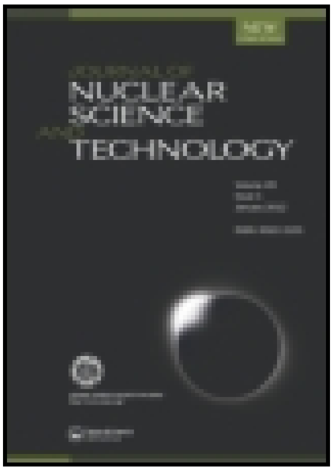

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Comprehensive support for nuclear decommissioning based on 3D simulation and advanced user interface technologies

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ARTICLE

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There is an increasing international focus on the need to optimise decommissioning strategies, driven by the anticipation of high costs and major effort for the decommissioning of nuclear facilities in the coming decades. The goals are to control and mitigate costs and negative impacts on workers, the general public, and the environment. The methods presently employed for many decommissioning tasks do not apply the latest advancements of science and technology. Therefore, there is growing interest in research and development into the adoption of novel techniques for improving safety, reducing costs, and increasing transparency.

This paper provides a comprehensive overview of the authors' results from investigating how current and emerging technologies can be applied to enhance the international decommissioning strategy, focussing in particular on three-dimensional simulation, virtual reality, advanced user interfaces, mobile and wearable devices, and geographical information systems. Our results demonstrate that emerging technologies have great potential for supporting adoption of new instrumentation, improving data and knowledge management, optimising project plans, briefing and training field operators, and for communication, surveillance, and education in general.

Keywords: nuclear power plant; decommissioning; radiation protection; 3D simulation; radiation dose; reactor safety; radioactive waste management; optimisation; ALARA

1. Introduction

The topic of nuclear decommissioning is becoming increasingly important due to nuclear installations reaching the end of their lifecycles, unfortunate events, decommissioning plans as a licensing requirement for new builds, and political decisions resulting in premature initiation of the decommissioning phase. As a response to the increased international interest in research and development into this topic, building on earlier experience [1–3], we intensified our efforts in this area [4,5], partly through the OECD Halden Reactor Project [6], a research program jointly financed by 20 countries.

Conditions and requirements for decommissioning projects differ depending on the background to their being initiated. Nevertheless, the main question is always the same: How can we optimise the project, i.e. maximise safety to be well within regulatory requirements, while minimising time and costs? The intention of this paper is to provide a comprehensive overview of how three-dimensional (3D) simulation, virtual reality (VR, interactive 3D technology inducing a sense of presence), and advanced user interface (UI, such as gestural interfaces and multi-touch interaction surfaces) technologies can be utilised to improve efficiency, safety, and transparency of nuclear decommissioning projects. The information provided here is the result of many years of experience in research and development by the authors on advanced computer simulation-aided technologies for realistic 3D simulation of work procedures, real-time 3D radiological risk assessment, and VR-based immersive training.

The authors have also been active in both research and the industrial application of 3D computer simulation and emerging technologies to support advanced visualisation of complex 3D data, registration of data connected to 3D environments, scheduling work tasks, and monitoring work progress, advanced communication (within the team and to stakeholders), and rapidly produced and easily perceived environmental monitoring and impact assessment.

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A number of software tools have been developed by the authors to support this work. The Halden Planner [7] is a 3D simulation tool for planning and optimising work procedures in nuclear environments. The Halden Briefer is a briefing and instructor-led training tool for demonstrating work plans developed using the Halden Planner. The Halden Simulation Editor [7] is a VR-based tool for producing interactive training in nuclear environments. The Halden Trainer is a tool for providing training produced using the Simulation Editor to trainees. These tools have been partially developed within the joint program of the OECD Halden Reactor Project [6] and are freely available to the member organisations. In addition to the more general-purpose software solutions developed within the joint research program, a series of case-specific custom tools have been developed in the frame of bilateral agreements based on the specific user requirements of targeted end-users. These customised tools are based on a commercial variant of the Halden Planner, the HVRC VRdose system [7]. For example, the Andreeva Planner has been developed specifically to support implementation of the as low as reasonably achievable (ALARA) principle and high-level safety culture during the planning of the rehabilitation of the most dangerous nuclear site in the northwest of Russia, operated by the Andreeva Bay branch of the Northwest Center for Radioactive Waste Management (SevRAO) [8].

In addition to the tools listed above, we have also developed a tool that interfaces to a geographic information system (GIS) to incorporate support for wide-area radiological mapping into our toolkit [7]. In addition, software for *in situ* data acquisition and analyses and communication has been developed as part of our research activities into using mobile computing technology to support field operators carrying out plans produced using our software [1,4,5,7,9].

Collectively, these tools provide a software testbed uniquely useful both for researching and developing efficient solutions for the nuclear industry. This software testbed in combination with our competence in technical [9,10], as well as human and organisational aspects [3], enables our research and development team to address issues contributing to failures or inefficiencies from a general perspective instead of tackling related factors individually.

