MÄLARDALEN UNIVERSITY
SWEDEN

School of Innovation, Design and Engineering

Human errors in industrial operations and maintenance

Master thesis work
30 credits, Advanced level

Product and process development
Production and Logistics

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ABSTRACT

Within maintenance activities and industrial operations, human is subjected to different kind of stresses and situation that could result in mistakes and accidents. The human errors in maintenance and manufacturing are an unexplored latter such that a little focus is invested in this area. The report aims to widen up the understanding of the human error in maintenance and manufacturing area. Aviation and marine operations are the most sectors that are subjected to human errors according to the literature. There are different types of human error that have effect on quality and overall effectivity. Human reliability models are one method to quantify human errors and usually used for the identification of human errors and HEP calculation. The most common reliability measurement methods are HEART, THERP and SLIM which are used depending on application and industry. As a part of efforts to define differences between those reliability models, literature including different industries is used and it is found that expert judgement influences the success and accuracy of such methods. There are many causes for human errors depending on the application but, communication and procedures followed are the most contributing factors. There is always a probability of existence of human errors as the mistake done by workers are inevitable. Industry 4.0 can help in decreasing human errors through the introduction of operator 4.0 as well as other approaches like training and upgrading organizational standards.

(Keywords: Human error, Human factor, Human reliability models, Maintenance, Industrial operations, Manufacturing)

ACKNOWLEDGEMENTS

I would like to express my gratitude and thank my supervisor at MDH, Dr. Antti Salonen, for his help and support in conducting this work.

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1. INTRODUCTION

The following chapter will discuss the background of the thesis topic along with problem formulation and present the aim and research questions which will be resolved in the thesis ending with possible project limitations.

1.1 Background

The role of human in the phases of industrial operations, manufacturing, assembly and maintenance is important and in cannot be neglected or substituted by latest technologies or advancements (Sheikhalishahi, Pintelon and Azadeh, 2016). Today's frameworks ordinarily are socio-specialized, their strength expect individuals to utilize them, to adapt to the unavoidable cases when innovation of technology falls. Even though individuals are truly adaptable and versatile, to adapt to the innovation disappointments, individuals should be educated to adapt to it, be permitted to rehearse their abilities, and be furnished with the perfect data at the perfect time (Salonen,2019).

As the complexity of technologies within production and industrial operations increases, the maintenance requirements become more complicated and it demand more skills and knowledge by technicians to perform (Morag *et al.*, 2018). Furthermore, this gap between technological advancements and maintenance practices allows for a bigger margin of error especially where poor management and preparation are performed.

According to Shappell and Depar (2000); Weigmann and Shappell (2001), 70-80% of accidents within aircraft are due to errors made by human and the human factor is more studied in the context of safety critical systems. The need of discussing human factors have developed since it is less studied in maintenance and manufacturing industries and in general, operators are not only required to operate an equipment but also perform maintenance and inspection practices. Nevertheless, Dhillon and Liu (2006) stated that the costs of plant maintenance in the US industry is estimated to be around $300 billion and almost 80% of this amount is spent on the efforts of correcting the failures of people, systems and machinery.

In the Swedish automotive industry almost 20-45% of the total breakdowns are caused by human factor and errors whereas those inaccuracies are basically resulted from the inadequate handling of equipment and machines, insufficient performing of preventive maintenance and bad cleaning practices (Salonen,2019). Moreover, the presentation of ergonomics standards in the design phase of machines and equipment is not only essential to reduce downtimes caused my maintenance but also decreases the possibilities of staff injuries and wounds (Sheikhalishahi, Pintelon and Azadeh, 2016). Human mistakes are to be considered and minimised to restrict financial misfortunes related with abandons and superfluous waste. Thus, ergonomics and human components discipline is viewed as a key practice region inside the lean manufacturing concepts (Torres, Nadeau and Landau, 2021). Therefore, distinguishing and understanding the human factors make the worker work more efficiently and along these lines more viable with respect to of authoritative destinations. The interest lies in distinguishing the principal factors impacting the push to accomplish the goals of maintenance. A few of the elements (for example a feeling of responsibility for machines, which affect the dependability and execution) will influence the maintenance and manufacturing through targets, and henceforth the viability of the upkeep capacity, and others will influence (for example inspiration) through productive asset use (Galar *et al.*, 2011).

According to Rothblum (2000), 75-96% of accidents that happen within marine operation are due to human error. The lack of proper understanding of the lessons that caused accidents in marine operation have jeopardized safety across workers and shipping staff (Celik and Cebi, 2009). The accident that are due to human errors are also found in nuclear power generation industry, as the exposure of radiation makes the workers perform in an unbalanced structure (Jeong et al., 2016). According to Kelly and Efthymiou (2019), most of the accidents that happen within aviation industry are not due mechanical malfunction, but human error is the huge contributor.

1.2 Problem formulation

The latter of human errors in maintenance and in industrial operations is an explored latter so that few researchers have made efforts to investigate the causes of human error and what are the possible actions that could be taken to reduce them (Salonen, 2018). The types of human errors are various and the methods of reducing them are still unclear. In relation with human errors, human reliability analysis and techniques are still not completely discovered and there is no clear guidance of what methods can be used in respective with industries like manufacturing, aviation, marine operations and oil and gas companies. However, there are advantages and disadvantages of these techniques in the actions of utilization and implementation. Almost more than 14 % of the total manufacturing cost has been wasted due to fault maintenance activities and unplanned breakdowns (Salonen, 2019). Due to technological advancements, errors resulted from human has increased in maintenance without realizing the causes that could help in diminishing those misfortunes. Most types of human errors in maintenance are figured out by multiple researchers but with no efforts in filling the gap of improper activities like inspection of defects (Sheikhalishahi, Pintelon and Azadeh, 2016).

1.3 Aim and Research questions

The main aim of this thesis is expanding the knowledge of human errors that happens in maintenance and industrial operations. In order to accomplish that, formulation of research questions was required. The purpose of this study is to identify the main causes of human errors in maintenance and manufacturing along with identifying human reliability analysis techniques with listing out differences and methods of implantation. Moreover, recommendation and possible ways of reducing human errors in maintenance was proposed.

- *What are the main causes of human errors in maintenance and industrial operations?*
- *What are the efforts done in order to diminish human errors and what are the possible implications?*
- *What are the major differences between human reliability models and techniques?*

1.4 Project limitations

As per fulfilling the main objective of the thesis, literature on human errors in maintenance and industrial operation were investigated. The first limitation to mention is that most of the literature found investigate human errors within maintenance so that there is a minimal effort of exploring human errors and factors in manufacturing so most of the journals used talks about errors maintenance. Most of the literature used in writing the thesis is updated within the last 20 years to get more insights about new theories and one search database was used which is Scopus. Since there are many human reliability analysis techniques only most common methods (HEART, SLIM and THERP) was mentioned and they are the most repeatable techniques in the literature. Industry 4.0 technologies is not only used in relation of human errors, but for general production efficiency optimization regarded to human operator.

2. RESEARCH METHOD

In this section, the methods of how this thesis was accomplished is stated. It was important to list out what type of research methodology is chosen along with in what way the data was collected and analysed.

2.1 Research Methodology

A well-structured research consists of a developed, scientific consistency of knowledge and scientific approaches. Generally, there are two types of research approaches: quantitative and qualitative. The research approach chosen for this master´s thesis is qualitative approach where Williams (2007) and Onwuegbuzie et al., (2012) stated that a qualitative research has an integrated approach that leads to recognition and uncovering of a certain topic. Qualitative research consists of explaining, describing and analysing the collected data by having a minimal structure for illustration and focuses on building new theories. The focus of this qualitative research is to theoretically study human errors in maintenance and industrial operations and the reason for choosing such approach is that there is a huge gap noticed after reviewing the literature in identifying the causes of human errors and investigating the possible ways and techniques in order to have numerical approaches upon calculating human error probabilities. Moreover, the approach was also inspired referring to the steps for conducting a qualitative research by Walliman (2017).

Table 1 Qualitive research steps (Walliman, 2017)

In this sense, this master's thesis started with illustrating some background information about the subject followed by a theoretical framework of human error concepts and types. Moreover, technical terms are identified by using multiple resources from the literature. All the data is checked and analysed carefully in order to answer the research questions and for the sake of drawing out a reasonable conclusion. According to Williams (2007), there are many research techniques for deducting a qualitative approach which are: case study, ethnographic study, grounded theory study, phenomenological study and content analysis study. The choice for this research was grounded theory study which is defined as the derivation of an abstract that starts with information to build up a theory. The process of conducting a grounded theory is driven by the repeatable actions of collecting and analysing data. The data can be extracted from different resources and by multiple methods such as interviews, scientific journals, surveys and records. The method usually integrates different aspects like formulating and describing research questions, research methods description, literature review, discussion and analysis of the theoretical framework.

The research method chosen for this master's thesis is a theoretical literature review. According to Hart (1988), a literature review main purposes are to separate what has been done and what need to be accomplished and to achieve a new perspective about a certain topic which is poorly mentioned in the literature. Moreover, the motivation of the technique used to write a literature review is inspired from Williamson (2002) which explained deeply the steps for applying a literature study and it is conducted as following:

- Categorization of the literature into subjects and topics that should be related to the research question.
- Writing an introduction mentioning the importance of the topic
- The body of the literature should be organized, and the heading should relate to the research question.
- Analysis and discussion of the results drawn out from the literature.
- Writing a conclusion with indicating if the research gap is filled and illuminated.
- Checking the consistency of the whole literature review written and answering the researching questions.

In this manner, this master´s thesis started with an introductory part to address the importance of the topic. The introductory part contains sections that discusses the aim of this thesis and limitations that are faced upon writing and searching for theory and research questions. A theoretical framework was built up containing aspects of human errors in maintenance and industrial operations. Although the title of the thesis upholds two sides of theory, that is maintenance and industrial operations, there was a lack of scientific efforts in discussing human factor in manufacturing\industrial operations such that more focus is drawn on the maintenance side.

2.2 Data Collection

In the process of writing this masters thesis, data is collected to fullfill the main puropose of the project. There are several databases and techniques used to conduct all the data used. The first database used was Scopus were a literature search was done using the platform and by the help of some keywords, search critirias and operators. Scopus is a multidisciplinary digital platform which can be used by Mälardalen Högskola library database. However, Scoups was not the only database used for extracting data as the latter is still unexplored so other databases like Google Scholar and the university´s library was used but the majority of papers were extracted from Scopus. The keywords used were, “human factor”, “human error”, “mainteneace”, “industrial operations”, “human reliabiility” , “manufacturing”. In order to get strong related resultes to the topic, search operator like “AND” and “OR” were used so that the search string is shown in figure 2.

(TITLE-ABS-KEY ("human errors" AND "maintenance") OR TITLE-ABS-KEY ("human factor" AND "maintenance") OR TITLE-ABS-KEY ("human factor" AND "industrial operations") OR TITLE-ABS-KEY ("human errors" AND "industrial operations") OR TITLE-ABS-KEY ("human factor" AND "manufacturing") OR TITLE-ABS-KEY ("human errors" AND "manufacturing")) AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"COMP") OR LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"BUSI") OR LIMIT-TO (SUBJAREA,"ENVI") OR LIMIT-TO (SUBJAREA,"ENER") OR LIMIT-TO (SUBJAREA,"MATE") OR LIMIT-TO (SUBJAREA,"HEAL")) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (EXACTKEYWORD,"Human Engineering") OR LIMIT-TO (EXACTKEYWORD,"Human Factors") OR LIMIT-TO (EXACTKEYWORD,"Maintenance") OR LIMIT-TO (EXACTKEYWORD,"Human") OR LIMIT-TO (EXACTKEYWORD,"Errors") OR LIMIT-TO (EXACTKEYWORD,"Manufacture") OR LIMIT-TO (EXACTKEYWORD,"Ergonomics") OR LIMIT-TO (EXACTKEYWORD,"Human Errors"))

Figure 2 Search string conducted for the extracting literature

After choosing the best keyword combination that are selected with respect to the topic and combining them in a way to get more related results such like ("Human error" AND "maintenance") OR ("Human error "AND "Manufacturing") a search string is created. The search string is created by combining Human error/Factor with another keyword (maintenance, manufacturing, industrial operations) with an AND operator then by an OR operator. The choice of the keywords is done by checking what kind of words relates to the topic of the thesis and by testing which keywords give more results. At the beginning, year limitation was selected to get more updated results about the topic but then due to the need of the papers, more papers are used before 2006. Some limitations were done to get more better results. Since the paper is in English only English paper are used and together with journal papers because they are peer reviewed and serves the major goal of reliability and validity of the thesis. The papers are also limited to a subject area which is conducted by several attempts to see which subject areas give more accurate and related results.

- Most articles used in this thesis are journal articles that were presented in the literature search.
- English language articles were extracted only.
- The related subject areas were Engineering, Computer Science, Social Sciences, Business, Environmental Science, Material Science, Energy and Health Professions.

After applying the search criteria, articles found are carefully examined through reading the abstract and deciding if the article is relevant to the topic or not. By checking the abstracts of all the articles, around 120 articles were extracted from a total of 600 article. The articles found were added in a reference manager application which is called "Mendeley". After plugging in the articles in Mendeley, the articles are furtherly examined by reading the findings of the study and check the relation if the article can contribute to the master's thesis. Moreover, Snowballing techniques were used to get additional articles. Snowballing method is used by checking the references of an article that may be relevant to the study. However, the overuse of this technique would out date the work, this is because the researcher would find articles made in past years.

2.3 Reliability and Validity

In order to deliver a high-quality research, two parameters must be kept in mind that is the reliability and validity of the work done (Ayodele, 2012). If a study is reliable, it means that the same results would be produced upon repeating the same methods used when deducting the study. The data used for this thesis is extracted from well reputed sites and databases which increase its reliability and the authors of the articles used are well known and highly cited. Moreover, the study contributes to real examples that happen in the industry.
According to Williamson (2002), the concept of validity is to check the results presented in a study if they can be applied. In other words, validity expresses how much the data presented is accurate. Since this study is theoretical, it cannot be clear if the results presented in this thesis can be used in a single industry as the topic handled human errors in maintenance and manufacturing in different industries.

