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Design of procedures for rare, new or complex processes: Part 1 – An iterative risk-based approach and case study

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Abstract

The paper describes a proposed approach for operationalizing the Common Operational Picture concept introduced in the EU FP 7 TOSCA (Total Operations Management for Safety Critical Activities) project, in order to jointly integrate and enhance safety, quality and productivity in the production environment. The approach combines different methods for the description and analysis of plant and operations, including Task Analysis, 4D process simulation, hazard analysis and Pareto optimization, and iterates through them to generate a final procedure. The proposed approach has been demonstrated on an industrial case study related to planning of infrequent cold water pressure testing of LPG storage tanks, and the process and results of this case study are presented and discussed. The plant management was provided with a detailed list of the main tasks (22), sub-tasks (115), the specific risks identified (26, considering procedural delays, occupational safety and process safety) and the specific recommendations (20) for safety and time optimization of the planned testing procedure. The approach was successfully demonstrated as a suitable vehicle for the analysis and planning of rare, complex, unconventional work tasks that are hard to visualize, where the establishment of a Common Operational Picture (COP) among all relevant personnel in the hazardous operations is a must.

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A B S T R A C T

The paper describes a proposed approach for operationalizing the Common Operational Picture concept introduced in the EU FP 7 TOSCA (Total Operations Management for Safety Critical Activities) project, in order to jointly integrate and enhance safety, quality and productivity in the production environment. The approach combines different methods for the description and analysis of plant and operations, including Task Analysis, 4D process simulation, hazard analysis and Pareto optimization, and iterates through them to generate a final procedure. The proposed approach has been demonstrated on an industrial case study related to planning of infrequent cold water pressure testing of LPG storage tanks, and the process and results of this case study are presented and discussed. The plant management was provided with a detailed list of the main tasks (22), sub-tasks (115), the specific risks identified (26, considering procedural delays, occupational safety and process safety) and the specific recommendations (20) for safety and time optimization of the planned testing procedure. The approach was successfully demonstrated as a suitable vehicle for the analysis and planning of rare, complex, unconventional work tasks that are hard to visualize, where the establishment of a Common Operational Picture (COP) among all relevant personnel in the hazardous operations is a must.

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1. Introduction

This paper describes the results of work undertaken to develop approaches for integrating and enhancing safety, quality and productivity under the EU FP 7 TOSCA (Total Operations Management for Safety Critical Activities) project (http://www.toscaproject.eu). The TOSCA framework is based on four pillars (Commitment in Action, Understanding Hazards and Risks, Managing Risk, and Learning from Experience) that support the establishment of Common Operational Picture (COP; see Leva et al., 2015) among all relevant personnel in hazardous operations; in other words, all stakeholders develop and share the same mental model. The term originates from the military domain where it is used to describe the complete graphical picture of the battlefield used by commanders to make effective command decisions (Looney, 2001). The aim of a COP is to share situation awareness among distributed stakeholders and the concept has also been applied in emergency management and humanitarian crisis management (McNeese et al., 2006). In addition, establishing a COP can serve as a vehicle for integrating and enhancing safety, quality and productivity. One of the TOSCA safety processes is Design and Planning for Safety (part of Managing Risk pillar), and to support this pillar a risk assessment process for complex work operations has been developed. The proposed process is suitable for assessing risks due to, for example, the introduction of new or rarely applied processes or procedures. The case study presented in this paper focussed on a non-routine maintenance and inspection task. Rare or unconventional tasks are good example of large uncertainties (due to lack of the required information/knowledge) that can easily lead to differences in COP among the personnel and procedure(s) to be followed. Specifically, differences in the COP/situation awareness, for example different perceptions of the involved personnel, different execution of the hazardous procedures, or different adherence to pertaining safety criteria to be followed, etc., can clearly lead to accidents. Thus this paper proposes an approach to improving the understanding of hazards, management of risks, and communication of processes in the case of rare procedures.

Abbreviations: COP, Common Operational Picture; LPG, liquefied petroleum gas; SCOPE, Supply, Context, Process and Effects; TA, Task Analysis; TOSCA, Total Operations Management for Safety Critical Activities.