In the following, we present the consecutive steps of the process that has to be followed during a decommissioning project implementation, noting some of the challenges related to each step and explaining how 3D simulation, VR, and advanced UI technology can significantly change the way these challenges are addressed. In this paper, the process of implementing a decommissioning project, or a task within the project, is split into five steps, as follows.

(1) Assessing the current (initial) situation – acquiring and analysing input information.
(2) Developing strategy – planning and scheduling work activities.
(3) Preparing the field team – briefing and training.
(4) Implementing plans – performing work.
(5) Evaluating, preserving, and transferring experience – documenting and reporting work.

These steps can be followed at both the level of the whole project and at the level of tasks and subtasks within a project. Ideally, an iterative implementation process would be applied, to detail the tasks and subtasks, using fresh data and experience to update strategy and safety protocols during the implementation of the entire project.

2. Assessing the current (initial) situation

The first step both in implementing a project and detailing a task within it is assessing the initial conditions within which the work will be implemented. In nuclear decommissioning, the most important component at this stage is radiological characterisation of the site the project is targeting. The overall cost of the project, associated risk, required safety measures, equipment, and resources will primarily be influenced by the radiological conditions within the targeted site [11]. Hence, facilitating this first step is crucial to enabling optimisation of costs, time, and safety. Radiological characterisation involves gathering as much data as reasonably possible and using the data in the best possible manner to determine radiological conditions, in order to support informed decision-making during the development of the decommissioning strategy. Issues associated with this step include:

(1) performing extensive sampling and measurements contributes to overall costs, and/or entails uncertain risks to humans performing the survey and
(2) insufficient or inaccurate radiological surveying can result in unexpected delays, costs, and exposures.

Optimising the number, location, and type of radiological samples and measurements required can facilitate the survey data collection. This can be achieved by taking advantage of any data already available, such as data from the operational phase of the plant, and any modelling results (activation calculations, contamination dispersion, and penetration estimates). Data from earlier decommissioning projects can also be useful, if extrapolation is possible. Furthermore, the sampling and measurement work can be done iteratively, to continuously refine plans based on acquired data. However, the decommissioning database containing all the radiological characterisation data is usually vast. Management of the database and analyses of the data contained in it is demanding. The radiological data acquired ultimately serves to help decision-makers understand the radiological conditions existing within the targeted site, and facilitate making informed decisions. Hence, effective presentation of the contents of the vast database to users is crucial. Since the data is related to a real environment, one approach to enabling rapid comprehension is to present the data to the user in the context of the environment it refers to.

In this work, innovative solutions, based on 3D modelling and simulation, have been applied to investigate possibilities for supporting efficient creation and maintenance of decommissioning databases and registration of radiological data, using spatially oriented 3D UIs [1,11].

In addition to providing efficient ways for inspecting and updating the data, it is important to facilitate the process of data acquisition. In this paper, we explored how advancements in hand-held and wearable computing technology could enable users to take the 3D simulation technology described above to the site where sampling and measurements is being done.

Acquiring a sufficient amount of data of appropriate quality is only the first half of radiological characterisation. Decision-makers need to be able to efficiently analyse the data in order to prepare reliable assessments on which to base the planning of decommissioning implementation tasks. Insufficient or incorrect radiological characterisation has resulted in:

(1) incorrect estimation of the amount of resulting radiological waste that need to be handled and
(2) incorrect estimation of the nature and extent of remedial actions (decontamination, conditioning of activated material, segregation of waste, etc.) required.

Both of these issues entail additional costs and delays in the project.

The need to develop better techniques for remote and *in situ* characterisation of complex sites is internationally recognised [12] and includes improving capabilities for identifying characterisation gaps, interfacing measurements with modelling, and assessing the quality of characterisation data. In this work, the authors investigated how advanced statistical analyses, data verification, and filtering based on user-defined criteria, and radiological assessment models, could be combined with 3D simulation and advanced UI technologies to support decision-makers during radiological characterisation in an effective manner. A software prototype has been developed for evaluating the potential of 3D simulation and appropriate UI technologies for radiological data management and radiological characterisation in nuclear decommissioning projects. The upper panel of **Figure 1** demonstrates visualisation of radiological data via a 3D interface showing a realistic model of the environment and the data in the context of this environment. The lower panel of Figure 1 shows how such an interface can be equipped with efficient functionality for radiological characterisation.

2.1. Results and discussion

Our results show that the technology demonstrated in Figure 1 could be efficiently applied for exploiting data records from the operational phase as the following:

(1) online monitoring data (dose rates),
(2) regular survey data (dose rates and surface contamination, radioactivity caught in filters – tramp uranium), and
(3) information resulting from maintenance work affecting radiological conditions, such as reapplication of protective painting layers, and incidents involving contamination (spills, leakages, fuel element failure – contamination in the primary circuit).

Furthermore, the technology could be applied for combining information noted above with data and assessments produced even earlier, during the planning and construction phase, including initial site configuration, geological, geochemical, and hydrogeological properties, radiation background, initial configuration of facilities (foundation, subsurface media), physical and chemical material properties, and natural radioactivity, U, Th, ^{40}K, content. This pre-operation data can be useful for comparing actual levels to those initially detected and as input for shielding and activation calculations.

