RESEARCH REPORT

VTT-R-01014-22

Heavy lifting – dynamic factors, hierarchical task analysis and human errors

Authors: Marja Liinasuo
Ilkka Karanta
Terhi Kling

Confidentiality: VTT Public

Version: 08.12.2022

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beyond the obvious

Report's title	
Heavy lifting – dynamic factors, hierarchical task analysis and human errors	
Customer, contact person, address VYR	**Order reference** SAFIR 3/2022
Project name New developments and applications of PRA	**Project number/Short name** 128648/NAPRA
Author(s) Marja Liinasuo, Ilkka Karanta, Terhi Kling	**Pages** 28
Keywords HRA, dynamic, heavy lifting, protective tube unit, hierarchical task analysis	**Report identification code** VTT-R-01014-22

Summary

Heavy lifting is critical to the safety of a nuclear power plant. The lifting of the protective tube unit (PTU) is reported here, from the HRA perspective; PTU was chosen because its lifting procedure is complex, and the related potential damage is severe due to its weight. The goal of this research report is to provide detailed and systematic information about the nature of heavy lifting and the possibilities of the related human errors.

As methods, seven crane operators and crane operator assistants were interviewed. Firstly, an earlier interview was reanalysed for the identification of dynamic, error-inducing factors related to heavy lifting. Secondly, hierarchical task analysis was used for the identification of the main tasks and sub tasks for the lifting of the PTU. Also, some error-related issues were identified during the hierarchical task analysis.

Five dynamic factors were identified related to lifting during outage. These potentially error-affecting factors are shift extension, working for a long time without a pause, background noise, constant haste, and multitasking, all lowering threshold for human error.

The proceeding of the PTU lifting was analysed, using hierarchical task analysis during the interviews. As a result, 13 main tasks and the related subtasks were identified. Along with the task-analysis process, possibilities for human error were sought for. Various sources for errors were found: human communication related issues, procedure related issues, human resource related issues, malfunction of machine of device, difficult lifting circumstances, and timing related issues. In the study, the proceeding of the lifting session was focused on, and the identified errors serve more like examples of possible errors. The identified errors are related to human injury, weakened situation awareness of crane operator and crane operator assistant, faulty operation of crane, outsiders in the reactor hall during lifting, and insufficient of matters in finishing meeting. Even this sample of dynamic features and other issues related to human error show that the reasons for human error can be a complex combination of factors, some affecting constantly and some occasionally, in a more unique manner. A more thorough understanding on issues increasing error possibility, as well as the possibility of the errors themselves, could be reached by the same methodology as used in this study, with just more resources.

Confidentiality	VTT Public

Espoo 4.1.2023

Written by	**Reviewed by**
Marja Liinasuo, Senior Scientist	Tero Tyrväinen, Research Scientist

VTT's contact address

VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, 02044 VTT, Finland

Distribution (customer and VTT)

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Approval

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Date:	29 November 2023
Signature:	DocuSigned by: Mikael Wahlström 1051F3A483A4482...
Name:	Mikael Wahlström
Title:	Research team leader

Preface

This document reports the results of project NAPRA, task T3.2, as reached in year 2022. NAPRA belongs to the Finnish nuclear safety research programme SAFIR2022, finishing at the end of 2022. The authors thank the hoisting experts interviewed, and Leena Salo and Mikael Kivi (Fortum) for arranging the interviews.

Espoo 4.1.2023

Authors

Contents

1. Introduction

Heavy lifting and, more generally, hoisting is an important activity in a nuclear power plant. During outages, items such as fuel rods, fuel assemblies and pressure vessel head need to be transferred. Transferring fuel rods to and from the spent fuel pool (SFP) is the main activity concerned with that system. During decommissioning, heavy lifting concerns not only those items but in practice much of the plant, including the pressure vessel, heavy equipment, cut pieces of concrete structures, and so on.

By necessity, the moving of radioactivity sources and heavy items involves risks. Some of these risks concern the item dropped. Dropping fuel rods involves the risk that cladding cracks and volatile radionuclide compounds are released to the reactor building. Dropping almost any item involves the risk that the item is damaged, and repair of the item and possibly expensive production break ensue. Other risks concern whatever the item falls on. Heavy load dropped on the pressure vessel or a critical safety system may result in damage to these (IAEA 2000). For example, Halada et al. (2004) found that heavy load drop in the turbine hall may affect service water system, residual heat removal, and emergency feed water systems of Mochovce NPP VVER-440 type Unit 1. Heavy load dropped on SFP liner may result in damage to the liner, water leakage, loss of cooling water, and eventually fuel damage (Garrick and Wakefield 2020). And naturally, heavy load dropped on a human may result in injury or even death.

Considering these issues, it is no wonder that heavy load drop – or more generally, hoisting of heavy loads – has received attention from nuclear regulators. Perhaps most influentially, NRC published NUREG-0612 report (George et al. 1980). In Finland, STUK addresses heavy loads in at least two YVL guides. In YVL A.7 (STUK 2019, item 401), hoisting of heavy loads is mentioned as one of the few items that shall be analysed as initiating events in probabilistic risk assessment (PRA). YVL E.11 (STUK 2019b), the YVL guide focusing on hoisting and transfer equipment, mandates (item 503) that hoisting functions and the design of hoisting device units shall be based partly on PRA. Item 514 in that document sets the scope of mandatory risk analyses. Item 515 specifies a mandatory scope of application of risk analysis results: “the design and layout of the nuclear facility’s buildings, structures and systems, and in the definition of safe handling areas for heavy loads.”

Risk management of heavy loads consists of a multitude of actions (see section 5.1.2.6 of NRC 1993). The following are some examples. To prevent load drops, fuel-handling equipment are required to be tested before use. To prevent negative consequences of drops, load paths are designed so that areas where spent fuel is stored, or critical safety systems are located are circumvented. To ensure the availability of safety functions, heavy load drops are analysed, and load transfers are planned so that at least one train of redundant systems is operable at any circumstances.

The present study has background in the studies conducted during previous years. Earlier, the concept of ‘dynamic HRA’ has been scrutinised in the light of literature, and also by interviewing operators about dynamic factors in their work (Liinasuo, Karanta & Kling, 2020). In this context, ‘dynamic’ refers to the changing work context that can affect human performance, increasing the possibility (probability) of human error.

In 2021, NAPRA T3.2 focused on dynamic features in outage (Kling, Liinasuo & Karanta, 2022). Several professionals around a nuclear power plant organisation were interviewed. The professional responsible for HRA in that plant mentioned that among the most critical events regarding human error in outage are heavy load drops. Also a crane operator, experienced in heavy lifting, was interviewed about the work qualities and especially error possibilities with heavy lifting. This interview bridges the earlier and the present study, as in 2022 T3.2 activity has focused entirely on the nature of heavy lifting and the associated possible human errors.