2.4 Data Analysis

The data collected is analysed in different ways, most importantly, the method of constant comparison analysis is used. The researchers utilize the constant comparative approach to develop hypotheses from information by scripting and evaluating at the very same period

(Taylor & Bogdan, 1998). Constant comparison analysis has five main features, according to Strauss and Corbin (1998): (1) to construct hypothesis rather than evaluate it; (2) to provide investigators with analytic tool for measuring data; (3) to aid researchers in interpreting different connotations from data; (4) to provide researchers with a rigorous and innovative method for analysing data; and (5) to assist researchers in understanding multiple meanings from data. Different theories, authors and interpretation building techniques are used to analyse the data such that the answers to the research questions are based on reviewing different authors opinions in different sectors like aviation, manufacturing and marine operators that talks about human errors and human reliability models. Tables and graphs are used to explain information and statistics so that the public can comprehend it.

The analysis section of this report is done in three parts related to the research question. The first part is discussing causes of human errors in the literature and a table were conducted followed by a pie chart. The table mentions different methods and techniques that are mentioned in the literature corresponding to different industries. The second part of the analysis, major differences between reliability models are compared. The reliability models that are chosen to be analysed are those that are most common in the literature. The idea behind choosing such reliability models came after checking most of the reliability models that are discussed in the literature and deciding to talk about those three. The last section is split into three section emphasizing the efforts to reduce human errors that are maintenance, industrial operations and industry 4.0. Maintenance and manufacturing are directly related to the topic and a table is conducted to discover some cases of decreasing human errors and by which methods. This is to allow the reader to acknowledge a general perspective about what kind of concept or ideas are related to reducing human errors.

3. THEORETIC FRAMEWORK

Key concepts and definition of various types of human errors is presented in this section. In addition, different theories from different industries within maintenance and manufacturing that are related to human errors is listed out and defined.

3.1 Human Factors in Manufacturing and Industrial Operations

The concept of human factors in manufacturing has been related to the relationship between machines or equipment and mankind. Hypothetically, this relationship is also defined as the study of human behaviour in the sense of socio-technical systems where the use of this study and comprehension also regarded to genuine settings meant by manufacturing, job shops and manual assembly (Ogbeyemi *et al.*, 2020). Another definition is given by Sgarbossa, et al. (2020), where the author described human factors as a comprehension of different activities among people and different components of a specific framework where its division applies to hypothesis, information, and strategies to plan in proper design in order to enhance human prosperity and general system execution. The relationship between system components and its performance with human factors is illustrated in figure 1.

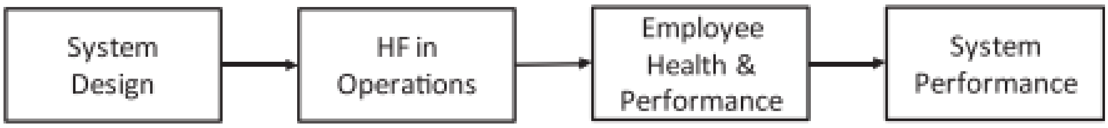

Figure 1 HF in relation with system performance (Sgarbossa, et al., 2020)

However, in order to get a good definition of how machine and human interact, a human-machine model is proposed by Oborski (2004). This model identifies six modes of communication between the machine and the human. The following points that are related to figure 2 illustrates in generally the relationship between human and machines.

1. Ordering of the process by the operator through a computer system (indirectly).
2. The operator gets the process representation he/she ordered.
3. The operator interacts with the computer to get more information.
4. The process demands additional information from the computer system.
5. Direct collaboration between the process and the operator.
6. The operator analysis the process in his own point of view.

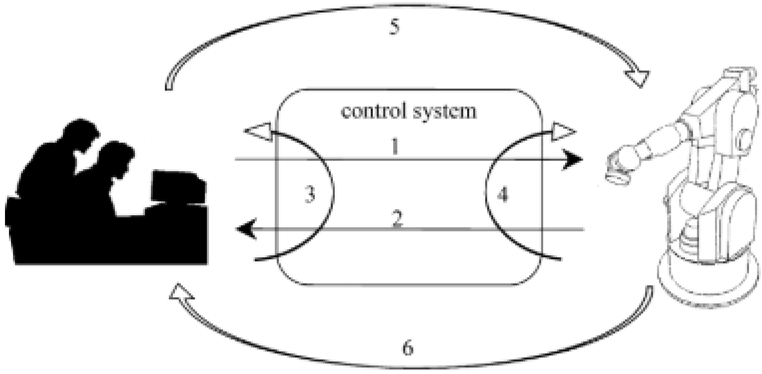

Figure 2 Human-machine interaction model (Oborski, 2004)

3.1.1 Human Factors and assembly operations

A manufacturing site is made up different types of process and activities where those activities are basically limited to the context of machining, welding, assembling, painting, testing, packaging and shipping to the final user or consumer such that the combination of those activities, if correctly implemented would invest in a good production process level, would reflect a superior image of production planning and scheduling (Ogbeyemi *et al.*, 2020). Manuel assembly concerns the actions of summing up pre-manufactured components or sub-assemblies into a single last product where the integration of human operator's skills and knowledge is a must in order to finalize a well done assembled product (Torres, Nadeau and Landau, 2021). Moreover, manual assembly is a set of information and instruction that requires that workers must build a special conceptual model in order to understand the information leading to a more adequate operations so that the success of assembly operations depends on the ability of operators to read and adapt to the instructions(Richardson *et al.*, 2006).

According to Ogbeyemi, et al. (2020), modern manufacturing systems proposes an electronic way to preview instructions in a more clear way but this doesn't mean that human errors are eliminated because those errors are subjected to what is called human variability. Consequently, methods of inspections that are related to quality and defects recognition are proposed as a method to recover from human errors. In addition, more methods of automation are used as a mean for visual inspection but this is not recommended due to the fact that the detection of defects is discovered late which leads to more costs due to rework (Torres, Nadeau and Landau, 2021). An overview of an example of a job shop within manufacturing and how all the components of manufacturing is previewed in figure 3 summing up also the activities of industrial operation previously mentioned in the literature.

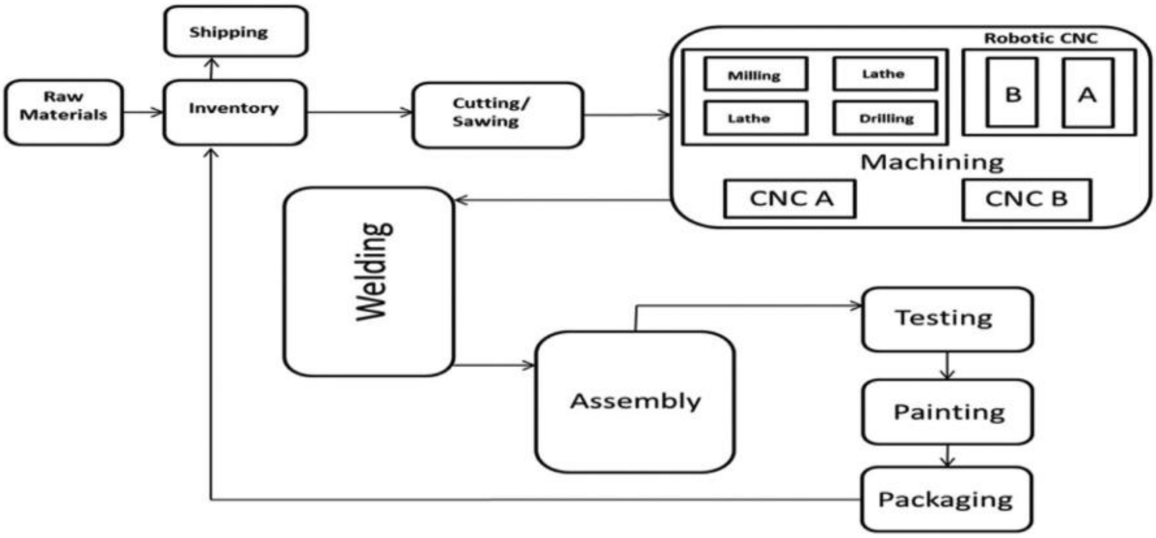

Figure 3 Job Shop overview within production process in manufacturing (Ogbeyemi, et al., 2020)

3.1.2 Quality Performance and Human Factors

In process management, the efforts of implementing HF concepts between workers and operators directly affect quality of products where two arguments are presented by Kolus, et al. (2018). The first argument is the time spent finalizing a given task and the second argument is the worker's overall posture while performing a task where those two arguments have a direct relation to quality problems. The concept of human factors has been frequently mentioned in the area of ergonomics and safety goals but has not been subjected to the efforts of performance improvement relating to quality and operations management. This gap between HF and operation management is still undiscovered. (Neumann, Kolus and Wells, 2016) have identified four terms corresponding to quality risk factors and they are on a product level, process level workstation and individual level.

- The product design QRF determines the characteristics of assembly tasks.
- Process design QRF identifies the stages of performance related to assembly such task distribution, strategies followed for material supply and flows.
- Workstation design QRF defines what kind of layouts used that would determiners operators postures while doing a specific assembly task.
- Individual QRF are those factors that contribute to mankind such like the knowledge and skills of operators.

Those factors impacting quality from a human factor perspective are also illustrated in figure 3. In addition, Kolus, et al. (2018) mentioned that the quality problems that happens due to human factors are not only due to operators faults and errors but also to managers. From lean manufacturing perspective, Hernandez-Matias, et al. (2019) described the importance of multitask operators in terms of quality check in each production process which could also be a huge contributor for increasing productivity and decreasing downtimes due to breakdowns of preventive maintenance and failures.

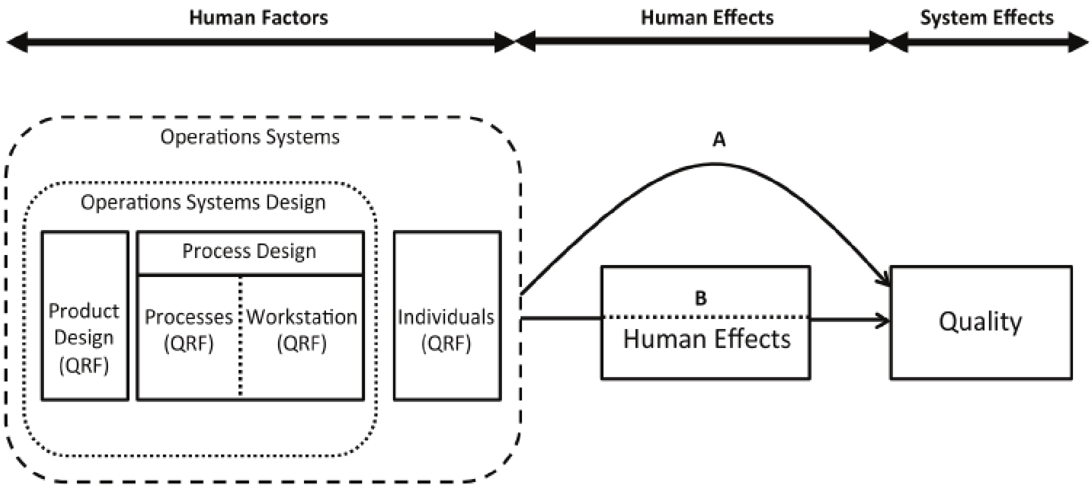

Figure 4 HF quality risk factors (Neumann, et al., 2016)

3.1.3 Classification of Human Error within Manufacturing

Within the past years, authors have given more than one identification on human errors with different classifications. Di Pasquale, et al. (2016) stated that human error is a fault behaviour from the operator towards a manufacturing task he is assigned to and it maybe an unsuitable decision he made concerning operations he is willing to make. Those fault actions would eventually lead to defects and an undesirable output or unanticipated result. Moreover, more definition on human error classification is given by Qeshmy, et al. (2019) that human errors are classified in performance levels. According to the author, there are two performance levels the first one is rule based where the performance of the operator is bounded in the experience, he has concerning an industrial operation and have been doing it to a point where it becomes more like a routine where he could also receive the knowledge through instructions. The other performance level concerns the faults an operator makes without no intentions or when the operator lacks the focus to complete a given task. Those errors are resulted from slips and unconscious behaviour when an operator is working under the influence of programmed instructions and patterns. (Erdinc, 2008) have also explained the form of human errors in the form of an ergonomic assessment and stated that human errors are reflected through the muscular structure an operator have and these problems are communicated not only within workers in a production line but also through manager and higher levels.

More taxonomies are presented in the literature by Böllhoff, et al. (2016) where the author described human error and they can be cause or occurrence oriented and there may be some cases where the error maybe resembled from the two types. More classifications are found out by the researcher in which human errors are categorized and three categories. The first category has classified the errors as errors of perception that prevent the operator to remember the methodology of finalizing steps of a process or a task. Those perception are illustrated in the parameters of quantities and types, motion and representations. Another category concerns the errors made due to loss of memory of the operator and the last category is related to the fixture and posture of the operator. Also, human errors can be described by reviewing the relationship between human and manufacturing tasks in a context mental framework. As Qeshmy, et al. (2019) explained this mental framework as the amount of mental contribution from an operator towards a possible task and the instability of this relation results in what is called human error. This mental framework also has characteristics an operator would like to have like the ability of

thinking, searching, looking and deciding and those also can be reflected by the task as how much it needs from every variable in order to be completed.
In addition, more taxonomies are used in the literature as Di Pasquale, et al. (2016) explained that errors made human can be classified in three categories:

- The first category divides human errors regarding human performance and contains variable like skill, knowledge and rule-based performance deriving the definition from also a perspective related to human factor as Qeshmy, et al. (2019) stated.
- The second category follows and information processing model and conduct mental operations in order to classify human errors.
- The third category handles the human errors according to temporary failures and false steps.