All of the above are potentially useful sources of information for planning further surveys and estimating associated risks. In addition to taking advantage of existing data, characterisation can also be facilitated [11] by

(1) ensuring high data quality (the number of sampling and measures that need to be repeated due to not meeting required data quality),
(2) applying an iterative approach based on a data quality objective (DQO) process[11],
(3) integrating sampling and measurements into other necessary tasks, and
(4) combining several types of measurement and sampling approaches.

Our investigations show that the technology demonstrated in Figure 1 could ensure successful implementation of the good practices listed above by supporting (1) registration and verification of data based on a DQO principle, (2) planning and keeping track of sampling and measurements, and (3) efficient data extraction for further analysis (e.g. statistical analysis).

Due to the typically large volume of data, allowing the user to customise the amount and type of data

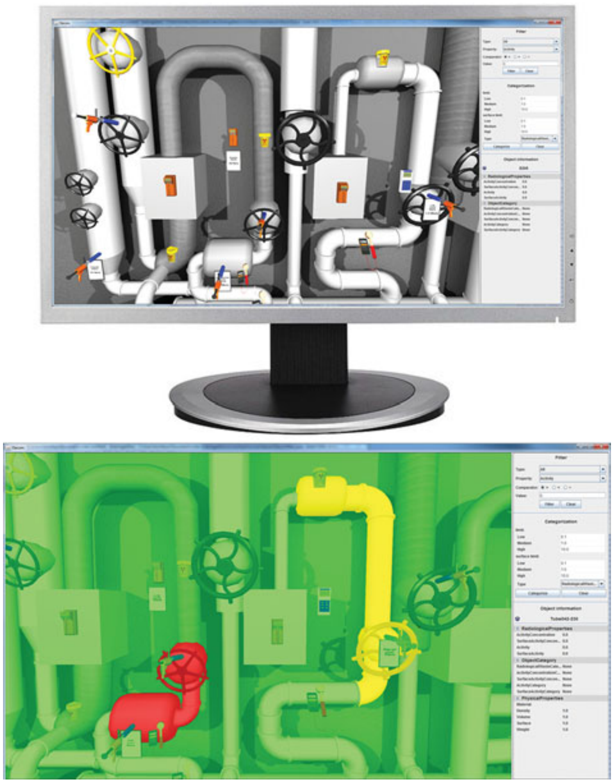

Figure 1. Interactive 3D user interface concept for managing decommissioning databases (upper panel), visualising contamination, classification of structures and materials, and quantification of radioactive waste (lower panel).

displayed can contribute to rapid understanding, i.e. filter the data shown based on user-defined criteria, and enable the selection of context-appropriate information visualisation techniques. For example, data can be filtered based on any parameters to visualise hot spots, samples not meeting required data quality, samples and measurements scheduled for or taken during a user-defined time period, data indicating the presence of certain radionuclides or either confirming to or deviating from user-defined nuclide vectors.

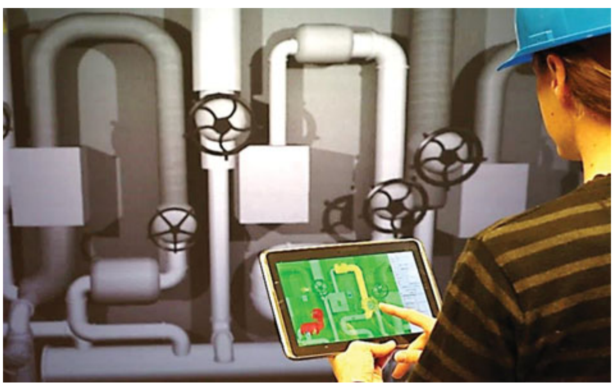

Figure 2. *In situ* support concept for radiological characterisation.

Our investigations show that the technology in Figure 1 has great potential for enhancing the characterisation of sites targeted by decommissioning projects by providing rapid and efficient

(1) identification of contamination (type, isotopic composition, location and concentration, physical and chemical state of contamination in structures, systems, components, and environmental media),
(2) quantification of activated materials and structures within the targeted site, and
(3) identification and classification of radioactive materials (supporting treatment, packaging, shipping, and disposal).

In addition, our results show that mobile computing technology, combined with 3D simulation and context-appropriate UI technologies, can ensure *in situ* availability of the functionality discussed above for field operators (**Figure 2**). Having access to such tools *in situ* has the added advantage of the potential to reduce the risk of registration errors, and if implemented with an efficient UI targeting the specific needs of the user, reduces the time the user has to spend registering or verifying data in a potentially hot area.