Heavy lifting was chosen as research subject because it is critical to plant’s safety. There are two kinds of heavy liftings to be conducted during outage, the lifting of the reactor cover and the one of the protective tube unit (PTU). The lifting of the PTU was selected because its lifting procedure is more complex. The potential damage is also more severe based on the weight – the reactor cover weighs 135 tonnes whereas the PTU, with the accompanying the biological shield, weighs 250 tonnes.

We reanalysed the 2021 interview of a crane operator, from the perspective of dynamic (error-inducing) features in heavy lifting during outage. We also interviewed several crane operators and crane operator assistants to identify the conduct of the lifting process. These interview results are contemplated from the perspective of human error in heavy lifting of a protective tube unit.

2. Goal

The goal of this research report is to provide detailed and systematic information about the nature of heavy lifting and possible related human errors. The systematism is pursued specifically by using hierarchical task analysis as the research method.

3. Methods

The method of information acquisition for this study was to interview seven hoisting experts. In the study, one earlier interview was reanalysed for the identification of dynamic error-inducing factors in lifting during outage, and seven new interviews were conducted for performing hierarchical task analysis and the related error identification.

3.1 Interview participants

All participants, 7 interviewees, have conducted lifting and hauling in a nuclear power plant. All participants except for one had experience on heavy lifting. During the interview, all participants worked in the same Finnish nuclear power plant; one of them had worked earlier also in another Finnish nuclear power plant. Experience on heavy lifting was almost 7 years on an average, ranging from 2 to 17 years. The title of interviewees varied; ‘crane operator’ was the title or part of the title for 4 participants, ‘maintenance’ was mentioned as part of the title for three participants, and one was titled as ‘construction worker’.

One of the interviewees described above participated in an interview about dynamic features in heavy lifting during outage.

All interviewees described above participated in a hierarchical-task-analysis interview pertaining to heavy lifting of the protective tube unit (PTU). All worked, except for one, as either crane operator or crane operator assistant.

3.2 Research methods

3.2.1 Data collection

Interview

In the interview about dynamic features in heavy lifting during outage, semi-structured interview method was used. The main questions were defined beforehand and based on how the interviewee responded, more questions were asked if considered necessary in the light of the purpose of the interview.

Hierarchical task analysis

Hierarchical task analysis (Annett, 2005) (HTA) analyses goals and operations so that complex tasks are decomposed into a hierarchy of operations and suboperations. The aim is to identify those operations that are likely to fail, due to poor design or lack of human expertise (Annett, 2005). Then, it can be used to propose solutions, which, depending on the concluded reason, could involve, for example, redesigning the task, providing more training (Annett, 2005), or redesigning the human-machine interface.

The level of detail varies depending on the purpose of the analysis (Annett, 2005). HTA has been applied in process-control and power-generation industries as well as in military applications. In this study, HTA is used in the nuclear domain, in a heavy-lifting task.

We specified HTA with features as follows (procedure based on Annett (2005)):

Step 1: **The purpose of HTA** was to get an overview of the proceeding of the operations in heavy lifting and insight of possible human errors during the task performance.
Step 2: **The task goal** is to lift the protective tube unit (PTU) to its destination.
Step 3: Crane operators and crane operator assistants were **identified as sources of task information**. Thus, the lifting was scrutinised from the perspective of controlling the crane, just mentioning the other parties participating in the lifting.
Step 4**: Data was acquired** through the related interviews. Simultaneously with interviewing, the **data was decomposed** into the form of a diagram
Step 5: **The validity of the diagram** was rechecked by showing the diagram, built during the previous interviews, to the next interviewee. The diagram was built during the interviews so that each interviewee always perceived immediately the output of the interview written as an operation in the diagram.
Step 6: **Significant operations identification**, presumed by the HRA procedure, was not performed due to the limitations of the project; there were not enough resources to conduct a systematic and deep task analysis.
Step 7: **Hypothetical solutions to the performance problems**, identified in the analysis, were not generated and tested as the HTA procedure requires, as the diagram was only developed to the level of identifying the most elementary operations.

The result of hierarchical task analysis is guided to be performed with a diagram, like shown in the left in Figure 1.

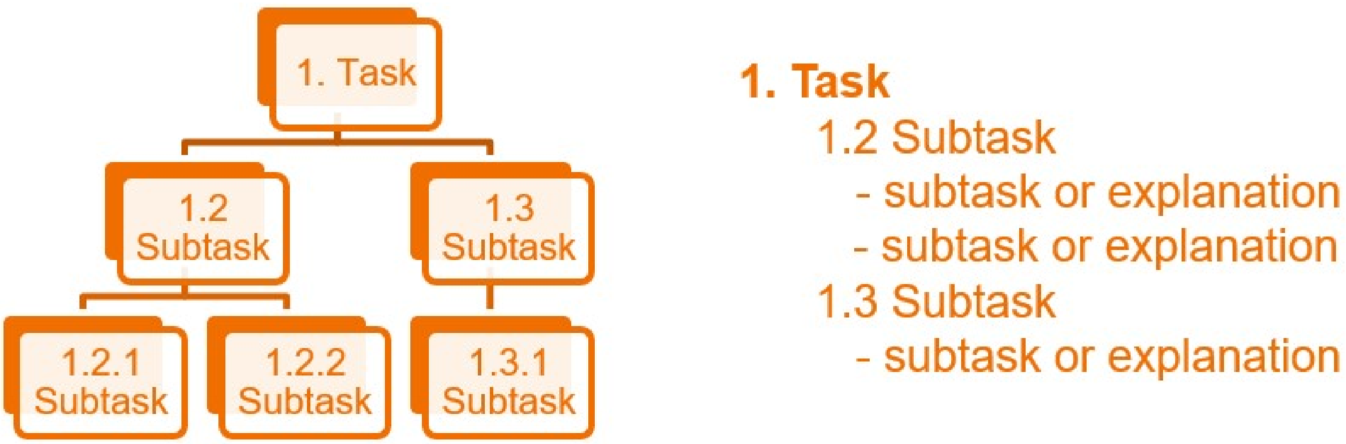

Figure 1. An example of a diagram format showing the result of hierarchical task analysis, shown in the left, and the format used in this report, in the right.

In this report, bullet-point type presentation is used (see Figure 1, the example in the right). Interview responses were directly written in this format. The task description lower in hierarchy is indented compared with the task description higher in hierarchy. Text instead of boxes is used because task descriptions in this report are often rather long and would not fit inside a box in an easy-to-read format. The long descriptions, in turn, were considered an appropriate choice because the task analysis is intended to be read by those not familiar with the task. Brief description would not include all information needed to understand the task. Only the two first levels are marked with a number as usually, only the two first levels are the different levels of tasks, and the third and the sometimes existing fourth level can represent a subtask for the previous level or provide an explanation without going to a more detailed task level.