One of the methods to identify human errors is the human error identification method (HEI) which is used to identify latent errors created by the operator. The HEI methods are also used within human reliability analysis and focuses on predicting and analysing human latent errors by the deep understanding of tasks done within maintenance or manufacturing and prioritising the main faults that may be occurring or for general assessment of those latent error (Cheng, Hwang and Lin, 2013). HEI can be used along HFACS or human reliability analysis techniques like HEART, SHERPA and TRACEr. However, the traditional HEI method does not allow for cost assessment and does not contribute to the ways of reduction of human errors in industrial operations (Aju Kumar and Gandhi, 2011). In addition, HEI method have two types: A quantitative and qualitative approach (Cheng et al., 2013). The quantitative approach deals with assigninmg numerical values for the probabilties of human errors (usuually integrated with HEART) and the qualtititave approach usually deals with error mode classifications in order to analyse an application or activity where human errors usually exists repetitvly.

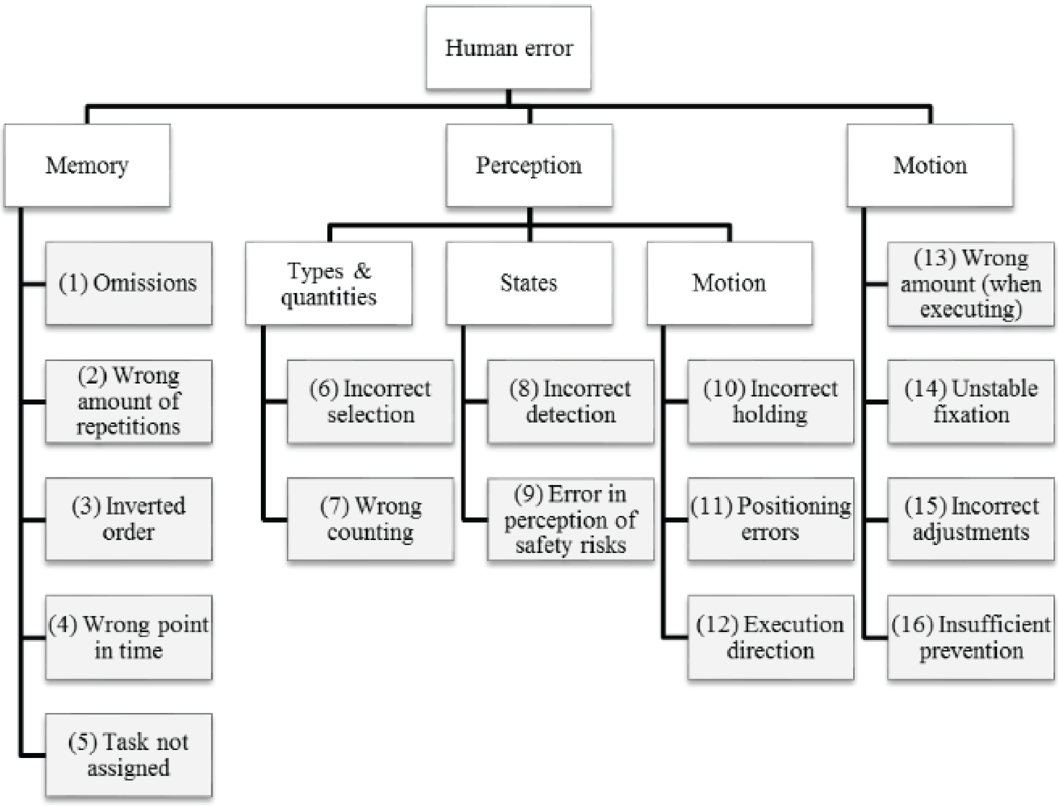

Figure 5 Human errors classifications according to Böllhoff, et al. (2016)

3.2 Maintainability and Human Errors

This section handles different aspects of human errors in maintenance, along with definition of some reliability methods and techniques. Also, aviation and marine operation maintenance tasks is defined.

3.2.1 Maintenance Tasks Overview

The act of performing corrections and repairing on the level of interval of times is what is called maintenance and the efforts done in doing this action can actually extend life of machines and equipment (Dhillon and Liu, 2006). Maintenance tasks are classified into periodic and non-periodic maintenance because the quantity of maintenance tasks within operations are much higher than the base control configurations (Heo and Park, 2010). Moreover, maintenance is defined as the series of physical actions to restore something to its original phase of functioning and perform satisfactory operation and a specific function. There are few types of maintenance described in the literature.
According to Dhillon and Liu (2006) , Desai and Mital, (2011), maintenance is categorized into three type:
‘

- Preventive maintenance: It is the type of maintenance that projects a planned rather depends on time intervals actions of reconditioning and checking to maintain a machine or equipment functioning correctly.
- Corrective maintenance: This kind of maintenance is done when operators and item users remark a possible defect or failure in a machine which lead to an unplanned maintenance action.
- Predictive maintenance: It is applied upon scanning and diagnosing machines within range of operation by using up-to-date measurement techniques.

In addition, activities within maintenance in a given industry depends directly on the types of machines and the type of the industry, and those activities are generally constrained in the actions of measurement, diagnosing, inspection and upgrading/replacement (Aju Kumar and Gandhi, 2011). One more type of maintenance is explained by Safaei (2021) which is premature maintenance. This type of maintenance proposes an early execution of maintenance before the planned time so the time between the early assessment and the schedule one is called task interval.

3.2.2 Human Error in Maintenance

Efforts concerning how to analyse the causes of human errors in maintenance is done by Morag, et al. (2018) where the author identified a focal factor through four main types of descriptive analysis. Those types discuss failure factors in relation with most repeated errors, link between the type of errors and the kind of shift (day or night), relations with special maintenance activities and duration of effective productivity between time of failures. However, human errors in maintenance is defined as the lack of success of performing a specific maintenance task or not following standardized procedures to comply a maintenance task which could lead to failure or damage of machines (McDonnell *et al.*, 2018). (Aju Kumar and Gandhi, 2011) and (Latorella, Prabhu and Pen, 2000) reviewed the types of maintenance errors followed by definitions which are also resembled in human errors in industrial operations whereas the type of the error depends directly on what kind of maintenance tasks are to be performed and how the maintenance technicians tend to perform them. Theoretically, those maintenance tasks tend to be routine or non-routine. Moreover, types of human errors within maintenance can be classified as mistake or faults that does not appear on the surface and in the most cases hidden and cannot be detected when applying maintainability or mistaken tasks like wrong adaptations (McDonnell *et al.*, 2018).

According to Aju Kumar and Gandhi (2011) the type of human errors within maintenance are classified as following:

- Slip: It is the unsuccessful adaptation of more common actions but without clear intentions like the improper installations of parts, over tension or minimal tension when torquing bolts etc…
- Lapse: Not enough amount of focus and attention when performing a specific task like forgetting and loss of memory.
- Rule-based error: It is the improper following of rules and standards which may be related to routine work or upon the conduction of fault decisions in more familiar conditions like failure to make checking procedures.
- Knowledge based error: Errors that are resulted from not following general rules and involve logical reasoning instead of abiding to standards.
- Perceptual error: It is when a maintenance technician perceives fail notes or information that builds up to decision making like misinterpretations or the inability to acknowledge specific fault patterns.
- Routine violation: Errors due to the divergence from typical standards and procedures and can be resulted due to lack of clear directions from supervisors or due to the intention to save time because the procedures are too strict.
- Situational violation: It is errors resulted due to stress and overwork or unstable work conditions like lack of staff, old and outdated tools.
- Exceptional violation: It is a huge deviation from procedures which could result in dangerous risks just for gaining advantage of something else.

It is also important to list out which industries are more subjected to human errors within maintenance operation as Sheikhalishahi (2016) that most of the errors happens in the aviation industry and more less errors happen in chemical processing power plants and nuclear industries, but this is also related to the frequency of subjects in relation with the literature so that more distributions are presented in figure 5.

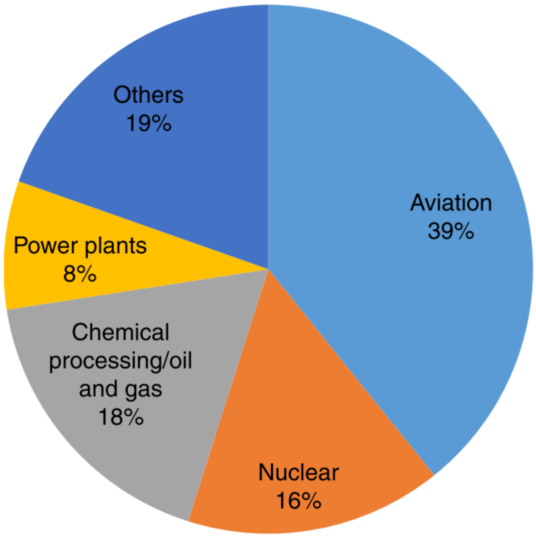

Figure 5 Human error percentages in relation with publications (Sheikhalishahi, 2016)

According to Heo and Park (2010), where the authors talked in depth maintenance related errors that are related to human, it also important to differentiate between the errors that are resulted from operating personal and maintenance technicians where is also important to note that more errors are being resembled by humans and not by mechanical malfunctions. So, in order to approach any maintenance problem that is obtained in relation to mankind, it is recommended to have better strategies in gathering the required data by the technicians and the operators (Kumar *et al.*, 2013).

3.3 Human Reliability and Maintenance Performance

In order to control the performance of maintenance there must be some maintenance performance measurement metrics to help in facilitating the root causes of human errors that occur in maintenance. The goal behind measuring maintenance human factors is to gain a leading advantage in predicting the possible errors and in that way not only maintenance performance will be improved, but also human productivity will be enhanced (Peach and Visser, 2020). However, since maintenance have a logistic departmental role, its effectiveness and efficiency is rather hard to measure in simple terms and in the most cases it is measured in terms of technical, organizational and economic ratio terms (Simões, Gomes and Yasin, 2011). That being said, as the measurement tools are used to decide if the function behind maintenance is acceptable and not only on an individual level, but the latter also discusses the relation between human factors as in teamwork (Peach and Visser, 2020). Moreover, upon analysing human errors in maintenance few concepts must be kept in mind like approaches about health and safety, training, psychological effects, working conditions and reliability analysis of machines. Also, more areas must be taken into consideration in order to extract the causes of human errors like the machines, facilities involved, materials and supplies and expertise (Kovacevic *et al.*, 2016). Two terms of psychology can be identified which are the individual psychology that can be what kind of tendencies and character a human have and the process psychology which is perception of human psychology toward a dynamic process. The individual psychology refers to the level of motivation, interest and abilities a human have (Wenwen *et al.*, 2011).

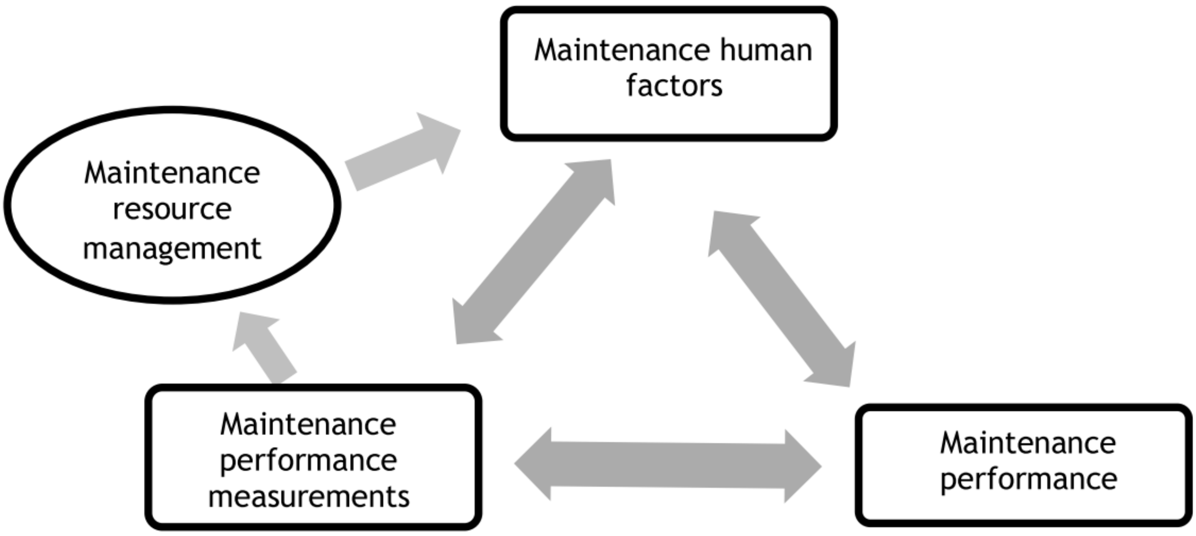

Figure 6 Relationship between maintenance human factors and performance according to Peach and Visser (2020)

Historically, the performance of human in a working cell was measured by the meaning of human error analysis where two strategies were used. The first strategy was what is called a first generation method which is called THERP and the measurements shifted in a second stage to what is called ATHEANA but this shift was due to the fact that the concepts of maintenance is changing by the day (Asadzadeh and Azadeh, 2014; Yang, et al. 2007). However, the performance metrics are not used to point that maintenance workers or operators are not doing their job or to conclude that there is no productivity in the work but the performance metrics and methods of measurements list out sides of improvements that would improve the overall efficiency (Kumar *et al.*, 2013). In addition, the shift in using performance measurements was due to the fact in the past the focus was drawn towards human insufficiencies and the characteristics of maintenance tasks but now, maintenance departments are also studying the overall environment and working conditions of the working site whereas human error analysing discusses those parameters instead of studying human (Asadzadeh and Azadeh, 2014). The environmental factors (except for the internal factors such as temperature, noise, light intensity or humidity etc…) can be external like difficulties in medication, food prices or education and family environmental factors (Wenwen *et al.*, 2011).

3.3.1 Human Error Probability and Human Reliability analysis (HEP & HRA)

In the area of human reliability analysis, human error probability is the section that handles human performance in a sense of empirical data. Human reliability analysis basically talks about three sections which are, human actions identification, human activity modelling and HEP(Islam *et al.*, 2020). That being said, HEP is defined as the calculated probability of a piece of work being wrongly accomplished in a well-known period of time and in a sense of relative frequency (Di Pasquale et al., 2016). Moreover, methods and techniques used upon calculation those probabilities related to human performance have to be close to accuracy where the miscalculations or underrating would lead to hazardous setbacks (Abbassi *et al.*, 2015). Other model of reliability begins with the presumption that errors happen at random, that they all have the same significance and implications for system efficiency, and that errors can be completely extracted from the origin and directed toward the main influence (Dragan and Isaic-maniu, 2014). According to McDonnell, et al. (2018) and Abbassi, et al. (2015) there are several methods in order to make a probabilistic assessment concerning human errors and are summarized in the following headlines.