3. Developing strategy

3.1. Assessment of risks to workers

Once adequate radiological characterisation has yielded sufficient information for decision-makers, the next major phase of the project, or a task within it, is the planning phase in which the work strategy is developed. This phase involves, among other things, estimating risks, balancing options, scheduling work tasks, allocating staff and resources, and communicating to regulatory bodies, advisors, and stakeholders. Since robotics and remotely operated equipment are seldom applied, except for particularly dangerous tasks and under water[12], one of the most important inputs required in this process is information about the risks to the workers associated with the foreseen jobs. However, estimating the risk to field operators associated with a specific work task is challenging due to the strong dynamicity of the exposure conditions. This is not only the case for risks associated with radiation exposure but also for other hazards in the environment, such as heavy machinery and temporarily unstable building structures, which could also be managed as part of an integrated solution.

The environment of a nuclear facility is generally stable during the operational phase. The radiological conditions might be somewhat changed during a maintenance procedure, but normally revert to a normal state once the procedure has been completed. In contrast, during the decommissioning phase the environment is continuously and significantly altered due to removing

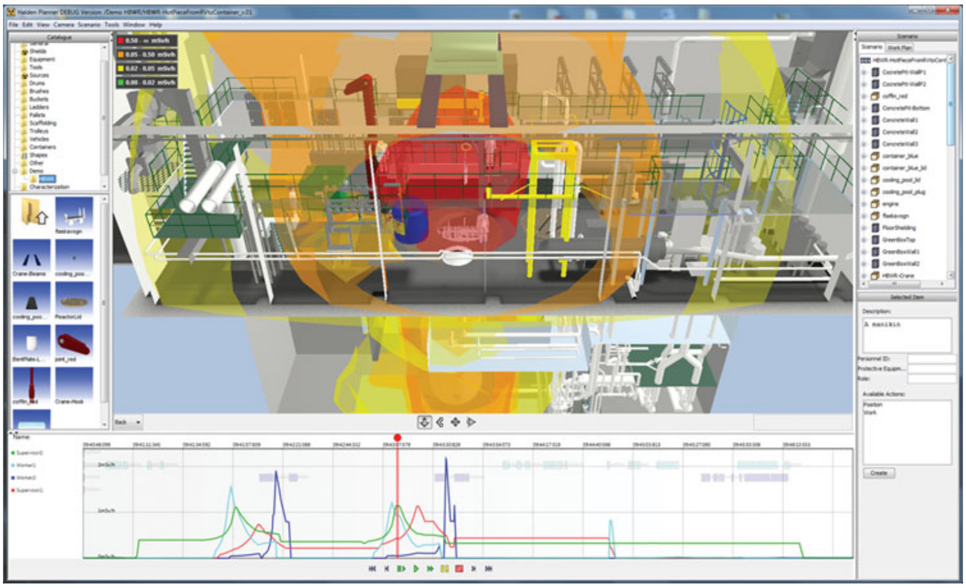

Figure 3. User interface of the Halden Planner showing a snapshot of a work scenario, associated dose charts, distribution of radiation exposure, and other data relevant to the scenario.

biological shields, installing temporary protection, moving and removing radioactive components, decontamination of contaminated surfaces, etc. Thus, there is a need to take into account continuous change to the exposure conditions, even for brief, routine, decommissioning tasks. The authors of this paper have been involved in research and development of novel solutions for dynamic, real-time estimation of radiation, and other risks [13,14] associated with maintenance and outage work activities in nuclear environments. In this work, the authors investigated how this technology can be applied to estimate risk to workers in decommissioning projects, focussing on estimating radiological risks associated with taking samples and performing *in situ* measurements, decontamination of systems, dismantling of structures, etc. The investigations were performed using the Halden Planner (**Figure 3**) and VRdose (see Section 1) software, both of which are tools that offer real-time calculation (update) of personal and collective dose, dose rates and dose history (dose charts) while allowing the user to dynamically modify work scenarios. This greatly facilitates identifying optimal worker routes, shielding configuration, order of subtasks, and so forth by enabling suboptimal solutions to be quickly rejected. Furthermore, real-time visualisation of radiation risks (dose) [13,14] aids users in understanding the radiological conditions and, thus in determining the best directions for refining a work scenario during the optimisation process. This also facilitates zoning the environment, by making it much easier to identify areas that should be controlled or free, including optimal resting and waiting zones. Both the Halden Planner and VRdose enable users to prepare and compare multiple alternative work scenarios for the same job, before selecting which alternative to schedule. Comparisons can be made based on multiple criteria, including collective dose, individual dose, and overall duration. It should be noted that though our focus is on real-time estimation, it is also possible to combine our techniques with high-accuracy techniques based on detailed radiation transport models, if necessary.