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The proposed approach combines four principal methods:

i. **Task Analysis (TA):** predominantly a human factors method, task analysis maps out the tasks, tools, and equipment needed to achieve the work;

ii. **4D Process Simulation:** uses the task analysis to drive avatars in a 3D model of the work environment. The 4D Simulation can be used to communicate the process, and as the basis for discrete event simulation;

iii. **Task HAZID:** identification and evaluation of hazards using the information from the task analysis and 4D simulation; and

iv. **Optimization:** identifying key opportunities to improve the process using the task analysis, 4D simulation results, operational costs, and sensitivity analysis.

These four main steps may be iterated several times until the task analysis is stable and includes all planned activities. The overall approach aims to identify potential hazards, as well as areas for improvement, both in terms of process safety and efficiency.

This paper will explain the overall approach, methods and tools in Section 2. In Section 3, the application of the approach and results from the case study will be presented. The case study concerns the rare periodic procedure of inspection of pressurized vessels for liquefied petroleum gas (LPG) storage. The complex cold water pressure testing procedure is applied rarely in the organization studied (in reality every 10+ years), and thus is affected by staff turnover, equipment changes, procedure difficulties, etc. Hence, the plant management are keen to reduce uncertainty around planning, monitoring, downtime and safety implications and help ensure the safe and efficient completion of the testing. Conclusions on the value of the recommendations generated by this approach for the plant management from the case study, as well as on the overall approach, are given in Section 4.

2. **Approach**

The approach developed in this work applies Task Analysis (TA) to provide a detailed description of the operation under analysis, and uses this TA as the basis for subsequent 4D modelling and visualisation of the operation. This combination of methods provides the analysis team with a clear representation of the details of the operation(s), equipment, resources, etc. It also enables the team to apply the hazard identification methods and perform qualitative risk categories ranking, as well as consider efficiency optimization (e.g., in terms of resources needed, time, staffing, and equipment, etc.). Fig. 1 describes the overall approach and highlights the point at which decisions should be taken, i.e. after the optimization step. At this point, recommendations from previous steps are compiled and assessed for completeness and the tolerability of the residual risk levels is determined. The approach also includes the ability to iterate the task analysis to facilitate the situation where the analysis leads to changes or additions to the steps in the operation. Each of the steps in the proposed approach are discussed in detail in the following sub-sections.

The approach assumes that the assessment team is adequately composed of both experienced risk assessors (e.g., considering task analysis, HAZOP and similar methods), as well as of the diverse technical personnel that can provide at least basic knowledge about envisaged work procedures, equipment, documentation, limitations, contractors, etc. Considering Fig. 1, the “End (Reporting)” is to be reached when the team members reach a common understanding (or COP) about the operation under analysis and relevant operational and safety issues.

2.1. **Task analysis**

Task analysis is a method originating from the human factors discipline that is used to describe human actions and interactions within a system. It forms the basis of further analysis of human activity within a system, and can be described as the analysis of how a task is accomplished. A task analysis includes a detailed description of the physical and/or mental activities undertaken by human actors, information on the task durations, frequency, complexity and allocation to human or other agents as well as describing the location or environment in which the task takes place, equipment and information required to complete the task, and any other factors of interest to the specific analysis (Kirwan and Ainsworth, 1992). The task analysis is an important representation of the operation and overall socio-technical system and provides a solid foundation for the subsequent system analysis that helps ensure comprehensive identification and evaluation of all relevant hazards and risks. The most common form of task analysis is Hierarchical Task Analysis (HTA; Annett and Duncan, 1967) and variations include Link Analysis (Chapanis, 1996), Operational Sequence Diagrams (Kirwan and Ainsworth, 1992), Cognitive Task Analysis (CTA; Stanton et al., 2005) as well as methods used more widely outside the human factors domain such as Business Process Modelling (Aguilar-Saven, 2004). Task analysis methods including hierarchical task analysis and process mapping are widely used in the design of procedures (e.g. Embrey, 2000; McCarthy et al., 1998) and as the basis for analysing safety, particularly when accounting for possible human errors (Balfe and Levi, 2014). In this approach and case study, the Business Process Modelling approach was applied as incorporated in the SCOPE software tool (Supply, Context, Output, Process and Effects; McDonald et al., 2011). The SCOPE software represents the task analysis in the form of a process map and links each task within this map to a template.
for hazard identification, using a technique similar to HAZOP (Kletz, 2006). Information to populate the task analysis is typically gathered from documentation, particularly procedures, where available, but also incorporates experiences of team members. Task analyses are also frequently refined through iterations, particularly when a clear procedure is not already defined, as was the situation in this case study. Interaction with the 4D modelling helps to facilitate the identification of constraints and alternative procedures that drive the iterations.