3.3 Interview data analysis

3.3.1 Analysis of a previous interview

The interview about challenges in heavy lifting has been conducted earlier, as part of the interviews pertaining to dynamic features in work during outage (Liinasuo, Karanta & Kling, 2021). This heavy lifting related interview data was reanalysed to identify dynamic features in the work.

First, the interview was analysed for identifying challenging factors in work, with the ultimate objective of finding dynamic factors, challenging work performance. During the analysis, it became evident that the challenging factors could be divided into two groups: the burdening, contextual factors that remain constant during work, with a cumulating effect on work performance, and burdening dynamic factors, affecting work in an abrupt manner. This analysis resulted in a table with two columns, one for contextual and another for dynamic features. It was found out that in some cases, the same issue could be identified as both a contextual factor and dynamic factor but, in most cases, only as either of them. This phase of analysis was needed to clarify the difference between these two factors.

Second, the collected dynamic features were grouped to conceptually larger entities. These entities form the dynamic features in heavy lifting during outage.

3.3.2 Hierarchical task analysis

In the interviews, the operations for lifting the protective tube unit (PTU) were identified in a top-down manner. In the beginning, the interviewee was asked to sketch the main phases of the lifting. Thereafter, the lifting was decomposed to a set of operations and suboperations in the order the lifting proceeds.

When the overall description was established, each interview usually focused on some section that appeared to miss information more than other sections. This way it was ensured that the overall description was rather balanced regarding the level of details when the interviewing was over.

The starting point of interviews was that nothing was known beforehand about the PTU. The same starting point is adopted in reporting the results. This means that in addition to building the hierarchical task description, some general-level data, considered important for understanding the nature of the PTU is maintained and reported beyond the task description.

Furthermore, it was realised in the beginning of the study that the resources available do not allow the tracing of the usage of procedures. This has two consequences. Firstly, the level of detail of analysis is maintained in a general level, not reaching the level of how procedures are used. Secondly, as there was no detail-level description on crane related operations, we provide a general-level description of the features in handling the crane outside the actual hierarchical task analysis. This is why the HTA-related results are divided into two sections: the background information and the hierarchical task analysis results themselves.

All information reported about the phases, operations and demands in the PTU lifting originates from the hierarchical task analysis interviews. The role of the interviewer was to take care that the task description is clear and structured and as balanced as possible, so that the description is in about the same level of detail throughout the task description. The hierarchical task analysis reported in results is mainly identical with the analysis when the last interview was finished. The only information added by the authors is part of the error related contemplations, concluded from the task description. Thus, some of the error related contemplations originate totally from the interviewees; some are suggested by authors and validated by interviewees; and some are based on authors' conceptions only, without having had discussions about this in the interviews.

Error related contemplations are divided into two groups: Factors predisposing to error and error possibilities. This division was made based on grounded theory – error related comments fell on these categories in this data set.

4. Results

Two different kind of interview results were obtained, the one related to dynamic feature in heavy lifting and the one pertaining to task analysis of the lifting of the PTU.

4.1 Negative dynamic features in the lifting of the protective tube unit

Dynamic feature is defined in this report as a work-related feature that threatens optimal work performance either by (a) presenting unpredictable, negative changes in work; or by (b) being such negative work-related circumstance, which has a cumulative negative effect; the dynamic feature increases the probability of a human error (Figure 2). The dynamic, negative feature affects human mentally and via that, work performance. Thus, we were not interested in, say, the possibility of a device getting broken in such a way that working becomes impossible or harder to perform. Instead, the negative dynamic feature, in the sense of this report, deteriorates human mental processes and hence, also work performance.

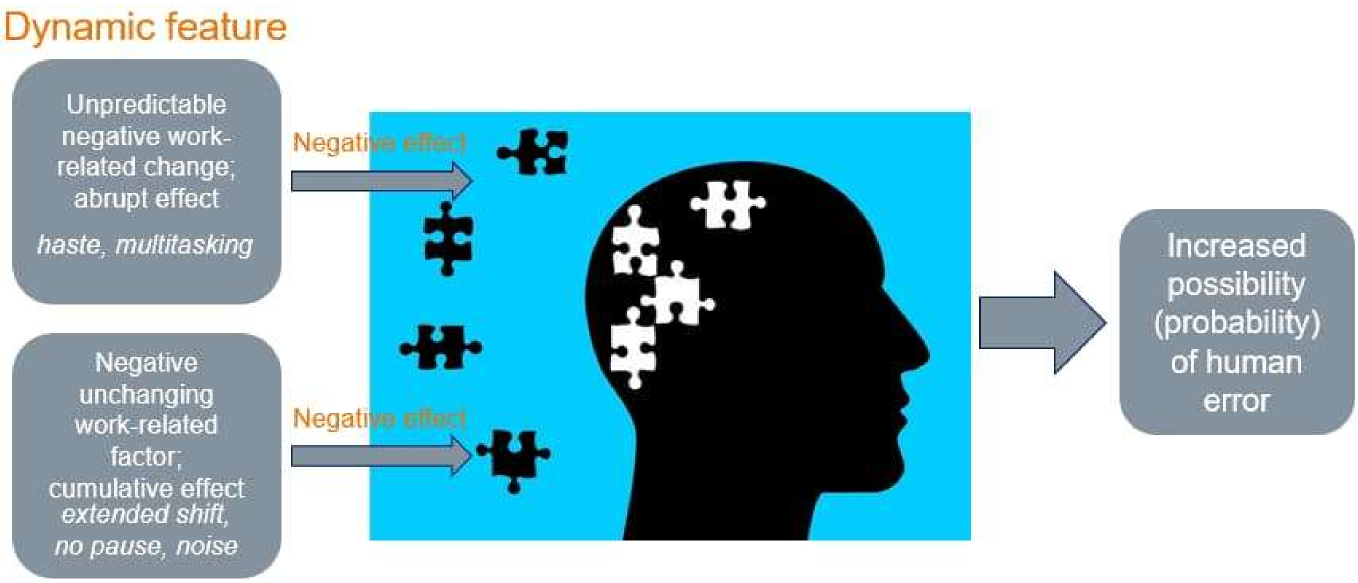

Figure 2. The effect of a negative dynamic feature on worker.