- Technique for human error rate prediction (THERP)
- Human error assessment and reduction technique (HEART)
- Standardized plant analysis risk human reliability analysis (SPAR-H)
- Technique for the retrospective and predictive analysis of cognitive error (TRACEr)
- Absolute probability judgment (APJ)
- Success likelihood index method (SLIM)
- Paired comparison (PC)
- Systemic human action reliability procedure (SHARP)
- Shipboard operation human reliability analysis (SOHRA)
- Cognitive reliability and error analysis method (CREAM)

In addition, within human error assessment, not all techniques handle the calculation of error probability as some of the method concerns the identification of most repeated errors (Torres, Nadeau and Landau, 2021). In the context of calculating HEP which results in a systematic quantification of human error parameters like performance shaping factors (PSF) must be defined beforehand. According to Kim and Park (2012) the determination of the shaping factors is connected to the modes of errors where the writer described some error modes that would help upon the selection of PSFs like wrong object or action, too little and omission which will be explained in later sections. PSFs are defined as the effect of human overall executions where chiefs and managers can list out them according to specific maintenance activities and the environment where the operators and technicians work in (Islam *et al.*, 2017). Kandemir and Celik (2021) stated the identification of PSFs is a part of HEP calculation where in some methods like THERP, the performance factors are identified in a form of dependence models and in the method of SLIM, PSFs are combined into an index having a single value. It is also important to mention the variables that can control the quality of PSFs so that according to Islam, et al. (2017) the shaping factors are considered an aspect of an operator/technician characteristics, work environment, organization view and task nature that would influence human performance. Moreover on human reliability analysis, researches identified different terminologies connected to HRA like Time cantered HRA where the operators within maintenance departments are asked to work for a longer period of time without stopping/pausing or upon configuration of new equipment (Bao *et al.*, 2018). Other types are stated by the researcher such as process cantered HRA which is identified as analysing human errors within tasks that consists of multiple steps and procedures where the operators and technicians perform in a more of a systematic approach and this is unlike the emergency HRA which analysis is done upon a sudden failure or power shortage in each system or maintenance tasks. Also, in the efforts of simplification, an equation of calculation HEP is demonstrated by Di Pasquale, et al. (2016) and Böllhoff, et al. (2016) having the following form:

$$HEP = \frac{Number\ of\ the\ percieved\ error}{Possabilities\ numbers\ for\ an\ error}$$

So that the deduction of human reliability or human reliability probability (HRP) is given as following:

$$HRP = 1 - HEP$$

According to Di Pasquale, et al. (2016), where the author described a specific methodology for HEP estimation in manufacturing systems, HEP methods like those that are related to time and process cantered reliability analysis are not always used in the same way and there is no single method that is used every time for probability estimation but, different methods are used depending on application like those that are used in aircraft, marine operations, manufacturing and oil and gas companies. (Torres et al., 2021) explained two methodologies or approaches for human reliability in assembly operations which are the traditional HRA techniques and what is called context specific techniques following by a methodology for HRA that consists of selection of critical duties where the managers study the most tasks that are subjected to human error then a task description is performed to study the work procedures together with some operators. After that identification of human errors is performed using HRA techniques and lastly quantification is done which consists of selecting PSFs and calculating error probabilities. Another methodology for HRA implementation is stated by Di Pasquale, el al. (2016) the methodology begins with data collection which can be the most complex task consisting of selecting PSFs and calculating experimental HEP using the first equation described above in an hourly basis followed by task identification and designing theoretical estimation of HEP with the of Weibull distribution method and lastly calculating error probabilities where the significance of this method is that is shows the difference between experimental and theoretical calculation of HEP.

Moreover, other models of reliability are mentioned by Dragan and Isaic-Maniu (2014) which differs from the original tools of human reliability assessment. Those type of reliability models are rather old deals with a time-domain class that is founded on the concept of tying the human element to structure reliability, as opposed to a data-domain class that takes the errors content as its main object. Other researchers

3.3.2 Performance Shaping Factors

According to Islam, et al. (2017), PSFs are important in order to estimate HEP and not all the shaping factors weigh equally as upon selecting PSFs, weighting also should be distributed according to the importance of the PSF in a maintenance activity as well as proper rating should be given to differentiate every PSF. Another name for PSF found in the literature as some researchers described them as error producing conditions (EPC) and this name is used in HEART technique for calculating HEP (Noroozi, Khan, *et al.*, 2014). An example of PSFs is reviewed by Hameed, et al. (2016) and Abbassi, et al. (2015) where the authors explained an external view of PSFs consisting of procedures, Woking hours, environment, tools used, supplies, breaks etc… and the other term is the internal PSFs consisting of training, experience, skills used, stress and physical conditions.

Moreover, the selection of PSFs is done in 4 stages beginning with the analysis of human actions in maintenance tasks, then checking previous literature to discover maintenance related PSFs, then the evaluation of human error prevention methods and lastly the combination of all PSFs gained upon realizing human error in the first three stages (Kim and Park, 2012). As for calculating PSF, there is no single equation to calculate weight/rating/value of a PSF because every factor is unique by itself and has multiple effects on other factors which make it hard to draw out an equation which can resemble the relation between all the factors (Abbassi *et al.*, 2015). Instead of a straightforward equation, modification factors can be added and multiplied by the nominal HEP deduction. In addition to external and internal PSFs, one type can be added which is the stressors like physical and mental condition of the operators as hunger/thirst, radiation, stress load, fatigue and high risk but the absence of stress does not mean perfection it can also lead to carelessness and procrastination such that a reasonable amount of stress should be added in order to have a good performance.

Due to the connection between error modes and performance shaping factors, PSFs are derived with respect to the error modes by Kim and Park (2012) and reviewed in the following list:

- PSFs for wrong object error mode are extracted by the method of root cause analysis where 10 PSFs are identified mainly in the areas of human engineering, communication, management, training and experience. Some of the PSFs are lack of supervision, lack of standardization and procedures, unavailability of object labelling, or naming, testing and first-time installation are done by the supervisors rather than the operators, level of illumination in each workplace etc…
- PSFs for wrong action error mode are selected by the help of the method of event analysis. Wrong action within a maintenance task is described as misusing tools that do not fit tasks and the possible PSFs are lack of full insights and formality in a workplace, tightness and not enough room in the workspace, closeness of the tools and the way the operators used the tools.
- Omission error mode consists of three main types. According to the method of error mode analysis omission can be resulted in preparatory work beforehand which means the neglection of an important action like testing. The second type is omission within the actions of reconditioning which means low success rates in restoring system to its normal

state after failure of testing tasks. Lastly, the inability of realizing abnormality in a specific system especially within the parts in the equipment which cannot be easily visible. PSFs within omission error modes are related to the unavailability of training or experience mainly in corrective maintenance tasks, not enough information, long work hours and stress/fatigue, failures due to lack of attention, lack of verification and validation.

- In the ‘too little’ error mode, the errors are mainly resembled in the form of not adding the required effort from the workers towards completing a specific task or putting too much effort. Common PSF can be lack of training and experience but there are no direct causes to this error mode. All the PSFs in `´too little´´ error mode is cantered around the weak evaluation of work tasks ahead of time. Some of the PSFs deals with no validation concerning task performance, weakness in work potential, lack of familiarity and lack of supervision.

The distribution and selection of PSFs is directly related to the industry where maintenance is performed, and most industries found in the literature are aviation, marine operations and O&G/petroleum companies. In other industries, that are characterized by having higher safety factors like aircraft industry PSFs sum up most of the human errors where more awareness programs are recommended but perhaps the most factor that is affecting the human performance is the mental workload. (Liang *et al.*, 2010). Yet in another article, the most repeatable performance factor that is connected to human errors in aircraft industry is the work environment which can be illustrated in the weather, level of lighting, workspace, location, sound level and noise but, on an organizational level other factors play a huge role in performance of human in aircraft industry like supervision, morals, pressures and size of the enterprise (Barbosa, Tiburtino and Carvalho, 2017). Other researchers like (Wang and Chuang, 2014) and (Chatzi *et al.*, 2019) talked about the importance of psychological factor and communication in the human performance within maintenance in aviation industry. Moreover, in oil and gas industries the error producing conditions are divided to four categories: cognitive, management, physical and instrumentation. In this context more PSFs that talk about responsibility distribution are selected (Noroozi et al., 2014).

3.3.3 Human Error Assessment and Reduction Technique (HEART)

HEART is one of the common methods to evaluate human error probability on the basis of a specific task requirements and based on risk equations, reliability and ergonomics which have the strongest effects on a given system performance (Noroozi, Khan, *et al.*, 2014). According to Torres et al. (2021) and Bowo and Furosho (2018), in the efforts of human error quantification, HEART methodology has three main components. The first component is the specification of generic task type (GTT) where the analyst should match HEART´s generic task type with the task object of analysis followed by the determination of nominal values for HEP in relation with GTT. The second component is the realization of PSFs which are called EPC in the HEART method and they act as moderation weights for the nominal probabilities. The third component is the calculation section which take into consideration the evaluation of PSFs weights and list them out according to their importance and weights in the studied task to obtain a third factor which is known for an assessed proportion for the EPCs. In this method the EPCs are acknowledged on the basis of experimental data based on human execution (Abbassi *et al.*, 2015). Usually, the number of EPCs ranges from 38 to 40 but, GTTs do not have a specific number as it depends on task condition and complexity (Kandemir *et al.*, 2019). In different case studies, HEART methodology is not the only way to represent HEP but it is implemented with other techniques like SOHRA in the terms of identification of human error and EPCs where the main difference is the EPCs modification (Kandemir and Celik, 2021). However, in HEART methodology the determination of the performance factors is dependent on the operators relation with the tasks and subtasks where every subtask is considered as a single scenario to be studied for proper utilization (Noroozi, Abbassi, *et al.*, 2014).

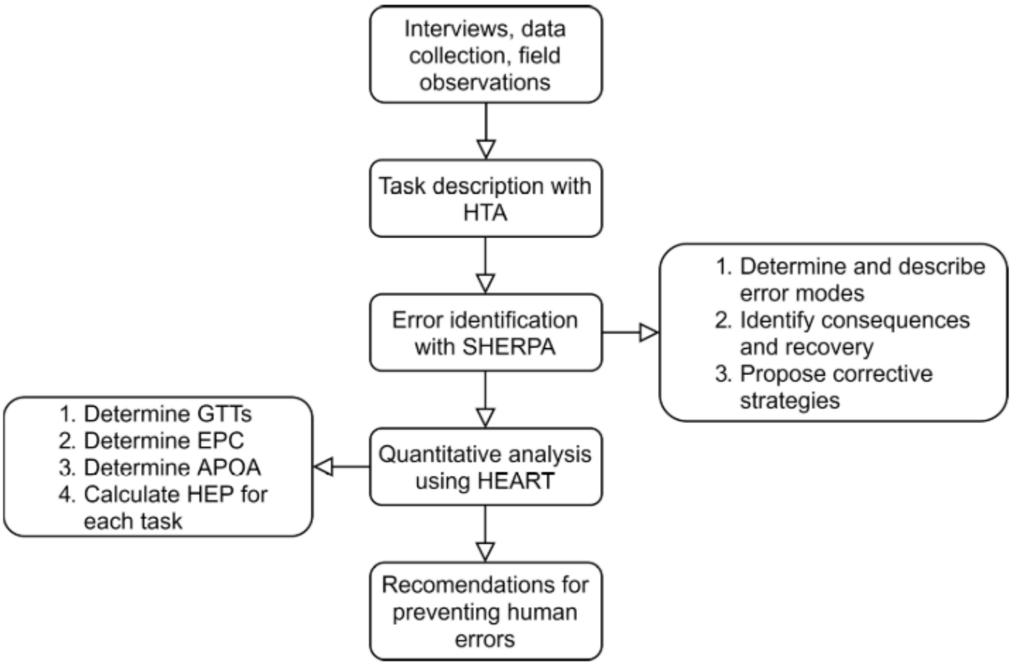

Figure 7 HEP Calculation methodology integrated with HEART and SHERPA Techniques (Torres, et al. 2021)

Moreover, HEART methodology is dependent on experts' opinions especially upon implementation and this would lead to involvement of people with higher experience in results discussion (Kazmi *et al.*, 2017).

3.3.4 Technique for Human Error Rate Prediction (THERP)

The method of human error prediction deals with human error identification, task description and HEP quantification where the PSFs are identified through dependency models and probability trees (Kandemir and Celik, 2021; Boring, 2012). Historically, THERP was used in the domain of nuclear plants as it is a foundational method, originally created within the first-generation methods for error detection and quantification (Voronov and Alzbutas, 2010). In this technique, the tasks are divided to levels and the nominal HEP for each task level is deducted referring to THERP handbook which is also modified regarding to the impacts of PSFs (Abbassi *et al.*, 2015). According to Shirley, et al. (2015) and Whaley et al., (2007), THERP handbook include all the types of human errors represented in tables and including HEPs for every error type. The values of HEPs are extracted from several literature and according to experts. Although the use of this method is known for errors probabilities calculation, but it is also used to evaluate the effects of human errors on an entire human machine system and the use of the probability trees is to demonstrate the importance of decisions, showing wrong and right alternatives (Böllhoff *et al.*, 2016 ; Dhillon, 2014).

In addition, the basis of this method is built on root cause analysis method (RCA) such that Rooney and Heuvel (2004); Williams (2001) explained that the method of root cause analysis is basically made up of 4 steps. The first step is the data collection, where most of the time is spent in this step as the quality of causes collected depended on the data extracted in the beginning. The second step done is the charting of casual factors where the investigators analyse the data collected to find out gaps and decencies. The third step is to identify the root cause which involves methods like 5 whys or decision diagrams. The last step is not directly related to root cause analysis where the investigators contribute general recommendation based on the causes found.