2.2. 4D modelling

Simulation can be defined as the use of a model to imitate a real-world process or system over time and 4D simulation describes the integration of a 3D computer model of an area with time related or schedule information with the first requirement being a 3D model representing the key characteristics of the environment in which the process will take place (Banks et al., 2001). In some cases, a 3D model of the plant or site may already be available from design works or in the form of a Building Information Model. In other cases a new model can be constructed from drawings, from laser scanning, or, as in this case, from photogrammetry. Once the 3D model is combined with schedule information, the simulation can then depict the operation of the process over the fourth dimension, time. The combination of schedule information and 3D models to create a 4D simulation of a process in order to assess health and safety issues has previously been applied in the construction industry (e.g. Ganah and John, 2011; Ciribini and Galimberti, 2005), but here we apply a more detailed task analysis rather than high level schedule information. The specific approach used in this paper focuses on the use of discrete-event simulation, which models a process as a discrete sequence of well-defined events in time where each event occurs at a specific time and marks a state change in the process (Robinson, 2004). To achieve discrete-event simulation, the process must have a predetermined start and end point and the events to be simulated must occur between these points.

Although currently 4D simulation is perceived as an advanced technology with associated high costs, the technology is increasingly in reach of even small enterprises and is already commonly used to monitor or predict processes and procedures in industries such as manufacturing. For this study, we focussed on the use of 4D simulation to build the ‘common operational picture’, building on the ‘learn by doing’ principle implicit in the simulation. Park et al. (2011) has previously found positive impacts of 4D simulation on productivity and safety in the construction industry. The case study in this paper considers a process that is distributed both across different roles and geographically across the site and one which is not frequently undertaken. In such cases, building a common operational is more difficult as the roles involved do not have direct experience, and may not routinely work with each other. Visualisation of the process can help overcome these barriers and Sacks et al. (2009) and Kang et al. (2007) have shown that logical errors in construction schedules can be detected quicker and more reliably using 4D models as compared to 2D drawings. The simulation can facilitate the personnel in visualising and reviewing the process virtually, suggesting potential improvements, and becoming familiar with the planned process and their role within it before the work begins. It can therefore be instrumental in developing a COP in the affected staff. A similar result might be achieved via a ‘dry-run’ or other planning activity on the actual plant, but the ability to achieve this in practice can be limited by lack of access or risk of damage to the plant or injuries to personnel. Therefore, simulation offers a practical method to optimize, plan and prepare for infrequent or complex activities and thereby minimize the risks during the actual operation.

2.3. Safety analysis

Once the task analysis and simulation are complete, the safety analysis can be achieved. The task analysis is used as the basic functional analysis to support a structured hazard identification workshop, similar to a HAZOP study (Kletz, 2006), where, instead of plant parts, the nodes in the task analysis are the unit under analysis and potential performance deviations are considered (as in Leva et al., 2012; Demichelis et al., 2014). For the case study, an analysis team containing all the required expertise (plant knowledge, operational knowledge, safety assessment expertise, human factors knowledge) was assembled to identify and assess the hazards. The assessment applied a semi-quantitative risk category estimation to distinguish between safety and productivity issues. Each consequence and its associated likelihood was rated on a scale of 1–5 and the product of these values gave the risk score. The SCOPE software was used to conduct the hazard identification and risk categorisation and to document the results of the assessment (Fig. 2). The capacity to perform the task analysis, hazard identification and risk categorisation in one software application streamlines the analysis and simplifies the documentation of the analysis itself.