In principle, the effect of negative outside factors on work performance can be scrutinised from many perspectives. These negative effects can be conceived to burden the worker physically (in this study, roughly, extended shift and working for a long time without a pause), emotionally (in this study, roughly, background noise and haste) and cognitively (in this study, roughly, multitasking). However, what the actual primary affected system is, is hard to define – physical, emotional and cognitive systems affect each other, and one negative factor can affect many systems simultaneously.

The dynamic features in heavy lifting, and the related comments, identified in the interview, are presented in Table 1 below.

One feature possibly deteriorating work performance is the extension of the regular work shift. This can affect more strongly when it takes place during night shift. The effect is even more emphasised during outage as then, the shift is longer (12 hours) than during normal operations. It is harder to be alert after a long night shift than a long day shift as circadian rhythms are not able to quickly adapt to a relatively rapidly changing activity schedule (Kuhn, 2001).

Working a long time without a pause is burdening. This takes rather easily place if there are only two workers in a shift. Then, it is difficult to organise time for biological needs such as eating or going to toilet. Imbalance between the intensity, duration, and timing of work with recovery time is also linked with fatigue (Dawson et al., 2011). Then, it can be expected that work concentration becomes more difficult to maintain.

Outage is a demanding period in the life cycle of a nuclear power plant with a lot of simultaneous, partly interdependent activities. Many operations require the usage of a crane, resulting in constant haste at work for crane operators. Haste is burdensome; it even has a relationship with occupational injury (Salminen et al., 2017). Time pressure increases mental load and, consequently, the likelihood of human error (Wegner, 2009).

Operating a crane requires focusing on many targets – crane measures related to the target that is being lifted, target relative to the surroundings so that nothing is hit, and surroundings so that nobody is endangered due to the proximity of the crane. This is multitasking. It has been shown that people who are forced to multitask perform significantly worse than those forced to work sequentially (Buser & Peter, 2012). Multitasking is cognitively demanding, and it can be assumed to increase the likelihood of human error.

Pertaining to the above-described factors affecting human work performance negatively, haste and multitasking represent such dynamic factors that may set human to abrupt changes, requiring instant reaction. Extended shift, working a long time without a pause and constant background noise are such static factors that have a cumulative effect on work performance; for a short period of time, they have no effect, but the longer the situation remains the same, the more likely it is for a human to make an error. Haste has also a cumulative effect as it is mentally exhausting to work in continuous time pressure.

Table 2.Contextual factors (i.e., performance shaping factors (PSFs) and matters affecting PSFs), which add worker's load by time, i.e., in a dynamic manner. The text below each numbered title is a (sometimes shortened) comment made by an interviewee, shedding light on the nature of the contextual, dynamic factor in question.

1. Extended work shift (12-hour shift)
shift may extend, also after a night shift (12-hour shifts)
almost everybody becomes tired if the work shift stretches after a 12-hour day
2. Working a long time without a pause
when there are only two people in a shift, there is hardly time for pauses and you may have to work continuously for 4 hours
when you have worked four hours with heavy lifting, reactor hall is opened, and others want you to continue working immediately from then on
in practice, there are easily only two people in a shift as no more personnel is available; when there are only two people and the other one gets sick, there is a problem
3. Background noise
background noise can destroy concentration
4. Haste

you must hurry up due to radiation
there is only limited time to do the work as you cannot bring stuff to the reactor hall beforehand, due to radiation
people rush you, there is terrible hurry
everybody is terribly burdened, you must do this now, it can be just shouting all over; shouting is now diminished
5. Multitasking
during lifting, you must share your attention between many things (where is the object to be lifted, are people away below the crane)
it is possible that somebody walks unnoticed below the crane and at that point, nothing can be done
while lifting, you must look at both the moving object and the environment as there might be people; changes in the situation must be taken into account

4.2 Background information for the lifting of the protective tube unit

In this section, the potential of a human error is indicated with red font colour.

4.2.1 Main work tools, human roles and work shift duration during the lifting

Heavy lifting is performed with polar crane. It moves circularly in rails, located in the ceiling of the reactor hall. The crane has two trollies. Hooks are attached to trolleys; one carries the big hook and the other two smaller hooks. The trollies move between two bridges.

There are several stakeholders and stakeholder locations relevant for the lifting of the protective tube unit (PTU). Crane operator and crane operator assistant play the major role in this study. They may be located at the floor of the reactor hall in the beginning but will, sooner or later, move to the control cabin up in the reactor hall for controlling the lifting. Crane operator wears an earphone but in one ear only, so that (s)he can hear the discussion elsewhere and still focus on what crane operator assistant is saying.

Reactor supervisor (“reaktorityönjohtaja”) is reactor operator by actual work role but during outage, one of the reactor operators from the main control room serves as a supervisor for mechanics and participates in lifting in a control desk, located in the reactor hall floor. It is usually in the same location. Cables in the desk are attached to the biological shield.

Reactor operator in the main control room monitors the lifting and ensures on his/her part that the situation in reactor (regarding radiation) and reactor hall (as perceived with cameras in the hall) is safe.

Radiation protection supervisor (“säteilyvalvoja”) and lifting supervisor (“nostotyönvalvoja”) are located near the crane operator, monitoring the lifting, and taking action if something deviant seems to happen.

Work shift is 12 hours during outage (from 7 to 7 o’clock); during normal operations it is 8 hours and a half-hour lunch.

4.2.2 General features in operating a crane

Each crane operator drives the crane in a unique way, even if all follow the procedures. The driving also depends on the crane operator assistant; driving is performed as a pair and other stakeholders, present in lifting, mainly monitor the work. There are differences in the speed the crane is made to move and the tranquillity of the crane operator as a whole.

It depends on the expertise of the crane operator whether the driving is conducted calmly enough, so that the final-point coordinates are reached without first driving past them. The level of accuracy is one millimetre or degree.

At its longest, one driving session during lifting (driving from one defined point to another without stopping or changing direction) is half an hour. A factor predisposing to error is the expected continuous concentration, which is burdensome in the long run.

Since 2022, crane driving is conducted at a low height to diminish the possible consequences of a falling object. Thus, during the interviews, the low driving is conducted for the first time. At this phase, low driving is new to crane operators but will become familiar as driving will be performed in this manner in all following outages. Thus, the identified error possibility becomes smaller during time. A factor predisposing to error is low driving as then, there is less space to drive. An error possibility is that the lifted object hits another object, either or both objects get broken, and the lifting is interrupted for further instructions.