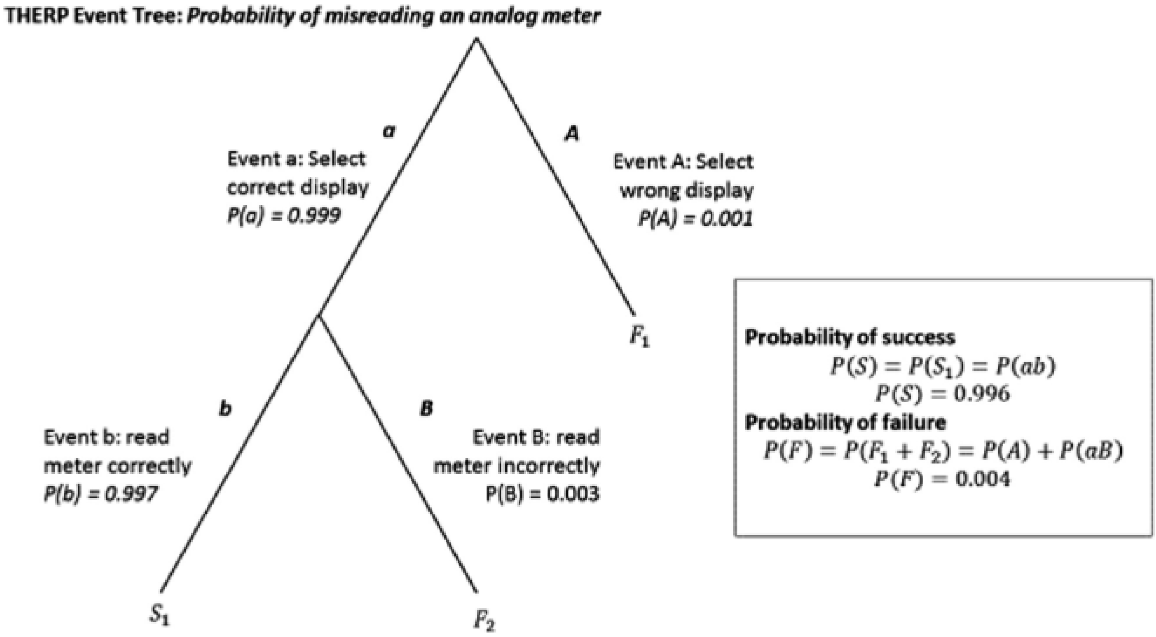

Figure 8 An example of a probability tree used in THERP technique (Shirly et al., 2015)

According to Abbassi, et al. (2015), THERP handbook contains four different levels of stresses which also are related to PSFs selection and cantered around task workload (low, optimum, heavy and threating). Speaking of PSFs, THERP handles three important PSFs: stress levels, tagging system and expertise. Along with the four stress levels, two additional experience levels are covered in this technique and mainly used in maintenance operations, step by step procedures and routines. However, unlike the step-by-step procedures, dynamic scenario and its application does not have to be a part of the validation process. Consequently, tagging PSFs does not have to validated since they are outside of the control room and cannot be controlled leaving the levels of stress and experience as the only factors of validation (Shirley *et al.*, 2015).

3.3.5 Success Likelihood Index Method (SLIM)

One of the most flexible methods for HEP calculation is SLIM as it used for professional judgment in which experts starts with the identification of performance factors and then make an overall judgment to assign weight for PSFs chosen (Abbassi *et al.*, 2015). Originally, the SLIM method was designed for human reliability analysis , but in another development stages, the method can be used in probabilistic reliability analysis. (Park and Lee, 2008) and (Abrishami *et al.*, 2020) have stated the stages for proper SLIM implementation for HEP calculation consisting of seven steps for execution:

- Performance shaping factors derivation.
- Ranking the PSFs based on importance.
- Weighting PSFs by the means of special judgmental actions where the most important PSFs are given highest values.

- Task rating relevant to PSFs selected also by judgment and assigning 0 and 1 for worst and best conditions.
- Success likelihood indexes computation (SLI) by multiplication of PSFs weights to rating (Summation of all PSFs weights/ratings)
- SLI conversion to HEP using a calibration equation: log (HEP) = a*SLI +b, where a and b are constants in the equation
- Judgment consistency calculation along with uncertainty parameters

According to Asadzadeh & Azadeh (2014) the method of SLIM is not only limited in the calculation of HEP in maintenance activities but it is also an important technique used in offshore process facilities. In contradiction, the use of SLIM in marine operation is not advisable because the manager need to follow a step by step procedure for HEP calculation which can take longer times (Islam *et al.*, 2017).

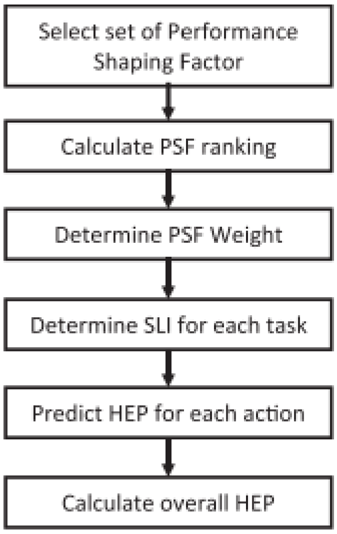

Figure 9 SLIM methodology overview according to Hameed, et al. (2016)

Moreover, the results of SLIM are commonly used for future improvements and the analysis opens the possibilities for contributing recommendation for error elimination and making sure fault actions are not repeated (Santiasih and Ratriwardhani, 2021).

3.4 Aviation Maintenance and Operations

Maintenance practices within aviation cannot be performed only by the help of technology as the use of technology in aircraft applications draws more responsibility in considering safety manners (Rashid, Place and Braithwaite, 2013). Technicians in aircraft maintenance face more hard moments of unreliability upon working with maintenance tasks such unclear gaudiness of what is wrong and what is right in order to finalize a job, lack of data and even more stressful situation like completing a maintenance task at the same time the passengers are boarding. According to Chatzi et al. (2019), among other human factors, communication was the biggest reason to catastrophic accidents in aircraft industry but, in such industry, communication is referred to as the actions of documentations and procedures where written communication is more subjected to faults than oral communication in maintenance activities and this usually because explanations and simplification are easier to gain which make it also simpler to detect human errors. However, the main aim behind maintainability in aviation maintenance is to

increase safety levels and proper restoration of aircrafts to acceptable conditions. This is being said, as preventive maintenance performed in aviation is not enough to meet the system overall reliability but on contrary overdoing those maintenance activities can result in more undesired human errors (Barbosa, Tiburtino and Carvalho, 2017).
In a study of risk identification resulted from aircraft industry, (Kucuk Yilmaz, 2019) identified a risk assessment method for human related risk factors in aviation maintenance. This risk assessment is kind of like human reliability analysis that have been covered in earlier sections where the overall aim is the systematic evaluation of risks within operation such that those in maintenance. The approaches can be qualitative which is based in expert's judgment or quantitative where the risk proportions are measured for hazardous events. Qualitative risk assessment process for aircraft maintenance is outlined in the following steps:

- Recognition of risk related to human with respect aircraft maintenance technicians: Those risks have on impact on human and the system which can be recognized from the literature or with the help of maintenance experts in aircraft.
- Categorization of the identified risks factors in the order of a hierarchical structure: Groups are formed containing a set of uncontrolled and controlled risks.
- Human risk factors probabilities identification: The probabilities in which a flight faces a misfortune is identified and the likelihoods are classified based on five levels (very improbable, improbable, frequent, remote and occasional).
- Impact assessment of the human risk factors: In this step, evaluation should be made taking into consideration all worst anticipated scenarios where the cases can be minor, major, dangerous, catastrophic or negligible.
- Human risk assessment matrix definition: The matrix methodology blends qualitative and quantitative probabilities ratings.
- Prioritization of human risk factors: This step is a part of the evaluation process where it separates what risks matter form those that are less important.
- Risk inter-relationships evaluation: Since risks does not appear independently, this step manages to evaluate risk interactions. Usually, the organization make description or visual presentation of the influence of risks on each other.
- Human risk mapping definition: This is last step in the risk assessment as mapping allow to establish different improvement potentials and help in understand the relationship between the tasks and the method outcomes.

In an article of economic assessment of human error costs, instead of being a stand-alone management method for addressing human error issues, the human error cost estimation tool is intended to work in combination with a company's risk assessment and management program (Liu, Hwang and Liu, 2009). This cost estimation tool consists of three stages which begins with identifying important human error cost factors, then observing the behaviour of those important costs and at last calculation of the costs.
In earlier sections, premature maintenance was defined as the early assessment of maintenance activities where time between the scheduled and actual time of applying a maintenance task is task interval but in aircraft industry the measurement of this gap is done by using factors like flight hours and time calendar (Safaei, 2021). In general, maintenance crews in aviation are divided into two groups. The first group is the set of technicians that work at the hangar and responsible for performing routine maintenance activities like engine overhauls and check-ups and the second group are those that work on the airport flight line. The second group are more responsible for doing pre-traveling checks, inspection, transit and overnight checks and they usually work on the basis of 24 h to ensure on demand service (Wang and Chuang, 2014).

In addition, (Rashid, Place and Braithwaite, 2014) defined a new concept of aviation maintenance monitoring process (AMMP) where the industry stakeholders and manufacturers implement this software by using the company`s data on maintenance . This main aim of this method is to monitor the probability of existing human error factors that occur in different process like design, manufacturing or within the working conditions. In the same sense, by using this method analysts were able to define two sets of factors resulting maintenance errors: main casual factors and organizational processes subfactors.

According to Rashid, et al. (2013), aviation maintenance tasks are more dangerous than other maintenance roles in other industries that is because the safety factors are much higher and the tasks must be performed in worse conditions like high altitude locations, tight spaces, high or low temperatures and open or closed workplaces. However, it is not the physical activities that are more critical in maintenance tasks but, it is the preliminary and the technical documentary.

Maintenance errors	Narration	Frequency (based on two years)
Inspection error	• Not Deactivated or reactivated equipment/system	1
	• Untraceable by inspection	2
Installation error	• Parts are not installed	2
	• Fault part installed	1
	• Wrong direction	1
	• Incomplete installation	4
	• Not closed access	1
	• Damaged on installation	1
Personal wound error	• Bashed by or against	1
Aircraft damage error	• Misuse of tools and materials	5
Uncommon object damage error	• Parts re left on airplane or engine	1

Table 1 Common maintenance errors in aviation based on a study by Liang, et al. (2009)

Also, in the efforts of identifying maintenance error related to human factor in aviation, Human Factor Analysis and Classification System (HFACS) is used where it defines human error in aircraft maintenance and divide accident into four categories which are unclear supervision, unsafe acts in preconditions and operators and organizational effects (Chiu and Hsieh, 2016).

Moreover, maintenance errors in aviation can happen in the earlier stages upon developing the maintenance plans and procedures like in the inspection stages where maintenance acts an important role in general aviation (Marais and Robichaud, 2012). The errors of aircraft maintenance generally can be incorrect installation, damaged parts, injury to workers and tools left behind (Usanmaz, 2011). In addition, according to Rashid, et al. (2013) one critical aspect to think of within maintenance procedures is the activities of communication and coordination and this is due to the long distance between the workplaces and the controlling rooms higher levels of noise and heat. In a study of maintenance errors in aviation done by Chiu and Hsieh (2016), the author stated that there are two sets of errors that happen in aircraft maintenance: Active human error which led to direct occurrence of accidents and latent errors which could lead to an indirect occurrence of accidents. Those active errors have to do with the operators where latent errors does not appear on the surface.

3.5 Maintenance in Marine Operations

Crafts performing at the sea are subjected to huge losses because maintenance alternatives and repair are limited so that most of the accidents that happen in the engine room are related to human errors (Kandemir and Celik, 2021). According to Islam, et al. (2017), there are two type of maintenance activities done in marine operations: preventive and planned maintenance. Within preventive maintenance in ships, most of the activities are centred around the parts of marine engines such like lubrication and cooling system, fuel injectors, pumps, valve drive mechanism and exhaust system. Moreover, Kandemir and Celik (2021) identified the roles and responsibilities of the ship crew that consists of two parts: crew on the deck and crew in the engine room. Those technicians that are responsible of duties on the ship deck generally have more work on the navigation of the ship, whilst technicians that work ion the engine room are responsible for maintenance of different parts in the engine room. In another study, Kandemir and Celik (2020) identified planned maintenance in marine operations as the actions of performing check-ups based on time schedules for preventing accidents so that this check-up must be performed even if there is no anticipated failure.
In a study done by Islam, et al. (2017), maintenance activities that happens in a high-pressure fuel pump that contributes to most failures are identified:

- Fuel injectors inspection for leaks and renewing nozzles every 4000 hour.
- Changing of the inner parts found in the injector holder.
- Cavitation and sealings inspection.
- Following up with fuel injection timing.
- Springs and plunger check-up.
- Cleaning and renewing fuel pipes.
- Changing the whole pump or overhauling pump elements.

3.6 Human and Industry 4.0

The threats to current cyber-physical systems are dominated by human actions. In Industry 4.0, human hazardous actions and mistakes can be the proximal causes of an accident, resulting in distribution delays, product errors, extra costs, or even industrial accidents (Angelopoulou, Mykoniatis and Reddy, 2020). The technologies of industry 4.0 have new ways to reduce the number of human mistakes committed by technicians and maintenance personnel. However, there may be certain difficulties, and these systems may have weaknesses in their ability to deter people from performing poorly (Salonen, 2019).

The introduction of industry 4.0 technologies (big data analysis, robots, IoT, AR etc…) made the systems more reliable and increased the dependability of approaching them, but this means that with this kind of increased reliability, the efforts in educating and increasing the skills of the operators is reduced (Baxter et al., 2012). Consequently, the abilities of the operator in problem solving will decrease. Moreover, since industry 4,0 technologies made the process faster, the operator have limited chances for interference in the process.