3.1.1. *Results and discussion*

Our investigations show that dynamic (real-time) tools that produce reasonably accurate radiological risk estimation can provide vital input information for decision-making, such as to be able to make an informed choice between remote-controlled and manual techniques for a decommissioning task. As a suboptimal decision typically results in unnecessary costs or increased risk to workers, it is important that optimal solutions can be efficiently identified and suboptimal solutions can be rejected [15]. Since radiological conditions may strongly change during a decommissioning task, dynamic radiological mapping of the whole environment, as shown in Figure 3, is very efficient for producing plans for zoning the environment in terms of risk to humans, e.g. plan safe and exclusion zones to apply during a job. In addition, due to the dynamic change of decommissioning environments throughout the whole project, zoning plans need to be time dependent as they should change for different stages of the decommissioning project as the situation changes. Furthermore, optimisation of the work plan is required for ensuring conformance with radiological protection principles, including the ALARA principle, especially for tasks for which a manual solution has been selected. However, since exposure conditions change during a decommissioning job, and optimisation requires analyses

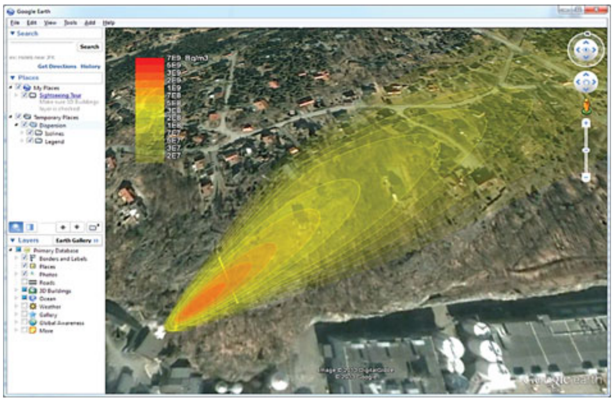

Figure 4. GIS-based environmental radiological impact assessment.

and comparison of a potentially large number of alternative scenarios, static radiological maps, and high-accuracy models are not suitable alone to support efficiently identifying an optimal solution. In contrast, dynamic modelling enables decision-makers to investigate how any change to the work strategy influences, resulting exposure to the participants in real time.

3.2. *Environmental impact assessments*

While the capabilities discussed above aid decision-makers in finding the optimal strategy in terms of risks to the workers, risk analyses associated with any job requiring a radiological work permit also need to address the potential impact on the general population and environment. Incomplete and/or incorrect assessment of potential risks to the general public and the environment can potentially lead to significant health and environmental consequences. Environmental impact assessment is therefore an integral part of the

(1) optimisation process, ensuring compliance with the ALARA principle,
(2) decision process, related to the planned end-state of the site, and
(3) planning emergency preparedness (crisis management) strategy, etc.

In order to extend the use of visualisation technologies as useful communication tools, the authors of this paper developed a software prototype based on GIS technology in order to evaluate the usefulness of the technology for providing easily understood environmental information (radiological and other) to decision-makers in decommissioning projects (**Figure 4**). Our goal was to investigate what kind of environmental data and associated impact projections are important to support different stakeholder requirements, and how data can be presented effectively. For example, we need to determine the best ways to display sufficient detail, while ensuring that the information is rapidly and, not least, correctly perceived by decision-makers.

3.2.1. *Results and discussion*

GIS-based efficient environmental impact information is very useful for balancing decommissioning and environmental remediation options during the planning phase, in order to identify optimal solutions resulting in as low as reasonably possible risks to the workers, as well as the public and the environment beyond the site perimeter. Such easily understood environmental data (e.g. abut surface and subsurface contamination of the land) are essential for an informed decision process about the end-state of the site, as long-term liabilities need to be justified against costs for decommissioning to green-field status, if green field is not a regulatory requirement. In addition, such information strongly supports the regulator in verification of compliance with site clearance criteria. GIS-based environmental information that includes risk projection is also useful for developing effective crisis management plans. GIS-based environmental data can enable efficient analyses and visualisation of information about environmental consequences of possible accident scenarios, required for preparing monitoring and emergency response strategies. Since the general population is becoming increasingly accustomed to using GIS-based technologies, such as GPS-based route planning in cars or on mobile phones, the technology is a potent option for disseminating information to staffing members that may be affected in the event of an accidental release, to inform about unsafe zones, evacuation routes, registration points, and so forth.

3.3. *Scheduling jobs and allocating resources*

Having found possible solutions for specific jobs within an overall plan, and possessing information on associated worker exposure and required resources, jobs can be scheduled within the overall project plan. At this stage, the main goal is development of an optimal overall strategy in terms of safety and costs. The optimisation process is mainly based on balancing alternative selection of decommissioning methods (jobs) and schedules in terms of their characteristic data taking into account the resources available. When scheduling an individual job or activity, we not only need to ensure that the resources needed are available, but we also ensure that we stay within all necessary constraints (worker dose limits, temporary storage capacity for waste, criteria for release of materials, etc.). This is especially challenging since we rarely want to execute jobs in a linear fashion as that would take unnecessarily long time. Hence, we need to be sure that jobs taking place simultaneously can be conducted safely, in particular if delays in one job could result in significant risk for a job in parallel, and thus require active coordination between the individual