General-level tasks of crane operator

- crane operator performs the tasks in crane operation
  - driving trollies
    - error possibility: trolley is driven too far
    - error possibility: the trolley is driven to rapidly, so that the lifted object starts to swing
  - controls hooks (spinning, lifting, lowering, attaching)
    - hook can be made spinning in 360 degrees; there are two velocities for spinning so when preparing to stop spinning, the slower velocity must be used
    - the hook is so heavy that it does not easily start to spin
  - listens to crane operator assistant (locates physically next to crane operator)
    - factor predisposing to error: when a procedure is updated, an error is inadvertently slipped in the procedure
      - error possibility: crane operator operates according to the faulty procedure
  - two-way communication is the principle according to which crane operator and crane operator assistant communicate
    - factor predisposing to error: two-way communication is not used
      - error possibility: crane operator operates according to faulty coordinates, provided that supervisor for lifting does not notice the error (crane operator assistant looks at a wrong point in the procedure/crane operator assistant provides wrong coordinates by mistake/crane operator mishears/crane operator operates incorrectly by mistake)
- crane operator assistant performs the assisting tasks
  - follows the procedure

        - error possibility: crane operator assistant does not communicate everything included in the procedure (it requires focused attention to deliver all information)
    - communicates the procedure to crane operator
        - error possibility: crane operator does not hear properly or is not focusing on the task and repeats the message in a faulty way
        - error possibility: crane operator assistant does not react on the utterance repeated incorrectly by crane operator and nobody else reacts either the conflict between the sent and repeated message in two-way communication
- supervisor for lifting supervises the lifting event
    - sits next to crane operator and assistant, monitors the proceeding of the lifting and ensures that everything goes according to procedures; corrects the performance of crane operator and crane operator assistant if an error is about to happen or has just happened
        - usually there is no need to intervene
- deviating situations
    - if something deviating happens, the lead of the situation is taken by a representative of one of the following roles:
        - reactor supervisor (manager of mechanics)
        - reactor operator (in main control room)
        - lifting supervisor.

4.2.3 Work development pertaining to heavy lifting

Simulator training is about to begin. Earlier there was no possibility to train heavy lifting, other than learning by doing (simulator is currently being developed). Presently, crane control is performed with a joystick, it is meant to be replaced with a real-like human-system interface. Camera display shows the environment as if constantly being up in the control cabin.

The crane driving session can be recorded. Thus, after the simulator drive, it is possible to go through again the drive if needed.

Presently, it is possible to try crane operations without any instructions or training before it. In the simulator run, only crane operator and crane operator assistant are present.

Procedures are constantly being improved; expressions are made clearer and simpler. For instance, two gauges were provided to the bridge earlier, now there is only one. The values are rounded to the nearest appropriate number. Previously, there were unnecessary sections in the procedures which have been deleted.

- heavy lifting duration could have been earlier, when lifting was performed without procedures, even double compared with the present time
- during lifting or immediately after lifting, crane operator assistant or lifting supervisor or reactor supervisor can make free-format comments to the procedure (suggestions for procedure development) – usually there is something to correct

- crane operator and crane operator assistant who have performed the lifting also correct the procedure with lifting supervisor or their superior
    - factor predisposing to error: in practise, due to lack of time, suggestions for procedure development are processed only after outage; then, it can be difficult to remember why some specific comment was made

4.3 Hierarchical task analysis on the lifting of the protective tube unit

In this section, the hierarchical task analysis of the heavy lifting of the protective tube unit is presented. The factors predisposing to error and the potential of a human error are indicated with red font colour. The Finnish terms that interviewees used and were unfamiliar to the authors, are written without translation, in square brackets and with quotation marks [“like this”].

1. Defining the lifting event

1.1 Anticipating the lifting

- already one day before lifting, objects may be moved away from the lifting route in the reactor hall and possibly also out from the reactor hall

1.2 Starting point to lifting

- the predefined time to start lifting may change during outage
- crane operator may hear about the lifting to be performed the same day the lifting will take place
- not all but only appropriate operators are used for heavy lifting; if needed (such as during illness), an appropriate operator will be separately called to the shift during which the heavy lifting will take place
- both crane operator and crane operator assistant must have ’lifting R’ (nosto-R), that is, the right to perform heavy lifting
- shifts are arranged so that in the shifts during which heavy lifting is probable to take place, those who have lifting-R are in the shift
- the target is to perform heavy lifting at night because then, there is less personnel at work, but it is not always possible
- heavy lifting can be in the beginning, in the middle or at the end of the shift

1.3 The duration of lifting

- time from lifting preparations to releasing the big gripper takes three hours
    - factor predisposing to error: heavy lifting can take place also at the end of the (night) shift, increasing fatigue
    - factor predisposing to error: the shift can extend over its temporal boundaries (also when night shift is in question), increasing fatigue further (for example, heavy lifting can start at 5 o’clock and end after 7 o’clock)

2. Preparing the lifting

2.1 The cover of pit 2 is opened (the same day or earlier than the launch meeting)

- the cover is located in such a place where there is space at that moment
    - factor predisposing to error: when objects are located differently from one outage to another, it is harder to arrange objects appropriately

2.2 Objects are transferred aside in the reactor hall, away from the lifting route (the same day as launch meeting)

2.3 The functioning of the crane and cameras in reactor hall is verified

- verifying the functioning of the crane
    - error possibility: malfunction of a component about to break may be unnoticed
- verifying the functioning of the cameras

2.4 Launch meeting

- procedure is scrutinised
- it is ensured that crane is operated
    - crane operator is identified
        - crane operator is possibly agreed on earlier
        - crane operator usually operates with the same crane operator assistant (but one crane operator assistant can work with several crane operators)
- it is ensured that a person, who reads procedures to crane operator and ensures on his/her part that crane operator operates according to procedures, is present during heavy lifting
    - crane operator assistant is identified
        - crane operator assistant is possibly agreed on earlier
- it is ensured that heavy lifting will be performed according to procedures
    - lifting supervisor is identified
        - lifting supervisor is agreed on earlier
- it is ensured that dose rate of everyone present in the reactor hall can be measured
    - the radiation protection responsible who remains in the reactor hall during heavy lifting is identified
        - radiation protection responsible is agreed on earlier
- it is ensured that the machine for fuel transfer is out of the way of lifting route
    - the driver of the machine for fuel transfer is identified
        - the driver is agreed on earlier

2.5 Headset connection used among crane operator and mechanics (linked to radiophones) is tested

- factor predisposing to error: if battery dies, a headset breaks down etc. during heavy lifting so that the connection is lost, communication will be interrupted for a while (so crane operator does not have connection to mechanics; this is not necessarily realised immediately)
    - error possibility: error due to weakened situation awareness
- factor predisposing to error: crane operator assistant does not have a headset
    - error possibility: error due to weakened situation awareness

3. Starting the lifting

3.1 Controlling the crane with radio control by standing in the reactor hall (read the general-level description on lifting in section 4.2.2, here are only special features for controlling the lifting on the reactor hall floor presented)