According to Gorecky et al., (2014), the user interface between cyber-physical system and the operator is known as a conjunction element in which it provides the worker enough insights about industry 4.0 and CPS and allow easiness of using such systems. The author mentioned that there are requirements for this user interface as following:

- A growing number of automation systems components are gaining mechatronic capabilities that can be parameterized and tracked, necessitating the development of a user interface. Rather than outfitting single CPSs with proprietary control panels, potential connectivity to a plethora of various modules and pages would be accomplished by a web user interface.
- The number of different types of automation technology components that need to be mapped is growing all the time. As a result, the device sophistication that the worker must struggle with is increasing.
- Due to the extreme widespread delivery and transmission of automation technology products, as well as the widespread use of wireless communication, it is becoming increasingly important to monitor component positions and expose them to staff.
- Around the same time, employee agility as a versatile problem solver is becoming more prevalent in Industry 4.0. The location of the worker must also be monitored in order to give them proper up-to-date information on-site and when required.

Industry 4.0 addresses the execution and use of innovation that is exchanging current manufacturing cycles, expecting to upgrade and improve them (Angelopoulou, Mykoniatis and Reddy, 2020). As most of literature discusses the concept of industry 4.0 in terms of technological enhancements and gadgets neglecting an important factor which is the human. Lately, with the improvement of computerized advances, which will lead us to the fourth modern industry, "Industry 4.0", the chance of applying trend setting innovations for productive learning and preparing of laborers in assembling frameworks has expanded (Enrique et al., 2021). Nonetheless, considering that assembling adaptability cannot be advanced just by purchasing new and more refined advances. All things considered, supervisors need to guarantee a climate that urges representatives to persistently look for new answers for complete their work and stay up with the latest.

Within the era of industry 4.0, the operator has changed from operator 1.0 to operator 4.0 such that operator 1.0 was defined as a human who is responsible for manual work with the help of mechanical tools. The introduction of computer systems and tools have upgraded to operator 2.0 then operator 3.0 accomplished combined work with collaborative robots and the relation is known for human robot collaboration. Currently most of the literature is discussing operator 4.0 which is the future operator basically enhanced physically and also with the help of sensor and other capabilities to become smarter and more skilled (Madonna *et al.*, 2019). The relationship between industry 4.0 evolution and operator is presented in figure 11. Moreover, on operator 4.0, there are more definitions that combines human with technologies like augmented reality, robots and big data analysis. (Romero *et al.*, 2016) illustrated several concepts of operator 4,0 which are represented in figure 12.

Within the applications of industry 4.0, the concept of maintenance 4.0 is identified as it is about forecasting potential asset failures and eventually recommending the most appropriate preventive measure by using sophisticated predictive techniques on big data about technological status, use, climate, and maintenance background, which can correlate with an asset's efficiency Jasiulewicz et al., (2019). According to Cachada et al., (2018), currently, factory maintenance is mostly reactive and defensive, with predictive strategies being used only in emergency situations. Traditionally, these maintenance techniques have failed to consider the massive volume of data produced on the production floor, as well as emerging Information and Communications Technology (ICT), such as the Internet of Things (IoT), Big data, and analytical tools. In addition, for maintenance 4.0 to work in an industry 4.0 context some minimal criteria are required as according to Najjar et al., (2018).

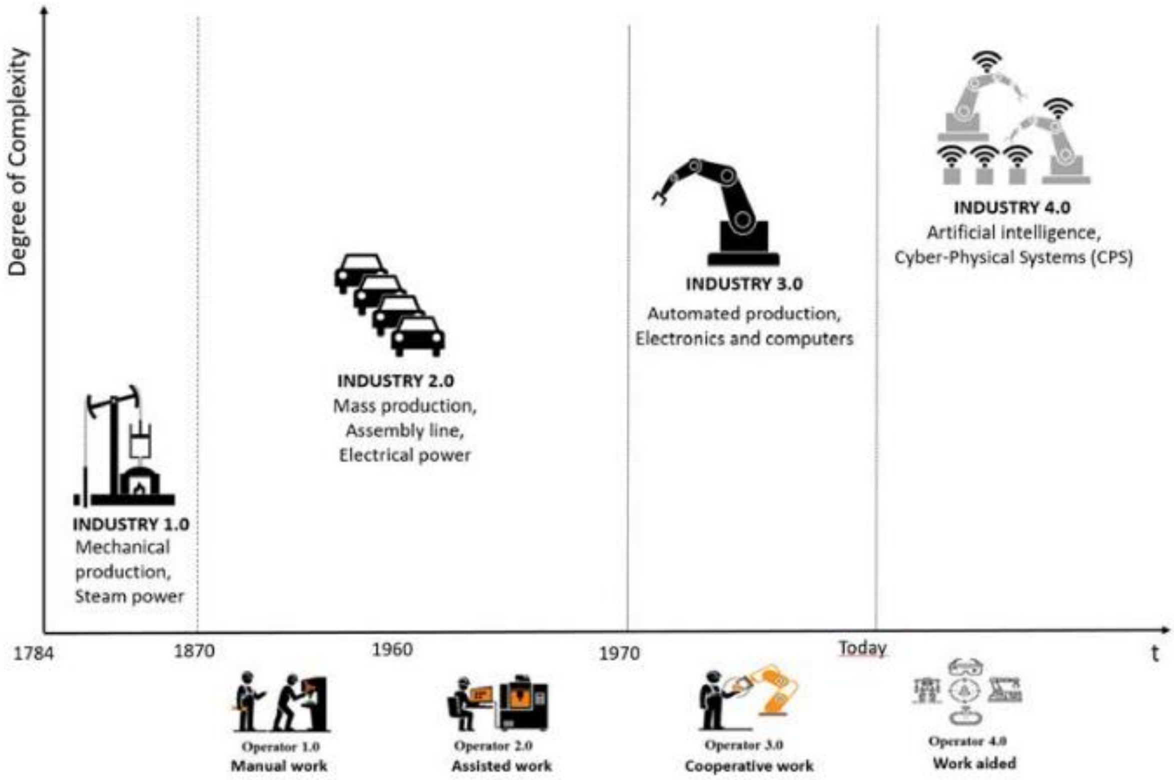

Figure 10 Evolution of operator with respect to industry 4.0 (Madonna et al., 2019).

Within industry 4,0, one of the ways of anticipating human error probabilities is the modelling and simulation model (M&S) such that human hazardous demonstrations and blunders might be proximal reasons for a mishap in Industry 4.0, prompting conveyance delays, item mistakes, overabundance cost, or even mechanical mishaps (Angelopoulou, Mykoniatis and Reddy, 2020). The simulation model presented by the author uses a system dynamic model containing different performance and criteria parameters in order to calculate HEP. According to Enrique, et al. (2021) and Valentina, et al. (2021) the labour flexibility within the context of industry 4.0 is defined as the increase of number of tasks an operator can make and the technologies that can aid the operator for human error minimizations are as follows:

- Augmented Reality: is characterized as a human-PC collaboration device that overlays computerized data climate continuously.
- Virtual Reality: is a human-computer interface that permits reproducing various conditions through a computational interface continuously and numerous tangible channels, permitting client association with these conditions.
- Collaborative robots (Cobots): A robot is a pretended element, either virtual or mechanical, that it is for the most part characterized as an electromagnetic framework

that, because of its actual appearance or developments, gives individuals the impression of being its very own user.

Actually, the introduction of industry 4.0 brought more challenges for the worker that could increase faults in mistakes upon operation. Madonna et al., (2018) defined a cognitive framework previewed in figure 13 to express the need of combination between different industry 4.0 technologies and the operator.

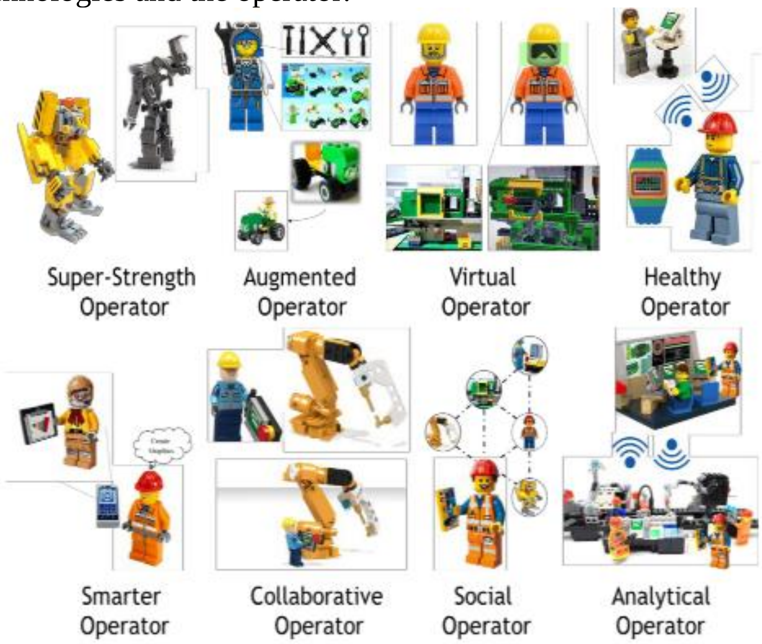

Figure 11 Types of operator 4.0 (Romero et al., 2016)

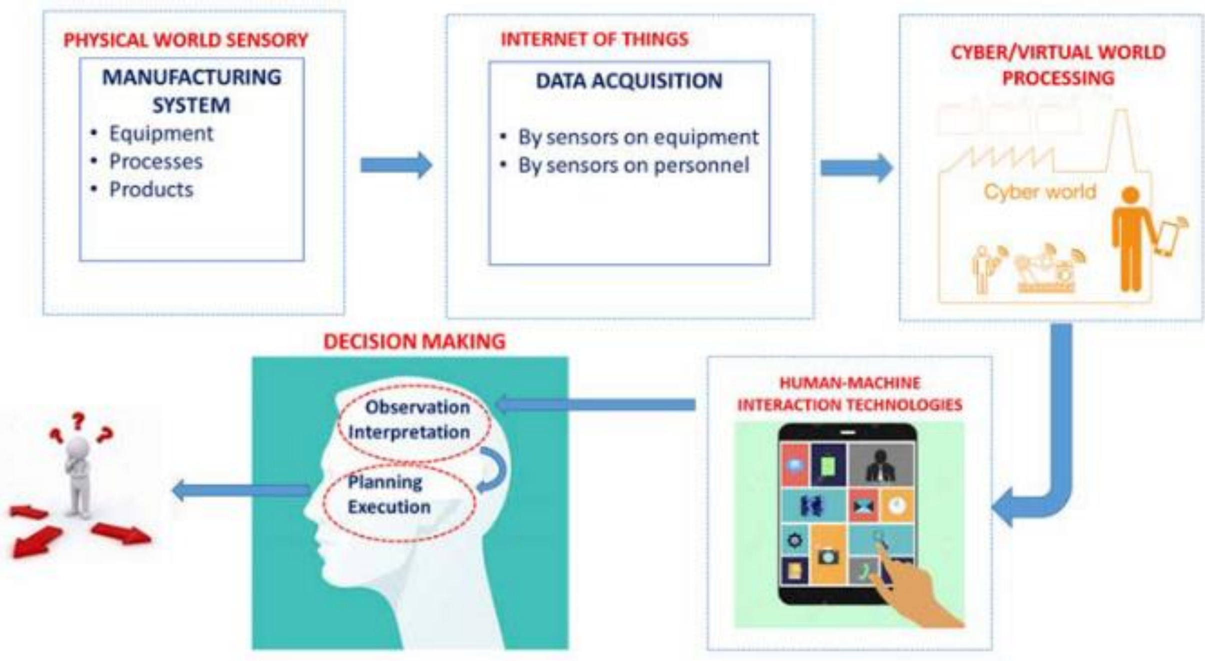

Figure 12 Cognitive framework of worker within the introduction of industry 4.0 (Madonna et al., 2019)

4. ANALYSIS

In order to answer the research questions, deep analysis of the literature is done to pick out different ideas, theories and methods presented by different authors. This section is divided in relation to the themes of the RQs.

4.1 Causes of Human Errors

In a study done by Morag, et al. (2018) where the authors contributed to a systematic identification of human errors in maintenance activities, the causes are listed out as follows:

- Communication: One of the most contributors to errors where the technicians and the operators misunderstand specific problems probably due to the lack of leadership and management aspects.
- Fatigue: This is found between the workers where they problems in their attention and memory.
- Tools and equipment: The inappropriate use of tools and equipment can lead to more hazardous situations and alter the general safety of workers. Also, the unavailability of equipment and tools would increase the chances of human errors due to the use of machinery that do not fit the given work applications.
- Skills and expertise: Within the non-routine activities that require a knowledge-based concepts, the probability of error is increased due to assigning workers for activities they have no knowledge in.
- Bad procedures: Errors are resulted due to bad information and the unavailability of standardized procedures.
- Documentation: Bad handling of documentation actions can lead to more human errors and this is because it has a direct relation with tasks performance and the familiarity of work that must be done.
- Procedure's usage: Sometimes the procedures to be followed are long which force the workers to adapt to informal procedures and depend on their own experience upon finalizing a given job.
- Time pressures: Overtimes and overwork would result the workers in making more faults this is because they would try to make shortcuts and adapt to easier work methods.
- Tool control and housekeeping: This is related to the actions of tracing the equipment used or disassembled from machinery.