2.4. Optimization

The final step in the approach is to optimize the planned process to achieve benefits in terms of safety, efficiency, or productivity. Two methods can be applied: first, applying Monte Carlo simulation or second, a simpler Pareto-type analysis. The first approach can use implementation and operating costs, for example, as the dependent variables and the Monte Carlo method applied to test different options on the use of resources (see Balfe et al., this issue for an application of this approach). The result is a local optimization within the system based on cost. For example, (sub)tasks that can be carried out in parallel can be identified and the relative benefit of using more personnel for some or all of the tasks explored, etc.

The second optimization method applies to the results of the task analysis and the hazard analysis, where the initial list of tasks is next refined and subjected to further optimization, considering the hazards identified and assigned safety measures. This approach is less complex than the Monte Carlo simulation, and was used in this case study. This optimization is best applied after the hazards have been analysed/revealed and the focus applies to non-safety related aspects such as individual task duration and cost. Opportunities for improvements can be identified using a Pareto type optimization (Pareto, 1906) or other form of sensitivity analysis.

3. Case study – process and results obtained

The case study discussed here is based on the periodic pressure testing of spherical pressure vessels at the premises of Plinarna Maribor d.o.o., LPG storage site located in Maribor, Slovenia (project partner). In order to understand the situation that led to this case study, the applicable legal background and implications on the preparations for the pressure test are explained in Table 1.

The procedure for cold water pressure testing of these vessels consists of many steps, all of which must be captured in the task analysis. The specific pressure vessel considered in this case study is one of two 1000 m³ spherical, above-ground storage tanks at the premises. Broadly, the procedure involves removing the product stored in the vessel, inertization (e.g., filling-up with water), conducting the cold water pressure test, emptying the vessel, conducting an internal visual inspection, ultra-sound and X-ray spot testing, and then finally returning the vessel to operation. Although

the older plant personnel were knowledgeable of the overall process and could easily produce a high level description of the work, due to the lack of procedures specific to this site and the use of other testing methods in recent decades, the detail of durations, potential hazards and criteria for safety proceeding to the next step, etc. were not readily accessible to plant personnel. The initial state of missing knowledge of how to plan the test procedure in detail was a good example of difference in required COP among the personnel, procedures to be followed and related equipment.

For example, the plant personnel perceived a large uncertainty about the overall duration; the required downtime per storage tank was assumed anything up to two months, however that deemed outrageous in terms of lost production. The study described here was pursued in order to reduce the uncertainty and facilitate better planning of the procedure to be used.

Table 1

<table>
<thead>
<tr>
<th>Summary of case study background and implications for the industrial partner.</th>
</tr>
</thead>
<tbody>
<tr>
<td>The LPG storage plant has two 1000 m³ above ground spherical pressure vessels, constructed in 1970s. The vessels have technical dossiers, including certificates from the initial and past periodic integrity tests (e.g., using cold water pressure testing). The pressure vessels are regulated in the European Union by a set of legislation and technical standards:</td>
</tr>
<tr>
<td>• At the top is the current Pressure Equipment Directive (PED) – EU, 2014, being transposed to the national legislation of the member states.</td>
</tr>
<tr>
<td>• In Slovenia, that is done through Rules on pressure equipment (RS, 2002) and the testing specifically by the Regulation on examination and testing of pressure equipment (RS, 2008). In addition Rules on liquefied petroleum gas also apply (RS, 1991).</td>
</tr>
<tr>
<td>• Details of the testing methods that can be used are set by the applicable European Standard EN 13445-5 Unfired pressure vessels – Part 5: Inspection and testing (CEN, 2014).</td>
</tr>
<tr>
<td>Thus, the current plant management had all the certificates on the integrity of the pressure vessels, but historical work records of the past preparations were not available any longer (cold water pressure testing was last performed in 2002, subsequently ultra-sound tests from the exterior were applied, as that is also permitted in the intermediate period).</td>
</tr>
<tr>
<td>As mentioned in the Introduction section, the current management were aware of the requirements, but in 2002 the detailed work procedure for preparations, testing and return to operations was not prepared (permits-to-work were used, but those records are no longer available). The older workers were knowledgeable of the general description of the work, but details for the specific procedure were not available.</td>
</tr>
<tr>
<td>Needless to say, the above mentioned legislation and standards do not specify in a detail how apply the procedure in a specific plant &amp; installation that needs to be prepared specifically (e.g., following CCP5, 2007, section 10). In addition, the related API publications and standards (e.g., API, 1994, 1996) are helpful here (e.g., API (1996) Appendix E as a procedure planning checklist), however, again the site-specific procedure needs to be developed in a detail.</td>
</tr>
<tr>
<td>To conclude, the plant management’s imperative was to address the uncertainty about the duration of the overall procedure (economic implications), accompanied by the safety concerns. The aim was not to identify possible improvements to the principal testing and inspection methods (CEN, 2014), but about developing a plan and subsequently an overall procedure to safely and efficiently implement the testing procedure in a specific plant.¹</td>
</tr>
</tbody>
</table>