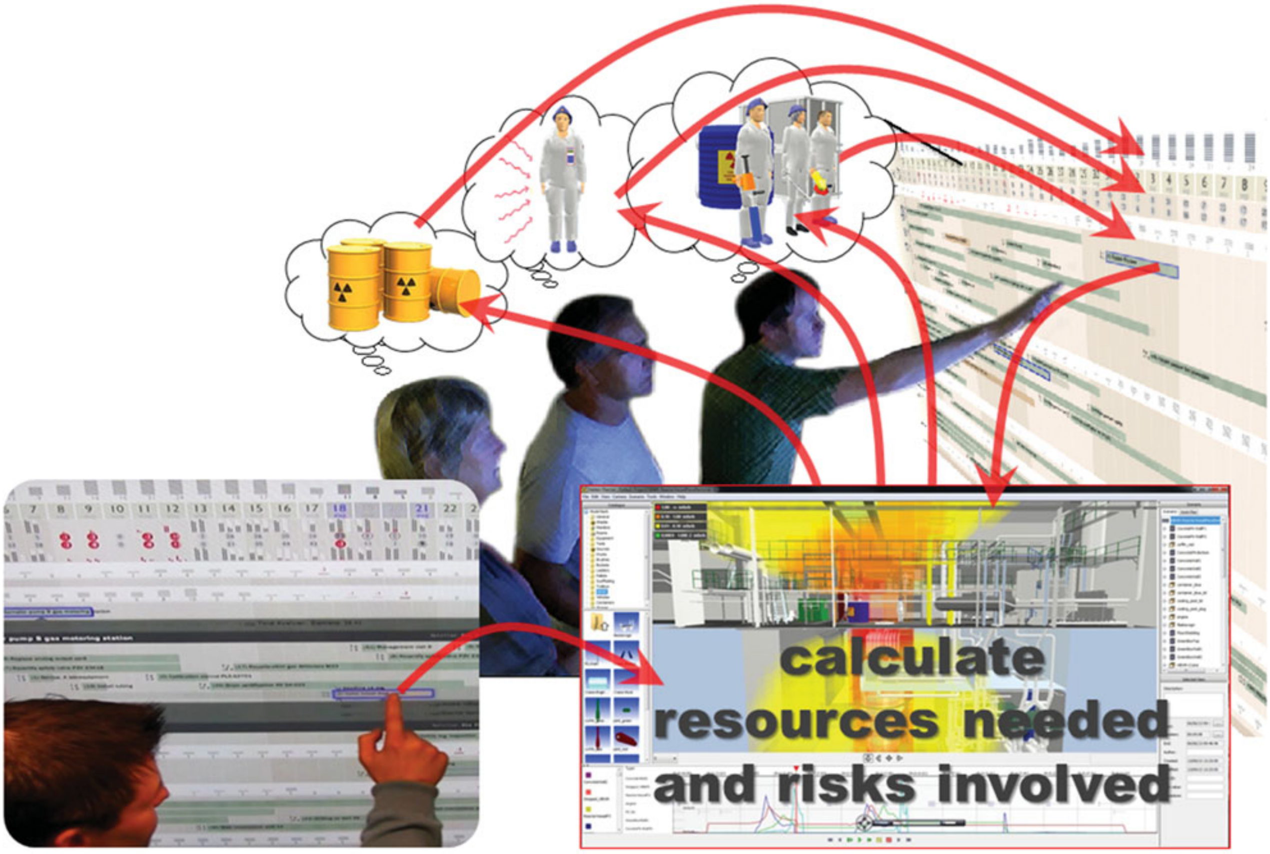

Figure 5. Scheduling work tasks and allocating resources by combining the results of 3D work simulation, to determine the details of jobs, and an interactive visual overview of the overall schedule, used to coordinate jobs taking into account safety and resource constraints.

teams of workers to ensure their common safety and efficient execution of their tasks. Suboptimal allocation of staff and resources will result in higher overall costs than necessary, without any safety advantage. Hence, finding the best solution in this phase is also vital for optimising costs and risks. In this work, we investigated the potential for applying 3D simulation and advanced UI technology to support a user-friendly process for scheduling jobs and allocating resources in decommissioning projects. Our investigations were based on experience in the development and application of the Halden Planner and the VRdose software, and experience from the development and deployment of tools based on advanced touch-screen UIs for scheduling tasks and allocating resources in the oil and gas industry [16] (**Figure 5**).

3.3.1. *Results and discussion*

Producing a 3D simulation of a work plan can also be useful for determining the level of resources needed for successful completion of a job, including requirements for man power (number of participants), equipment (cutting tools, decontamination equipment, tools for manipulating heavy components, etc.), radiological monitoring, communication (e.g. for coordinating parallel activities), type of containers for transporting radioactive materials, temporary biological shielding, remote controlled equipment, etc. Furthermore, 3D simulation of work tasks combined with the 3D radiological characterisation technology, as presented earlier, also facilitates quantifying and classifying both radiological and non-radiological waste resulting from tasks. Subsequently, 3D simulation contributes to well-informed assessment, and balancing of risks and resources needed to select an optimal work scenario. Our results also indicate that 3D simulation of work plans combined with semantic techniques based on advanced UIs for supporting scheduling and allocating resources taking into account associated constraints (Figure 5) specific to nuclear decommissioning sites could greatly facilitate the overall planning and management of decommissioning projects. Such compound systems will greatly facilitate optimisation of decommissioning strategies by supporting optimal selection of decommissioning methods and schedules taking into account the resources available and constraints applicable. In addition to supporting the development of the high-level decommissioning plan, this technology could also greatly facilitate the implementation of plans by enabling an efficient system for rescheduling jobs, in case of unexpected delays. This could significantly lower additional costs and exposures due to unexpected events.