In another study of causes of maintenance errors in a mining companies, Kovacevic, et al. (2016) mentioned that the cause of human errors is identified by the method of ranking (fuzzy AHP method), where the most important factors are related to organization, training level of operators, availability of equipment, experience and work instructions. In a similar study, using the method of root cause analysis and in combination with ranking human error factors in aviation maintenance Chuan Chiu and Hsieh (2016) stated that how the task is executed, defects are identified, procedures followed, information transmitted to the decision makers and the excessive use of visuals are large contributors to active errors in aviation maintenance. However, in the context of identifying causes in aviation maintenance, Rashid, et al. (2014) figured that there are main casual factors for maintenance error that are: organizational processes, documentation, design of aircraft, supervision, resources availability and maintainers preparation and the method of detecting such causes was with the help of AMMP software that showed supervision strategies

have the highest weight on causing maintenance errors. In a study of investigating aviation maintenance error causation, Rashid, et al. (2013) mentioned that the inspection practices create more errors if performed in the same way over all the maintenance activities. Moreover, in a literature review of exploring communication and trust factors in aviation maintenance, Chatzi, et al. (2019) reviewed that miscommunication and trust are huge contributors to human errors in several industries and that trust is and an underestimated factor in most reliable industries like aviation. (Islam et al., 2017) and (Kandemir and Celik, 2021) stated that in marine industry the most important factors of human errors are the lack of training, experience, communication and cultural differences of employees doing ship tasks and services such that among other elements, fatigue for example has contributed to 33 % of injuries within marine operation. The fatigue of employees is generally caused from different parameters like the absence of enough sleep, poor illumination, low quality of ventilation and vibration. Using the method of risk assessment, Kucuk (2018) identified 20 risks and factors of human errors stating new factors like lack of management, instability of technician's emotions, social responsibility of individuals, distractions, ethical background and corporate policies of layoff and relocating employees.
In addition, Barbosa, et al. (2014), integrated the model of PEAR to list out the factors of human errors in maintenance of aircraft stating that people, environment, actions and resources are the main contributors to human errors. In oil and gas industries, Noroozi, et al. (2014) used a human reliability assessment method to detect that experience, work demand and other administrative procedures lead to errors in maintenance tasks.

According to Neumann, et al. (2016) and Kolus, et al. (2018), in studies of human factors in production and manufacturing, where the authors studied the relationship between quality problems and human errors such that those factors affected product and process. The factors that related to product are the complexity of the design, task characteristics, difficulty (including distances and visibility) and load. Those that are related to the process are instructions and procedures available, management strategies, training and relations between employees and suppliers. Moreover, Kim and Park (2012) used the method of human error analysis and PSFs extraction within the frame of human related root cause analysis method to find out that 6 factors for errors in maintenance are procedures, experience, communication, management practices and supervision. In another case study, Ogbeyemi, et al. (2020) found that job performance is influenced by factors such as job skills, job satisfaction, exhaustion, and turnover and this was concluded after critical observation of assembly line structures within manufacturing companies and the movement of the employees and operators.

According to Liang, et al. (2010) the most common causes of errors were routine and monotonous tasks, failure to obey work procedures, and complacency. According to the questionnaire, some of these mistakes may be due to technician maintenance actions and the new work card configuration. This result was founded based on two years of reviewing data from 40 events at a specific airline business and referring to questionnaires done by the authors.

The following table shows different findings with respect to different researchers showing the factors and the methods used to conduct and show these factors. The table also shows the factors in different industries and applications like maintenance in aviation or marine operations.

Industry/ application	Method used	Factors	Source
General maintenance activities	Systematic identification	Communication, fatigue, Tools and equipment/skills and experience, bad procedures, documentation, time pressure, tool control and housekeeping	(Morag et al., 2018)
Maintenance in a Mining company	Fuzzy AHP	Organizational, training, availability Of equipment, experience	(Kovacevic et al., 2016)
Aviation maintenance	Root cause analysis	Task execution procedure, transmission of information, defects identification, excessive use of visuals	(Chuan Chiu and Hsieh, 2016)
Aviation maintenance	AMMP	Design of aircraft, communication, organizational, Maintenance preparation, maintainers preparation, documentation, supervision, resources availability	(Rashid et al., 2014)
General maintenance activities	Human error analysis of a helicopter	Inspection	(Rashid et al., 2013)
Different types of industries and applications	Literature review	Communication and trust	(Chatzi et al., 2019)
Marine operations	HRA (SLIM)	Communication, experience, lack of training, cultural differences	. (Islam et al., 2017) and (Kandemir and Celik, 2021)
Aircraft maintenance	Risk assessment	Lack of management, emotion instability, social responsibility, distractions, ethical background, corporate policy.	(Kucuk, 2018)
Aircraft maintenance	PEAR	People, environment, actions and resources	(Barbosa, et al. 2014)
General maintenance tasks	Human reliability assessment	Experience, work demand and administrative procedures.	(Noroozi et al., 2014)
Manufacturing	Systematic literature review	Cognitive, physical, and psychological	(Neumann et al., 2016) and (Kolus et al., 2018)
Mainteneance	Human error analysis and	Procedures, experience, communication, management practices and supervision	(Kim and park, 2012)

	through PSFs extraction		
Manufacturing	Case study/ assembly line observation	job skills, job satisfaction, exhaustion, and turnover	(Ogbeyemi et al., 2020)
Mintenance	Questionnaires and analysing errors in an aircraft company	Routine and monotonous tasks, failure to obey work procedures, and complacency	(Liang et al., 2010)

Table 2 Causes of huamn errors w.r.t industry and method used

The following figure is conducted by referring to table 2 to show the most eight contributing factors to human errors. It is obvious that communication and procedures followed are the most common causes to human errors in most of the papers. The themes are categorized by counting the repetitive factors such that from the selected literature that discusses factors of human error. Communication for example was mentioned 7 times whereas equipment and tools for example was mentioned 2 times.

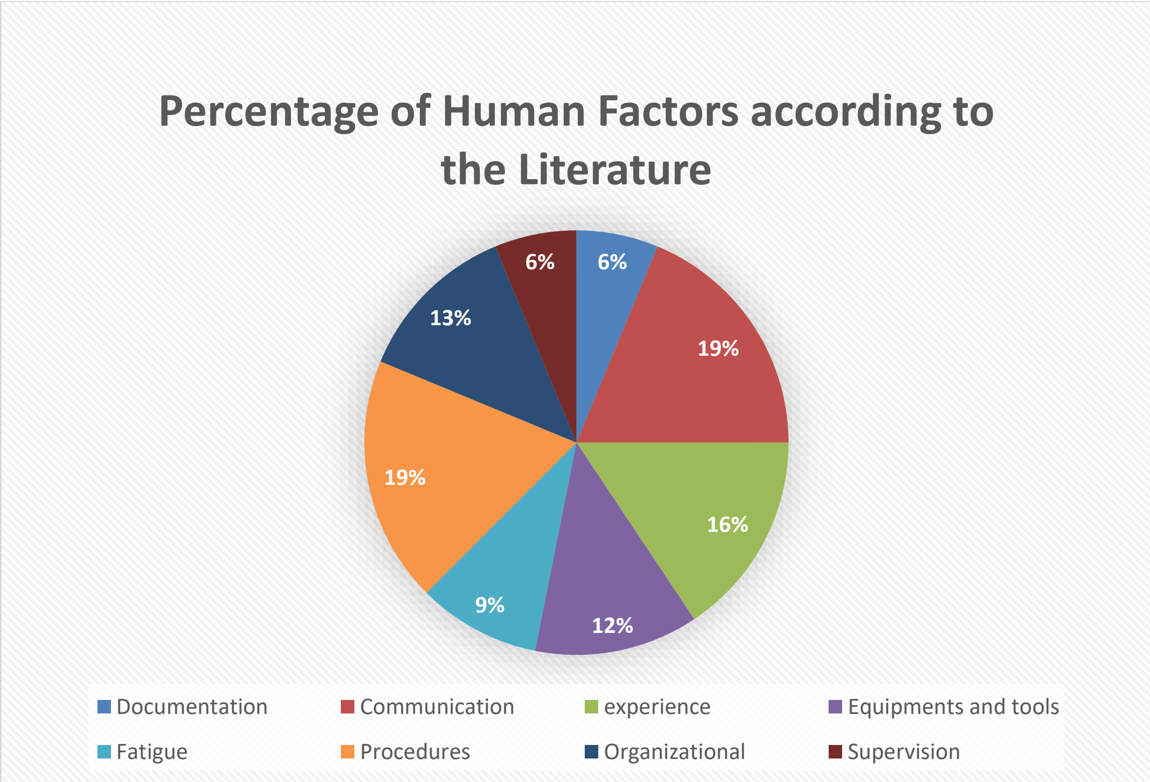

Figure 13 Pie chart showing percentages of common human factors mentioned in the literature

4.2 Human Reliability Models and Techniques

Within the efforts to define HRA techniques, the literature showed different uses and contrasts upon applying those methods in a variety of sectors such aviation and maritime. The major techniques used in the literature were HEART, THERP and SLIM. More authors have contributed to other reliability methods, but the contributions were also based on those methods that are more familiar.

According to Islam et al., (2019), in a study of defining an improved version of HEART technique which is called hybrid HEART, the author stated that regardless that HEART is an easy and simple technique to calculate HEP, but within marine operations the method does not supply an accurate determination of seafarers assessed proportion of effect on the possible error producing conditions and, in this way, the probability calculations of errors would not be accurate. Kandemir and Celik (2021), agrees with this point as the conventional HEART methodology introduces typical set of EPCs depending on the industry used with the need of variability, especially in marine operations since the maintenance tasks and the type of failures happens unpredictably as most of the problems are found in the engine room and in the sequence of independent actions. Both authors advice the use of a second party method called SHERPA to help with the identification of performance shaping factors, but in contradiction Di Pasquale (2016) found that SHERPA model suggests that nominal HEP follows a Weibull distribution, but due to the complexities of human behaviour, this assertion may not be true in all cases. Other problems with HEART technique are mentioned by Noroozi et al., (2014) in a study of human reliability assessment of oil and gas facilities that even though analysts consider worse scenario conditions, situations where operators perform in very cold environments (location of the facility was in the arctic) are not generally considered in conventional HEART method which also have significant effects on calculating HEPs.

Bowo and Furusho (2018) also agrees with the theories that HEART can be easily applied within marine operations, but the magnitude of the measured proportion impact is difficult to calculate since the amount is subjectively determined by the researcher. In contradiction, in a study of quantification of human errors in assembly and manufacturing operations, Torres et al., (2021) found out that the implementation of HEART methodology aids the observer by presenting a database of validated influences that influence human success and can be compared based on their relative effect on human error probabilities and this is what Böllhoff (2016) disagreed with, that the evaluation of human error, especially in the tasks of quantification is rather complex and the claim that heart help the analysts with proper data is not always true since the success reliability depends on the availability of trusted data.

Kazmi et al., (2017) and Noroozi et al., (2014), found the strengths and drawbacks of using HEART in the industry such that, HEART is highly reliant on expert advice, the findings are often influenced by the level of knowledge and experience of the experts. This flaw can be overcome by creating a long-term historical record of slope collapses in the affected area, but the main strength is that the method is simple and easy to handle, HEART's main advantages is that it provides the necessary data to conduct human reliability assessments, which can be accomplished by human error detection, quantification, and elimination.

Other researchers used another HRA and reliability assessment methods like SLIM and THERP. According to Abbassi et al., (2015), THERP does not allow any deviation of nominal HEPs which is also known as a justification factor. This was done in a study of human errors of marine operations where the authors implemented a new method of RFID for HEP minimization and after the realization of this weak point, HEPs is decreased by 1,09 % in their study. Since THERP does not consider nominal factors, it usually integrated with other methods for the compensation of the required data. In a probabilistic safety assessment of a nuclear power plant, Voronov and Alzbutas (2010) agreed on the original claim that THERP method is good enough for qualitative assessment and this is because through its dedicated task analysis and PFSs identification within the handbook. Moreover, in a theory of validating THERP technique, Shirly et al., (2008) examined this validation for stress and experience PSFs and found out that in the situations where high levels of stress is involved, the related dynamic tasks does not have a corresponding multiplier to compensate HEP measurement nominally, instead expert assumption is involved which could also affect the calculations. For justification purposes, Boring (2012) and Whaley et al., (2007) agreed to the claims of using THERP for qualitative assessment noting that the method is rather mixed up with other methods for proper HRA such that all the other methods are created based on THERP. Also, agreeing to those claims, Yang et al., (2007) previewed a comparison of different HRA techniques stating that THERP is more reliable than other methods but not for high sensitivity cases such that a method like HEART can be used to analytically verify THERP results.

According to Islam et al., (2017) and Hameed et al., (2016) within marine operation human error quantification, SLIM is useful method for assisting in the decision-making stage in a brief amount of time. This method allows chief engineers or captains to choose the most qualified seafarers to successfully complete maintenance activities depending on operating and environmental conditions, reducing the likelihood of human error and injuries. However, the author claims that SLIM method is not advisable due to its complex steps as it is time consuming. In contradiction, the efforts of Abrishami et al., (2020) in a literature of improving SLIM, derived that SLIM calculates the overall HEP of an operation as a total of the HEPs of the errands, disregarding the conditions inside the HEPs due to common PSFs, given an operation comprising of a number of assignments. Moreover, the author stated that the conventional SLIM technique does not handle uncertainties, and this is due the inability of the method to establish probability distribution of PSFs so that the approach is more deterministic. Agreeing with that was Park and Lee (2008) that found that among other expert judgment-based methods, SLIM has inconsistency due to the judgment and problems within the consideration of PSFs.

Moreover, Abbasi et al., (2015) agreed with the fact that the success of SLIM depends on the selection of judges as this is the critical factor for proper calculations and this author found one more disadvantage that is the selection of anchor point and there is little evidence to suggest that the calibration equation is well established.