¹ Note: There is also anecdotal evidence about the actual practices used in a part of the LPG industry (not specific to a given organization or country) to prepare for the cold water pressure testing and visual inspection inside of the LPG pressure vessels. Such practices include use of the natural air ventilation to remove the gas phase completely out of the emptied and opened vessel (thus directly violating the above-mentioned standards and legislation).
### 3.1. Task analysis

The task analysis was initially based on knowledge of the procedure elicited from site personnel, and was constructed in the SCOPE software. The development of the task analysis provided site management with the opportunity to describe the high level tasks and document details of the foreseen sub-tasks (Fig. 2). Actors, information, tools and expected duration were also captured for each envisaged task. In total, 23 main tasks and 115 sub-tasks were identified as the ‘Original’ task list to be pursued within the testing procedure. This was used as the basis for an assessment of the total duration, which equated to 368 h (15.3 days), considering 24/7 operations.

### 3.2. Creation of 3D visual and 4D model/simulation

In order to provide a basis of the 3D model, the site was extensively digitally photographed. Pictures were taken across the site from all possible angles of the buildings, equipment and layout of the site. Photogrammetry software was then used to create

![Fig. 3. 4D simulation illustration from the case animation.](image)

### Table 2

<table>
<thead>
<tr>
<th>#</th>
<th>Recommendation</th>
<th>Related tasks</th>
</tr>
</thead>
</table>
| 1 | Prepare a detailed written cold water testing procedure, following the tasks identified and implementing the specific recommendations given next. Suggested main topics:  
- General and specific planning of the testing (e.g., assurance of the contractors/equipment, list of all personnel (internal/external)),  
- Logic sequence of the tasks and sub-tasks, for each to consider validation criteria for completeness, as well as to mention anticipated hazards and required permitting,  
- Testing reporting – progress in time, persons involved – on suitable forms and check-lists, as well as to appoint approvals to next step(s). | All           |
| 2 | Use of the torch with two pilot flames with thermal lock system – in order to assure reliable pilot flame | 5, 23         |
| 3 | Consider purging of the remaining LPG gas in the storage tank at level between 95% and 100% by nitrogen, from either car tanker with vaporizer, or from the bundled bottles. Prepare a detailed nitrogen purging protocol, related to recommendation 1. | 7, 8, 22      |
| 4 | Permanently monitoring of the tank water fill-in process; to assure adequate staffing and specific appointed person. Setting on the SCADA for an audible alarm at 98% of full tank. | 7, 22, 23     |
| 5 | The measurement instruments used, are to be checked constantly during the test, related to strain gauges and movement of the tank observations. In case of the deviation(s) stop the procedure, thus the criteria must be defined prior the cold water testing starts. Note: additional task to be added to the previous task analysis to assure the mentioned equipment and contractors. | 7             |
| 6 | Plan the engagement of the contractors. Risk assessment of the operations and safety measures to be in place according to the national legislation on occupational health and safety, e.g., regarding work at height, falling objects/tools, work in closed spaces or potentially oxygen depleted atmosphere/flammable atmosphere, as well as common workplaces. | 8, 16, 18, 20, 21 |
| 7 | Consider in the procedure to check the water level before removing the valve at the end of task 8 (in order to assure low enough amount of the remaining gas inside tank). | 8             |
| 8 | In recommendation 1 consider also planning of the suitable crane with long enough arm to reach top of the sphere. | 8, 21         |
| 9 | While planning the high pressure water feed connection from the fire water system into the storage tank (considering the selected high pressure pump):  
- specify flexible hose rated for high enough pressure (30 bara) – validate with vendor/supplier,  
- as a back up plan for hose failure/leak, prepare in advance a fixed piping, or prepare sufficient fixed pipes and joints parts, to assemble connection on the spot. | 9             |
| 10 | Plan strict use of the validated and calibrated equipment (e.g., pressure and level measurements), validate also high pressure water specific rate, to be received from the contracted inspector. | 12            |
| 11 | Plan in a detail where to install blind flanges at the storage tank connections, in order to assure tightness at the connections during the high pressure test. | 12            |
| 12 | In recommendation 1 consider also correct sequence of actions to lower the water pressure in task 13 (13.3, related to the potential high pressure water jet, injuring the personnel). | 13            |
| 13 | Plan the electrical wiring and electrical installations to be installed only from the top opening, and not from the bottom opening, in order to prevent electrocution hazards, related to the potentially falling objects/tools for visual inspections, ultrasound testing and X-ray testing, expected to be done inside the storage tank. | 16, 18, 20    |
| 14 | Check with the insurance company about the liability coverage on cold water testing procedure, considering the own and the contracted personnel, as well as the equipment used/present. | All           |
the 3D models of the buildings and equipment at the site. These buildings were placed inside a high-resolution image of the site, which was taken from Google Earth. The result was a highly accurate and easily recognisable 3D model of the site, which was constructed without the effort and cost of manually creating the model.