- first, crane is controlled by standing on the reactor hall floor, with radio control, later crane operator and crane operator assistant move to control cabin (when this is done depends on the crane operator, latest at point 6.5)
- crane operator listens mechanics and reactor supervisor, located in reactor hall through a headset (the other reactor operator is in the main control room, monitoring the nuclear process in the background)
- crane operator monitors the lifting visually
    - factor predisposing to error: the upper part of the biological shield is not visible when looked at in the reactor hall or by cameras (but it would be visible if seen from the window in the control cabin)
        - error possibility: a human is trapped between the biological shield and the gripper
            - suggestion: some cameras more would be useful
        - crane operator gets information of what happens in the reactor through a radio phone only
        - people who come up with the PTU are not visible (would be visible when looked at from the control cabin) but there is a radio-phone connection
- crane operator performs the lifting (read the general-level description in the section 4.2.2)

3.2 Keeping other personnel away from the lifting area

4. Transferring the biological shield to reactor

4.1 Transferring is done with radio control, standing in the reactor hall, or in the control cabin

4.2 The biological shield is attached to the crane

- hook is driven above the biological shield according to procedures

- hook of the crane is attached to the gripper of the biological shield
  - hook is run in the hole in the biological shield
  - pivot in the hook is run through the hole so that the hook becomes attached
    - mechanic monitors the situation and guides crane operator with a headset
      - factor predisposing to error: the talking of mechanics is not audible for crane operator, because the headset is broken
        - error possibility: attaching takes more time
    - mechanic verifies that everything proceeds as expected; it is easy to observe

4.3 The biological shield is raised to lifting height

4.4 The biological shield is run over the reactor

- factor predisposing to error: if driving too far, an element in the reactor (“reaktoripilkki”, an element that can be disassembled and transferred) is reached
  - error possibility: the biological shield hits the element in the reactor (”reaktoripilkki”) and the element can be broken – nothing hardly happens to the biological shield, but cameras and electric cables can get damaged

4.5 The biological shield is laid on the reactor, the shield remains supported there

- the weight of the biological shield remains in the scales, the gripper is let down to the surface of the PTU
  - crane operator monitors the value in the scales

4.6 The gripper of the biological shield is let down to the reactor

- speed needs to be slackened: when the weight of the gripper falls, the gripper is in the surface of the PTU, that is, in the desired height
  - crane operator monitors the value in the scales

5. Attaching the biological shield to the PTU (crane operator waits)

5.1 Lifting supervisor monitors in the reactor hall that everything proceeds according to procedures

5.2 Mechanic and radiation protection responsible go inside the biological shield before reactor supervisor acts

5.3 Collaboration between reactor supervisor, mechanic and radiation protection responsible to attach the biological shield to the PTU

- reactor supervisor attaches (drives, pushes a button in a control desk) the gripper of the biological shield to the PTU
  - collaboration with mechanic, the discussion is also audible to crane operator

        - it would be good that also crane operator assistant hears what is going on (a headset has been asked for crane operator assistant as well)

- mechanic ensures that the biological shield is attached to the PTU
    - radiation protection responsible goes inside the biological shield with mechanic
    - mechanic ensures that the gripper of the biological shield becomes attached to the PTU (communication with reactor supervisor)

5.4 Mechanic and radiation protection responsible get out from the biological shield

6. Emptying and closing reactor hall

6.1 Based on the functioning of the access control system, it is known who is in the reactor hall; those not participating in heavy lifting are removed

6.2 It is announced from the control room that heavy lifting starts in the reactor hall, outsiders to that must leave the hall

6.3 A notice is put outside the gate of the reactor hall, saying ”heavy lifting is going on, access forbidden”

6.4 The gate is locked by personnel in the control room; the gate is the only route to the reactor hall and when locked, the gate does not open even if the personnel card would be shown to the card reader

- error possibility: the gate is not locked, and unrelated personnel can enter the reactor hall
    - (once a fifth person was waited to arrive to the reactor hall, it was incorrect information; thus, the gate was not locked even if it should have been locked and two mechanics arrived in the reactor hall inappropriately)

6.5 Mechanics, crane operator, crane operator assistant and radiation protection responsible go to the control cabin at this phase at the latest (cabin locates up in the reactor hall)

7. Controlling the crane in the control cabin

7.1 Crane movement is controlled in the control cabin (the location to protect against radiation) (read the general description about lifting in the section 4.2.2, here only the specific features for crane control in the control cabin are mentioned)

- there are 5–6 people in the control cabin, everybody is focusing on crane operator
    - factor predisposing to error: being constantly focused on, crane operator becomes nervous
- crane operator monitors actively the situation
- crane operator looks at the camera display, the camera can also be turned, and there is also one movable camera)
- crane operator monitors a computer display; there are scales, the degree of the bridge, hook orientation, the height of the hook, the location of the trolley in millimetre, and other measures

- crane operator assistant can, in addition to using two-way communication, write the coordinates (millimetre or degree) to a post-it paper; at least one crane operator assistant does this
  - factor predisposing to error: crane operator can erroneously interpret the handwriting of crane operator assistant
  - post-it paper supports the keeping big numbers in mind
- crane operator assistant monitors measures
- crane operator listens to radiation protection responsible in case of increased radiation (is usually a silent follower)
- crane operator listens to mechanic and reactor supervisor, both located in the control cabin [another reactor operator is in the main control room]
- crane operator listens to lifting supervisor, who sits near and monitors that everything proceeds according to procedures and corrects the operations of both crane operator and crane operator assistant in case for an error
  - usually, there is no need to get involved in the lifting
- crane operator preforms the lifting (read the general-level description from the section 4.2.2)

8. The transfer of the PTU from the reactor to the pit number 2 (about 20 meters as the crow flies, driving route about 21-30 meters; during this, everybody remains in the control cabin)

8.1 The biological shield and the PTU attached to it are lifted to the lifting height, according to the procedures

8.2 The biological shield and the PTU are driven to the storage of the biological shield (the driving is set via the storage because the recharger, otherwise on the route, must be avoided)

- crane operator assistant tells crane operator the coordinates to the storage of the biological shield
- crane operator repeats the coordinates aloud, keeps the coordinates in mind and drives the crane accordingly
- crane operator monitors the surroundings proactively so that nothing is ahead in the driving route

8.3 The crane is stopped at the turning point

8.4 The biological shield and the attached PTU are driven above the pit number 2

- crane operator assistant tells crane operator the coordinates to the pit number 2 (based on the coordinates, the crane turns automatically)
- crane operator repeats the coordinates aloud, keeps the coordinates in mind and drives the crane accordingly
- crane operator monitors the surroundings proactively so that nothing is ahead in the driving route