3.4. Communication

Communication with relevant regulatory bodies and stakeholders is also an important part of the decommissioning planning activity, in particular when preparing the high-level overall plan needed to proceed with decommissioning. Demonstration and justification of plans toward the authorities and approval by the regulator are inescapable requirements. Tools facilitating transparency towards the regulator may greatly facilitate the process of obtaining approval. In this work, we analysed the possibilities for applying 3D simulation and GIS technology to facilitate transparency in decommissioning projects. Our investigations were based on earlier experience in applying 3D simulation and GIS technology in the nuclear industry.

3.4.1. Results and discussion

A significant advantage of realistic 3D simulation and GIS-based visualisation to conventional solutions is that the information presented visually is easier to understand. Hence, this technology is especially useful for providing a common communication platform for stakeholders in a decommissioning project with very different backgrounds (**Figure 6**). Decommissioning plans also need to be documented in reports. The Halden Planner and VRdose can produce reports for printing or archiving (Figure 6) based on the 3D simulations of jobs. The reports typically contain illustrated descriptions of plans, with supporting tables of data, in a similar format to a conventional radiological work permit request or a detailed job description.

4. Preparing the field team

Following the planning phase, the next step is normally a briefing and training phase, where the field team is assembled and prepared for performing the work in a safe and efficient way. The goals of this stage are to ensure that members of the team are familiar with the environment and have a good understanding of the tasks scheduled, the risks associated, safety protocols to follow, including their justification, and have practice in the task to be performed. Depending on whether the decommissioning work is carried out in-house or is partly or entirely transferred to an external contractor, requirements in preparing the decommissioning team may differ. For example, if the decommissioning work is planned to be carried out by retrained operational staff, the preparation programme can focus less on educating the team members about the environment, existing conditions and safety protocols, and operational history of the facility. However, many decommissioning-specific jobs require new skills that were not acquired during the operational phase. Consequently, the process of preparation of existing staff for decommissioning work can begin with a training programme focussed on acquiring essential skills and understanding, to be able to do particular kinds of work. High-quality training can have the added advantage of contributing to retaining high-quality specialist staff [2], who value the opportunity to acquire new skills and find job satisfaction in the fresh challenges offered by the job.

During the operational phase, field workers acquire routine understanding and skills in the regular tasks required to ensure safe operation of an installation. However, as the decommissioning phase approaches, conditions and tasks will change, requiring a transformation in the mind-set. Hence, general education of the operational staff to establish an appropriate safety culture for decommissioning is desirable, to prepare them for an environment with dynamically changing conditions, complex safety protocols, and multiple interdependent teams working in parallel over relatively long periods. In addition, due to the increasing demand for safe and cost-effective decommissioning services, companies specialising in nuclear decommissioning are emerging. For such contractors, maintaining highly educated staff in general decommissioning work, and having a safety culture that is in line with safety requirements in nuclear decommissioning, is vital.

Due to the increasing need for specialists in decommissioning, and existing employees leaving due to job insecurity, new staff may be hired during decommissioning projects. Obviously, preparation of the newly hired decommissioning specialists needs to focus less on acquisition of basic skills like that for existing operational staff being retrained to participate in the decommissioning. Instead, the training programme should focus more on providing familiarity with the environment, existing conditions, safety protocols, and operational procedures. Especially if most of the decommissioning work is allocated to external contractors, it is very important to transfer all historical information, including undocumented information, relevant for decommissioning from the operational staff to the new decommissioning organisation.

Ensuring that the workers are qualified to do a job is an important pre-requisite for initiating the implementation of the job. In the next step of the preparation phase, the main goal is to make sure that the team has a good understanding of the work steps and strategy developed during the planning stage. This is usually ensured by demonstrating the plans to the field team before the implementation of the tasks begin. In addition to demonstration of the overall work plan, especially for more complex work protocols, a briefing session at the start of each work shift is usually performed to achieve safe and efficient execution of the plan. The pre-job briefing is especially important for decommissioning work in radiological environments as the situation regarding