The 4D simulation was constructed by combining the 3D model with information from the task analysis. The behaviour of the individual tasks were modelled, including stochastic values for process and movement times. The simulation resulted in a video of the planned operation, which was annotated with information from the task analysis, for example naming each step being carried out in the video. Thus, the simulation demonstrated the planned operation in order to support the development of the common operational picture at the plant by providing a method to communicate the complex procedures to the plant personnel, and to facilitate optimization of the tasks. Fig. 3 illustrates a screen capture from the simulation.

3.3. Safety analysis

The safety analysis took the form of a task based hazard analysis, using both the task analysis and 4D model as inputs and generating a list of recognised risks and additional safety measures as outputs. The team identified 26 potential deviations with the potential to lead to accident scenarios. Three main types of negative consequences emerged during the analysis which are listed below in increasing severity:

i. **Procedural risks (work delays):** examples included too few fitter personnel at piping re-assembly, crane arm too short to perform PSV removal at the top of the sphere, and a low flow-rate for filling the vessel.

ii. **Occupational safety risks:** examples included personnel injuries due to LPG torch flame-off/on, working at height, suffocation or electrocution hazards inside vessel, etc.

iii. **Process safety risks:** examples included damage to equipment and/or personnel injuries/fatalities due to water ingress into compressor, tank vessel static overload with water (deteriorated legs), sphere damage by applying pressure above 25 bar, etc.

The outputs of the analysis were compiled as a list of recommended additional safety measures to be incorporated into the testing procedure. These are reported in Table 2.

The safety analysis also identified the need for additional, unforeseen tasks, the possible rescheduling of some subtasks, or the addition of specific precautions as part of a task. The task analysis was therefore updated to reflect these changes to the procedure, producing the ‘Optimized’ version of the plan and related graphical diagrams from the SCOPE software. Both procedures are presented for comparative purposes in Fig. 4. Changes of note include the merging of some tasks (e.g. 9 and 10 merged into a new 9) in order to emphasize close connections between subtasks, the addition of explicit decision points (e.g. new task 17, old 17 became 18), and the addition of new tasks (final 25. Start up of the site), with the final Optimized procedure featuring 22 top level tasks.

3.4. Optimization

The total duration of the ‘Original’ procedure was assessed to about 368 h (15.3 days), considering 24/7 operations. This was compared to an initial estimate prepared by the plant prior to this study, based on organisational memory, of about 30 days. For the ‘Optimized’ list of tasks to be pursued within the test procedure, the total duration was assessed to be about 354 h (14.8 days). The optimization was obtained by considering the safety recommendations (Table 2) and identification of tasks that can be done in parallel; the comparative time saving gained from ‘Original’ to ‘Optimized’ list of tasks of about 14 h is also a result of identification of overlapping tasks that can be done in parallel (specifically, main tasks no. 3, 8 and 20).