8.5 The biological shield and the attached PTU are lowered to water in the pit number 2

- the biological shield remains outside the pit, supported by its borders, and the PTU is slowly lowered inside the pit number 2
    - the weight of the PTU is known so when the PTU is on water as expected, its weight gets lighter
        - the crane is driven to the coordinates provided (i.e., value for height, in the accuracy of millimetre); when correct height is reached, weight reaches zero (meaning that water supports the PTU) and the grippers can be detached

9. Detaching the biological shield from the PTU in the pit number 2 (crane operator follows the situation, having no role in this)

9.1 All parties take their position for finishing the lifting

- radiation protection responsible, reactor supervisor and mechanic leave the control cabin
- crane operator and crane operator assistant remain in the control cabin
- lifting supervisor remains in the control cabin – sits next to crane operator and assistant, monitors the proceeding of the lifting and ensures that everything goes according to procedures; corrects the performance of crane operator and crane operator assistant if an error is about to happen or has just happened
        - usually there is no need to intervene

9.2 Mechanic and radiation protection responsible go inside the biological shield

9.3 Collaboration between reactor supervisor, mechanic and radiation protection responsible to detach the biological shield from the PTU

- Mechanic and radiation protection responsible detach the biological shield from the PTU
    - mechanic detaches the PTU from the gripper of the biological shield
    - radiation protection responsible monitors radiation related values
- Reactor supervisor opens the elements (“steggerit”) in the gripper using the control desk
- Mechanic monitors the situation and supports the operation as reactor supervisor detaches the biological shield from the PTU

9.4 Mechanic and radiation protection responsible exit the biological shield

10 The transfer of the biological shield to its storage

10.1 The gripper of the biological shield is lifted with the crane, so the attached biological shield becomes lifted as well

- when the grippers are off, the crane is lifted carefully, and the crane operator ensures that the value of the scales does not raise more than the weight of the gripper

10.2 The biological shield is driven, according to the procedures, above the storage

10.3 The biological shield is lowered to the storage

10.4 The big hook of the crane is detached from the biological shield

- mechanic follows the situation and guides crane operator, using headset
- mechanic checks the situation by looking (it is clearly visible)

11 Preparing the crane for the next lifting

11.1 The big hook of the crane (”265”, i.e., lifts 265 kiloton) is lifted up

11.2 The trolly (the one to which the big hook is attached, used only in heavy lifting) is driven to its parking space

- this way another trolley can be taken into service; or the trolley to be used next is defined and the trolley in question is transferred to the next lifting location; usually, after the lifting of the PTU, another specific lifting takes place

11.3 Crane operator and crane operator assistant can exit control cabin (but if they want, they can also remain in the control cabin)

12 The finishing the PTU lifting

12.1 The reactor hall is opened

12.2 Part of the items are possibly moved back to their locations

13 Closing the PTU lifting

13.1 The finishing meeting

- present: crane operator, crane operator assistant, lifting supervisor, reactor supervisor
- heavy lifting is discussed
    - was there something to comment
    - what was successful
    - what could be amended
- the finishing meeting is targeted to be kept immediately after the lifting
- error possibility: there is not always time to have the meeting right after the lifting, meaning that all essential matters are not remembered or are remembered incorrectly during the meeting

5. Discussion

In this study, human errors and, especially, factors predisposing to error are identified for the lifting of a protective tube unit. There are two kinds of predisposing factors: ones are dynamic, affecting the situation in a general way and others are specific to the operation in question.

Five negative dynamic features in outage were identified from an interview conducted earlier. They are

- the long, 12-hour **shift may extend**, also after night shift
- crane operator and crane operator assistant may have to **work for a long time without a pause**
- there is constant background **noise**
- there is constant **haste** due to radiation and people asking for lifting objects
- especially the work of crane operator, when controlling the crane, requires **multitasking**.

Regarding these features, one must bear in mind that in the context of the interview related to the negative dynamic features, features related to outage as a whole were asked for, not the ones specific to heavy lifting. It is possible that pertaining to some factors, the features are not valid for heavy lifting.

However, it can be concluded that the extension of the shift can be detrimental to heavy lifting. It is even highly possible that the effect takes then place as heavy lifting is often conducted at night. Shift extension affects human at night the most, because that's when human is also most tired.

Working a long time without a pause is exhausting and it is as valid for heavy lifting as for any other duty. If there has not been a pause just before PTU lifting, the lifting becomes more loading as it takes several hours itself. It can be assumed that pausing in the middle of heavy lifting is highly avoided.

It is unclear, whether background noise is loud during heavy lifting as then, reactor hall is closed from outsiders. On the other hand, authors do not know either whether the functioning of the crane is noisy as such. To avoid misinterpretation, it can be stated that background noise is present at least outside heavy lifting. Then, being an otherwise constant environmental factor, it has affected human before heavy lifting and its effect may partly extend to also affect the period of heavy lifting.

Haste can be assumed to affect heavy lifting due to radiation related temporal limitations. However, heavy lifting has become more rapid with procedures, meaning that from that perspective, there is more flexibility in the timetable for heavy lifting than earlier. Reactor hall is also empty during heavy lifting, so that the usual bustle is not affecting the circumstances. Thus, the effect of haste is not known – it could be smaller in heavy lifting due to the above-mentioned factors, but it can also be the other way round as outage is busy time, which may affect all activities during outage.

Multitasking is a feature belonging to controlling the crane – the crane movement must be focused on, along with the various measures showing on the screen, as well as the possibility of having some object in the route of the crane.

Hierarchical task analysis enabled us to identify more factors predisposing to human error (Figure 3). These factors, when grouped to data-based categories, are

- human communication related issues
- procedure related issues
- human resource related issues

- malfunction of machine or device
- difficult lifting circumstances
- timing related issues.

The related errors are difficult to categorise because they are in various levels of detail (Figure 3). Error identification may be difficult and there was not much time in the project for that either. Furthermore, errors are hard to conclude by authors because authors are not familiar enough with the detailed operations of heavy lifting. That is why the list of possible errors are to be treated more as examples than close to a fully developed list. The more specific errors, with a clear consequence, are in the beginning of the list, and the more obscure ones are at the end of it:

- human is trapped between the biological shield and the gripper
- trolley is driven too rapidly, resulting in load swinging
- crane hits an object
- trolley is driven too far
- lifting takes more time
- gate is not locked, and outsiders enter reactor hall
- crane is operated based on faulty coordinates
- essential matters are not remembered in finishing meeting
- weakened situation awareness.

The results can be conceived like a sample of factors affecting the emergence of human errors and a sample of errors themselves. Dynamic factors affect lifting throughout its proceeding. Even in the most optimal lifting situation, the nature of lifting itself, requiring multitasking, makes the lifting demanding. In addition to the general-levels factor(s) loading the crane operator and crane operator assistant, there are operations during the lifting, which are more prone to be erroneous than other operations. Even this sample of error-inducing factors shows how PTU lifting is demanding for crane operator and crane operator assistant.