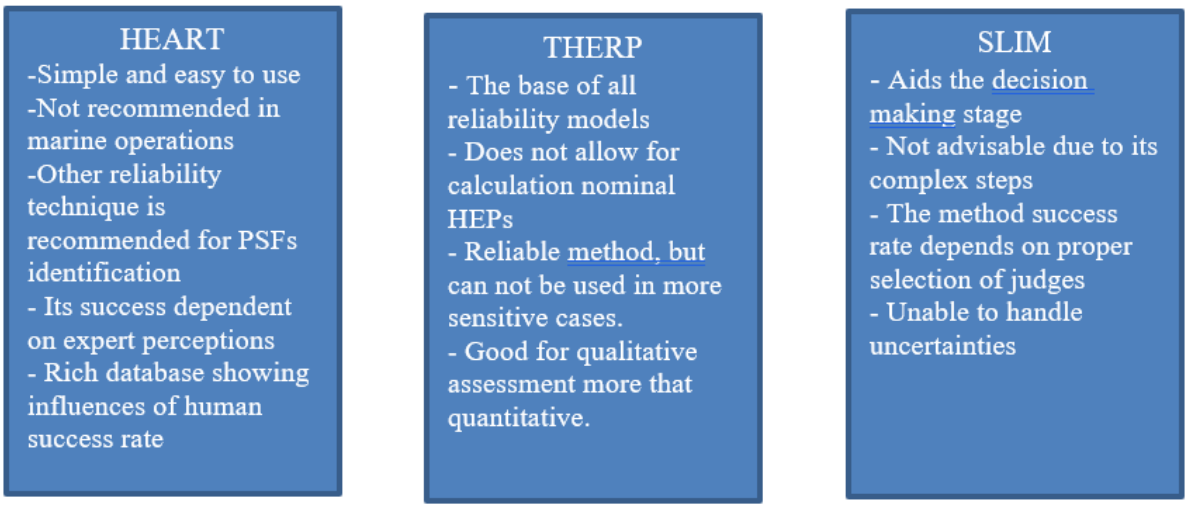

Figure 14 Key take-aways of different reliability techniques

4.3 Reducing Human Errors and Possible Implications

In this section ways and thoughts of decreasing human errors is analysed through the literature and divided into three part.

4.3.1 Industry 4.0

Accoridng to Oborski (2004) and Gorecky et al., (2014) in studies of investigating human-machine interaction upon the introduction of industry 4.0, the proper collaboration between artificial intelligence and human can significantly improve overall production performance so that the operator will understand their maximum potential and assume the role of a strategic decision-maker and agile problem-solver in the complete cyber-physical environment with the help of technical assistance. Moreover, Madonna et al., (2019) and Enrique et al., (2021) talked about the introduction of AR/VR technologies in the era of reducing human errors stating that virtual and augmented reality may be helpful teaching aids since they enable operators to behave safely in complex and unpredictable situations using on-line step-by-step procedures. These solutions such AR/VR help to improve worker productivity, reduce human mistakes, and eliminate potential ergonomic issues. Virtual reality (VR) and augmented reality (AR) are two related systems that are commonly used to mimic and include manufacturing processes and operator activities.

However, counter arguments are presented by Qeshmy et al., (2019) in a literature of investigating if augmented reality can help in decreasing human errors founding that augmented reality solutions are not the right method for dealing with human-caused mistakes. The biggest explanation is that the technology is not yet advanced enough, so the number of times augmentation can occur would render the role of an augmented reality device pointless. Disagreeing with that was Oborski (2004) adding one recommendation and limitation that the design between the machine and the human controlling it is done by a programmer who is maybe not conscious about the problems a human would face upon using such technology so that a poor design would reflect a negative performance. Moreover, Enrique et al., (2021) added that within the introduction of technologies such like AR/VR decision-makers must carefully consider which requirements are required for each of these innovations to be implemented.

Qeshmy et al., (2019) recommended the use of pick to light systems, for example, can be used to assist assemblers in making decisions and also serve as a quality control method by ensuring that the installer has chosen the correct piece as a more efficient way that AR.

The operator typology presented in figure 13 by Romero et al., (2016) is useful for further understanding the possible roles of humans and robots in human cyber-physical systems factories but within a study of smart operators, especially operator 4.0, technologies must be done with care and accuracy considering that the impact can be radical on the operator and on the production performance because of the variability of the human behaviour. Trust and acceptance are top challenges upon implementing those challenges (Valentina et al., 2021).

As for maintenance 4.0, Jasiulewicz et al., (2019) investigated such technology in a frame of sustainable manufacturing noting that maintenance employees should be given a proper level of thorough maintenance orders based on their level of experience. Digital information (e.g. virtual modules, disassembly manuals, diagnostic information, etc.) that is required to support repair operators can be overlaid directly into the physical workspace using augmented reality in conjunction with maintenance 4.0. In addition, Najjar et al., (2018) and Cachada et al., (2018) has counter arguments about if the cost of maintenance would increase upon the introduction of industry 4.0 noting that the introduction of a good maintenance management would decrease the maintenance cost since human errors and mistakes are decreased but in contrast, using certain sophisticated and complex maintenance techniques, such as Maintenance 4.0, which lead to an increase operating expense. However, it makes no difference how fast the maintenance expenditure grows if the maintenance expense per high-quality product decreases.

4.3.2 Manufacturing and Industrial Operations

Although the literature was not rich with the subject of human error in manufacturing and industrial operation, but some recommendations are presented by different authors who talked about ergonomics and reliability within manufacturing or industrial operations. According to Santiasih (2021), Torres et al., (2021) and Kim and Park (2012) compiling precise work directions as part of a worker safety review is one of the recommendations provided to diminish the power of error likelihood such that by supplying assembly orders that engage the worker's senses more efficiently, the likelihood of mistakes may be minimized. This lends support to the previously mentioned notion in the literature that assembly work directions have a significant effect on dynamic sophistication and can be optimized to reduce cognitive burden. However, according to Salonen (2018) the convergence of flow-oriented cell manufacturing, staffed by fewer operators, and a rise in the number of duties and obligations assigned to the shop floor places a significant burden on the workers. So even though flow-oriented production would sound an advantage for the production efficiency, but it means bad news for the works. In this context, Santiasih (2021) added that providing clear work instructions is also not enough such that the implementation of training programs with good supervision activities would support the idea of clear responsibilities.

Moreover, Ogbeyemi et al., (2020) provided some recommendation in a study of human error in small manufacturing companies stating the following:

- Reciprocating roles among employees reduces job exhaustion and, as a result, improves job efficiency.
- Employees may be introduced to a new shift schedule or minimal overtime in order to minimize lead time and rework of customer-returned jobs.
- When integrating job rotation into production planning and scheduling, shop floor personnel should be assigned a reasonable workload.

4.3.3 Maintenance

In this section, ways and methods of reducing human errors will be presented according to different industries and theories. In a study of listing out human related error type in aviation industry, Usanmaz (2011) suggested an aircraft maintenance personal training model to be given before and after the licence such that one could be given in an approved organization for general maintenance procedures and the other is more dedicated on the tasks which is given after the licence. Safei (2021) presented a methodology of premature maintenance actions and its ability of reducing maintenance costs due to decreased human errors and this is what Heo and Park agreed to as non periodic maintenance would not prevent human errors, it is the adequate planning that is done beforehand can decrease the amount of accents. In another study of aviation maintenance, Latorella and Prabhu (2000) and Galar et., (2011) recommended some future direction to adequatlly perform inspection activities after finding out that it is a main a factor,

those directions are providing training and aiding personnel with training, identifying organizational structure and work characteristics. This is also what Wenwen et al.,(2011) agreed to concerning training, adding that it is not only sufficient to provide training programs but it also needs commitment from the staff in the actions of studying hard and participating. In addition, Rashid et al., (2013) and Rahid et al., (2014) expressed the need of proactive thinking toward the solutions of minimizing human errors in aviation maintenance tasks. In another study where fatigue was the main human factor that results errors in aviation maintenance, Wang and Chuang (2014) agreed on developing training programs for maintenance, adding two main parameters that could decrease fatigue and consequently reduce errors. The first parameter was for the organization to contribute that is giving enough rest and breaks for the employees and the second parameter was more for the technicians as they must have enough amount of sleep before beginning their shifts. Moreover, Chiu and Hseih (2016) and Wang and Chuang (2014) agreed that a proper collaboration to solve communication, coordination and planning problems would results in a less fatigue for workers. However, Chatzi et al., (2019) found that training is the only way to develop communication and trust between the employees.
Most importantly to mention that HRA aim to calculate those probabilities of human error and consequently aim to reduce them but an approach of zero errors is a wrong approach such that from a realistic standpoint, zero errors is impossible to achieve because it denies the presence of a wide range of human actions, and certain kinds of errors are hard to eradicate (Dragan and Isaic-Maniu,2014). In addition, Wenwen et al., (2011) mentioned some recommendations to reduce human errors:

- Improve staff safety awareness and skills by improving employee’s overall qualities by training.
- Improving basic management practices by setting clear rules and regulations.
- Spreading leadership concepts.
- Promoting motivation and taking into consideration staff´s psychological activity.
- Workplace with a fair design and a healthy atmosphere.

In the following table shows some cases that are presented in the literature mentioning strategies to reduce human error. Those findings are contributed in different ways and by using different methods.

Industry/ application/ source	**Method**	**Finding**
(Bowo and Furusho, 2018) Marine Operations	HRA (HEART)	In certain emergency situations, seafarers must exercise emergency response. To reduce the chance of physical injury or disruption, it's critical to keep the working environment in good shape.
Aviation maintenance (Chuan Chiu and Hseih, 2015)	HRA	According to the results, the most effective way to eliminate errors relevant to information mental abilities is to address teamwork, collaboration, and preparation issues.
Aviation maintenance (Liang et al., 2010)	Online maintenance assistance platform	This framework includes a list of possible human errors for each operation, an overview of the effects of human error on devices and humans for each procedure, an operator error influence probability index based on each

		procedure's severity rank and frequency, and a visual detail aid for each removal and implementation procedure.
Maintenance (Kim and Park, 2011)	Analysing task characteristics and work conditions.	Human error, such as lack of a crucial task stage, may be reduced by following a step-by-step procedure and referring to procedural steps.
Grinding Activities (Santiasih and Ratriwardhani, 2021)	HRA (SLIM)	By enhancing supervision activities and spreading clear regulations and instructions the company were able to decrease HEP to the half.
Marine Operations (Abbassi et., 2015)	Integration of RFID within maintenance tasks	A reduction of 1.09 % HEP was accomplished after utilizing RFID technology tools within maintenance activities of a pump.
Product Maintenance (Desai and Mital, 2011)	Building ease of maintenance into the design of products	Upon applying ease of maintenance methodology and comparing between two products, human errors decreased due to the fact of enhancing the design of the product to fit with maintenance activities.

Table 3 Solutions to reduce human error in selected literature

5. CONCLUSIONS AND RECOMMENDATIONS

To conclude this thesis, direct answers to the research questions are presented in this section with some recommendation and future work insights.

What are the main causes of human errors in maintenance and industrial operations?

The main causes of human errors in different sectors and applications are presented in table 2 and this is with respect to different literature where the authors have common approaches or definitions of human factors leading to human errors. Figure 14 shows the most repeated factors according to the literature having communication and procedures followed the most contributing causes/factors to errors. Those factors are not only found in a single sector or industry, rather they are found in multiple applications including maintenance activities as most and this is because most of the literature investigated human errors in maintenance with minimal focus on industrial operations/ manufacturing. It is also important to say that there are other factors that did not show in the chart but also are huge contributors in other studies like inspection practices and environmental aspects. Moreover, it is concluded that the use of human reliability method helps to reveal those factors since the use of those techniques centralize the identification of PSFs. In fact, the most known reliability models are used to identify those factors as a priority for proper HEP calculations.

In general, human can not take responsibility for all the mistakes and faults that happen in the workplace, specifically those that are due to human because other aspects from the company itself influence the workers to admit such mistakes. Organizational factors and the process of recruiting employees can be responsible for a notable percentage of mistakes and this is because some of workers are being assigned to tasks out their experience and skills which would cause this unbalance. More attention should be drawn to the criteria of employing staff so that the tasks would fit their needs and skill scope.

What are the efforts done in order to diminish human errors and what are the possible implications?

The report handled ways of reducing human errors on three levels. The first level is the introduction of industry 4.0 and different types of operator 4.0. Although, technologies like AR and VR can enhance human productivity, but due to the unclear advancement of such technologies some authors did not encourage the use of them. The other levels discussed reducing human errors in manufacturing and maintenance operations. Most of the researchers agrees that training is an effective way to reduce errors resulted from mankind and this goes in agreement with the cause found such that a huge percentage of causes lies in the inability to follow procedures which can be referred to the improper implementation of training programs. As the goal of preventing all errors is rather than impossible to achieve and errors are inevitable. Table 3 shows some scenarios and methods of reducing human errors that are found in different literature.

What are the major differences between human reliability models and techniques?

Various reliability techniques were discussed and analysed in the report and in relation with different sectors. Those models have their advantages and disadvantages depending on the application and the context they are used for. Figure 14 shows some takeaways of the most used reliability models that are used in the literature. It is important to say, that there is one common concept between those models is that the success rate is dependent on the experts that are implementing them. HEART for example, is much common that other methods but frequently used quantitative assessment, where as THERP is used for quantitative assessment of human errors. The literature also proposes some of the ways to enhance those techniques by the acknowledgement of their week points.

6. DISCUSSION

Discussing the main findings is an important part of this master thesis. In the beginning, causes of human errors are identified and a pie chart was conducted to see what kind of causes are mentioned in the literature. It was obvious that the lack of communication and the abidance of following procedures are the most known causes for human error. As the errors resulted from human will constantly occur and there is no way to prevent them because after all the variability of human and his presence while working is the most contributing factor around all the errors. Wither the researchers agree or do not agree, human have a part of many system failures without acknowledging this fact. It also important to say, that there is no common agreement that that kind of causes happens in a single industry or application. As the industries and the methods to detect those causes were many. One way to model human errors was human reliability modelling. Through the literature, HEART, THERP and SLIM were the most common reliability models to calculate the possible occurrence of the faults. After analysing the literature, it was seen that those types of reliability models, especially HEART and SLIM gives different results due to expert opinion in the early implementation of the method. It is recommended, to have better strategies toward data collection and listing out of related PSFs to have more accurate HEPs. The last part of this thesis discussed strategies and possible efforts done to reduce human errors. Training is the most repeated course almost in most of the literature. As training in aviation before and after giving a licence for conducting maintenance work or general activities. As well as, enhancing the ways of communication between staff and this strategy agrees with the fact that communication and documentation are the most contributing factors to human errors.

The thesis discussed also concepts around industry 4.0 and the possible technologies that can help with reducing human errors. More future research should be down around this area specifically the use of VR technology in performing training and preparation for assembly staff and maintenance technicians. Also, in order to stress on the issue of human errors in maintenance and industrial operation, it is recommended to discuss the economical side of this issue before implementing human reliability models and industry 4.0 technologies.

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