Fig. 4. Task analysis diagrams for both the Original and the Optimized alternatives of the cold water pressure testing procedure.
Next, a Pareto style analysis was applied to optimize the task list, specifically by sorting the main tasks in decreasing duration time based on information collected during the task analysis. The longest tasks were subject to further analysis in order to identify possibilities to reduce their duration. The cumulative results for both Original and Optimized procedure alternatives are presented in Fig. 5. Here it is clear that the top 5 main tasks of the total 22 (22.7%) are related to 70.1% or 72.8% considering the ‘Original’ and ‘Optimized’ alternatives, respectively.

After consultation with the plant management, it was identified that some tasks could be accelerated using more resources (e.g., contracted personnel), although the same person hours are needed. This alternative was acknowledged by the management (see Table 3, e.g., items no. 15 and 20), but not yet evaluated within the duration of the ‘Optimized’ task list.

While not exactly following the proposed 80/20 Pareto rule, the approach provided additional insights about tasks that prove the value of time optimization. In addition, for those tasks optimization opportunities were listed, and are to be added to the previous list in Table 2.

4. Conclusions

This paper has presented an approach to designing and planning for safety, consisting of interconnected methods and tools, namely task analysis, 4D simulation, safety (hazard) analysis, and optimization. The approach is proposed for complex or rare procedures, where there is a level of uncertainty related to the procedure or its implementation in a new environment. The proposed approach was tested on a case study of cold water pressure testing of LPG storage tanks and it identified 26 potential deviations that could lead to delays, occupational accidents and process safety accidents. In addition, it provided in total 20 specific recommendations for the industrial partner on how to plan in detail this infrequent and demanding testing procedure. In other words, plant manager, plant personnel, and contractors all gained better understanding and sharing of the Common Operational Picture about the testing procedure (equipment, resources, interactions), related hazards, risks and operability and safety measures that shall be planned and executed. Based on the recommendations, the plant manager developed a detailed Procedure for periodic testing of the stationary LPG storage tanks (the procedure is thus a controlled document within the organization’s management system).

While it was not possible to carry out the actual field testing procedure in order to compare the performance with the tasks and evaluate the recommendations in this paper, a comparative risk assessment among ‘Original’ and ‘Optimized’ alternatives and cost-benefit analysis is available (Gerbec et al., this issue). In addition, the plant management provided strong support for the approach, which provided benefits of increased clarity across all

Table 3
Summary of recommended measures from the optimization step (see Section 3.4 and Fig. 5). Note that numbering continues from the list provided in Table 2.

<table>
<thead>
<tr>
<th>#</th>
<th>Recommended measures</th>
<th>Related tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Evaluate alternative to apply more personnel at re-assembly task for entry flanges and</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>SRVs, as overall person-hours needed should be the same, thus less time here.</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Evaluate alternatives in organizing work on 8 h per day, against e.g., 24 h x 7 days</td>
<td>12, 16</td>
</tr>
<tr>
<td></td>
<td>per week basis, for whole testing procedure.</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Expected water flow rate into tank is unknown; plan and perform a small scale tank</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>fill-up test using same conditions and equipment in order to get at least some</td>
<td></td>
</tr>
<tr>
<td></td>
<td>estimate.</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Consider using larger pipework (over 2&quot;) and/or shorter pipework, in order to</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>increase water flow out rate and save time here.</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Assess and plan which tasks and sub-tasks can run in parallel, e.g., this one</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>during water flow out sub-task.</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Consider more inspection personnel to speed up the work.</td>
<td>12</td>
</tr>
</tbody>
</table>

Fig. 5. Pareto chart for cumulative duration of 22 main tasks for ‘Original’ and ‘Optimized’ procedure alternatives. Data suggest that top 5 out of 22 overall tasks (22.7%) are related to 70.1% or 72.8% considering the ‘Original’ and ‘Optimized’ alternatives, respectively.

stakeholders of the plan, and increased confidence in the time and resources needed to complete the works.

Finally, the proposed approach can be easily applied on other safety or production critical operation, especially when the tasks are hard to visualize and the human factors play a relevant role (e.g. batch processes). A transferability study of an overhaul procedure at a power plant is described in Balfe et al. (this issue).

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