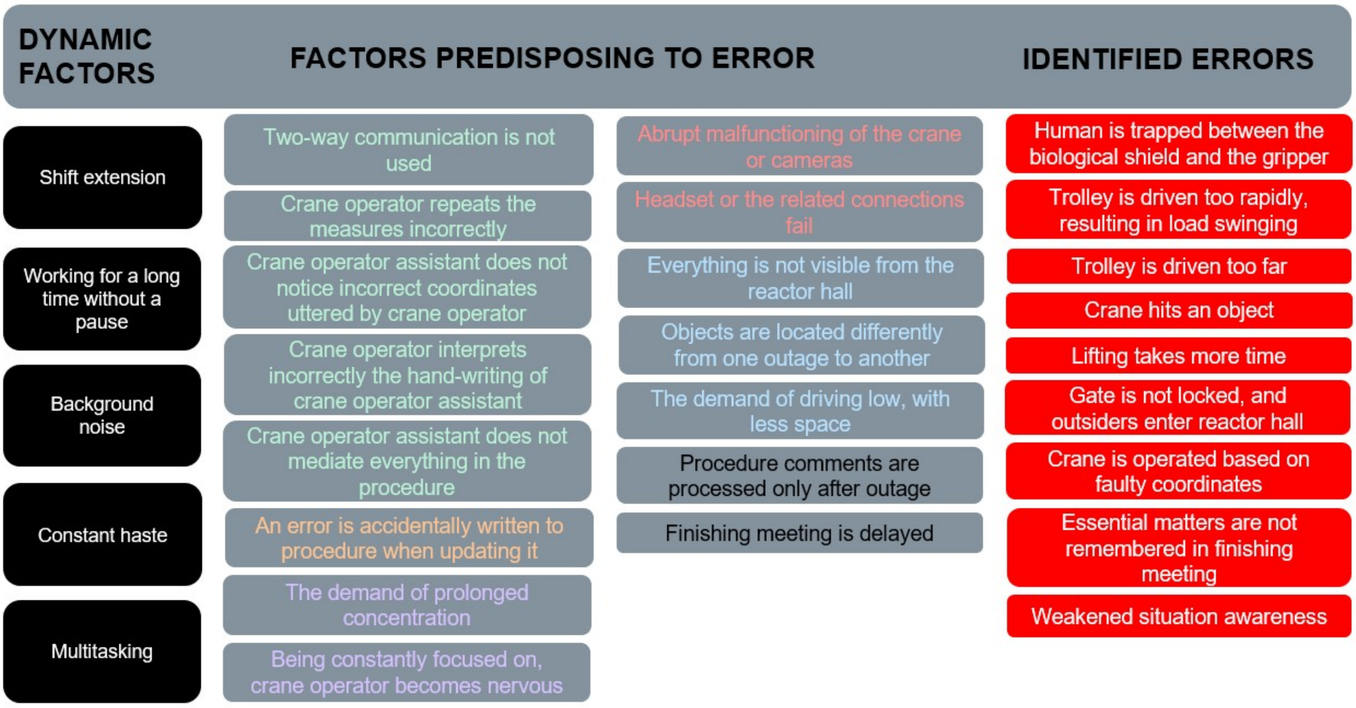

Figure 3. Dynamic factors, identified in an interview, and factors predisposing to error as well as the identified errors, identified in hierarchical task analysis. Regarding factors predisposing to error, ***green*** *colour refers to communication related factors,* ***orange*** *to procedure related issues,* ***violet*** *to human resource related issues,* ***red*** *to malfunction of machine or device,* ***blue*** *to difficult lifting circumstances and* ***black*** *to timing related issues.*

To build a more comprehensive list of all factors and errors, one of the two options should have had taken place. Firstly, if having had enough time, the PTU lifting would have gone through in a highly detailed manner so that also each step taken with the procedures had been included in the study. When all relevant information is included in hierarchical task analysis, it is possible, according to SHERPA (Systematic Human Error Reduction and Prediction Approach) (Stanton & Baber, 2002), for human factors/HRA professionals to conclude the possible errors. Alternatively, more interviews would have enabled crane operators and crane operator assistants to contemplate the possible error inducing factors and the errors themselves.

With more time, errors could have been analysed further. Then, what follows an error could have been described, error probability and criticality would have been estimated (both in highly rough scale) and the way recovery could take place would have been described.

The factors predisposing to error, identified by authors, belong to the group of human communication related issues. They are of the kind, which are possible to identify without thorough understanding of matters involved with controlling the crane.

As care has been taken when collecting the data and interpreting it, results are, as conceived by the authors, reliable albeit imperfect regarding all possible factors identifiable in the lifting of the protective tube unit.

Lifting is also being supported. Procedures are designed and they are improved by crane operators and crane operator assistants based on their lifting experience. It is excellent that the experience of those who perform the lifting is used in improving the procedures. A more systematic approach could also be used – the way the procedures are being improved (by finalising values to be more user friendly) indicates that the first version has been far from finalised. Furthermore, if the procedures are only improved by separate operators, in a separate way, just after each lifting session, procedures may remain somewhat inconsistent. It would be highly beneficial pertaining to the quality of the procedures to have a consistent and systematic approach in procedure design. It can be reached by creating explicit principles and rules according to which the procedure shall be built and then by developing procedures according to them in a focused manner.

Lifting simulator is also being designed. When it is finalised, the best of it could be reached by planning simulator training, i.e., some principles according to which the inexperienced operator uses the simulator, to avoid such a situation that no feedback and guidance is provided accompanying the driving with the simulator.

6. Conclusions

In this study, the lifting of protective tube unit was focused on from the perspective of factors affecting human error and the errors themselves. Factors affecting error occurrence are classified into dynamic features, affecting in the background irrespective of the phase of heavy lifting, and the more specific factors, which may occur during the various phases of heavy lifting.

Even this sample of dynamic features and other issues related to human error show that the reasons for human error can be a complex combination of factors, some affecting constantly, some occasionally and in a more unique manner. The method used – hierarchical tasks analysis combined with data-based analysis of error-inducing dynamic work-related factors – proved effective in identifying relevant tasks and the related issues with human error. A more thorough understanding on issues increasing error possibility could be reached by the same methodology as used in this study, with just more resources (the amount of person months and the number of interviews).

The results of the present study can be used in subsequent research. However, the SAFIR programme period is about to end, and no studies about this subject are to be expected in SAFER (the programme that continues the nuclear research legacy after SAFIR) in the near future.

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