, T.L., 1990. Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World. RWS Publications, Pittsburgh, USA.

Saaty, T.L., Kearns, K.P., 1985. Analytic Planning – the Organization of Systems. Pergamon Press, Oxford, England.

Shorrock, S., Kirwan, B., Smith, E., 2003. Individual and group approaches to human error prediction–a tale of three systems. In: Proceedings of IBC Conference on Preventing Human Errors and Violations, London, UK, pp. 27–28.

Spallek, M., Kuhn, W., Uibel, S., van Mark, A., Quarcoo, D., 2010. Work-related musculoskeletal disorders in the automotive industry due to repetitive work-implications for rehabilitation. J. Occup. Med. Toxicol. 5, 1–6.

Stamatelatos, M., Dezfuli, H., Apostolakis, G., Everline, C., Guarro, S., Mathias, D., Mosleh, A., Paulos, T., Riha, D., Smith, C., 2011. Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners. National Aeronautics and Space Administration NASA, Washington, USA.

Stanton, N.A., Salmon, P.M., Rafferty, L.A., Walker, G.H., Baber, C., Jenkins, D.P., 2013. Human Factors Methods: A Practical Guide for Engineering and Design. Ashgate, Aldershot, UK.

Swain, A.D., Guttmann, H.E., 1983. Handbook of Human-Reliability Analysis with Emphasis on Nuclear Power Plant Applications Final report. U.S. Nuclear Regulatory Commission, Washington, USA.

Ulin, S.S., Keyserling, W.M., 2004. Case studies of ergonomic interventions in automotive parts distribution operations. J. Occup. Rehabil. 14, 307–326.

United States. President's Commission on the Accident at Three Mile Island, 1979. The Need for Change, the Legacy of TMI: Report of the President's Commission on the Accident at Three Mile Island. President's Commission on the Accident at Three Mile Island, Washington, USA.

Whaley, A.M., Kelly, D.L., Boring, R., 2012. Guidance on dependence assessment in SPAR-H. In: Proceedings of PSAM11 & ESREL 2012 Joint Probabilistic Safety Assessment and Management and European Safety and Reliability Conference, Helsinki, Finland.

Whaley, A.M., Kelly, D.L., Boring, R.L., Galyean, W.J., 2011. SPAR-H Step-by-Step Guidance. U.S. Department of Energy National Laboratory, Idaho Falls, USA.

Whalley, S., 1988. Minimising the cause of human error. In: Proceedings of 10th Advances in Reliability Technology Symposium. Bradford, UK, pp. 114–128.

Zheng, G., Zhu, N., Tian, Z., Chen, Y., Sun, B., 2012. Application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments. Saf. Sci. 50, 228–239.

Please cite this article in press as: Petruni, A., et al. Applying Analytic Hierarchy Process (AHP) to choose a human factors technique: Choosing the suitable Human Reliability Analysis technique for the automotive industry. Safety Sci. (2017), http://dx.doi.org/10.1016/j.ssci.2017.05.007