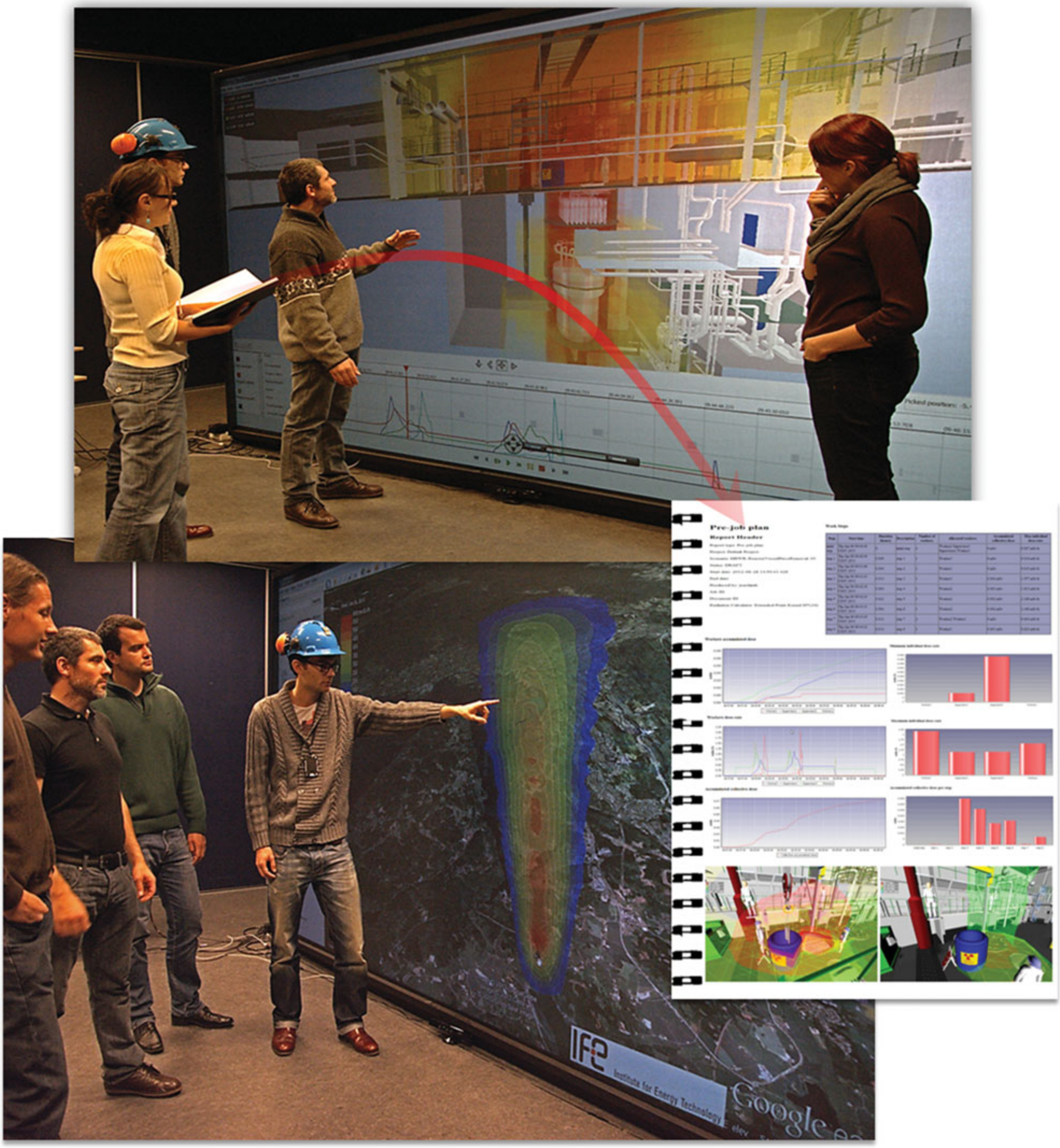

Figure 6. Environmental impact assessment aided by GIS technology, 3D work simulation, and printer-friendly reports for communication between participants, authorities, and stakeholders.

safety precautions may change from day to day and will often be dependent not only on the stage in the plan that the job is at, but also the results of actual measurements in the field.

In this work, we investigated the potential for using 3D simulation, virtual reality, and advanced UI technology to enhance training and briefing of field operators in nuclear decommissioning projects. Our research was based on prior experience in the development and application of 3D simulation, VR, and advanced UIs for supporting training and briefing for maintenance and outage work [2,17–19].

4.1. Results and discussion

The results of our research and development on effective solutions based on 3D simulation, VR, and advanced UI technology indicate that education of staff for decommissioning jobs can be cost efficiently enhanced within the nuclear sector by applying these technologies

Figure 7. VR-based interactive immersive training.

[2] to provide both individual immersive (**Figure 7**) and instructor-based classroom training (**Figure 9**), expectedly resulting in lower costs and improved safety of decommissioning projects.

While conventional physical mock-ups are useful for learning how to do decommissioning specific jobs from a physical viewpoint, they are inflexible or dangerous for realistically emulating situations, where the operator can learn to handle errors or risks. Training in a virtual environment (Figure 7) can supplement physical training by focussing on the more cognitive aspects of learning procedures and understanding why certain precautions are necessary, and, not least, what can happen if they are not followed. Virtual environments can be especially effective for visualising danger and safety zones, as well as enabling trainees to see inside structures to understand what is happening. To some extent, it is possible to use augmented reality technology in a physical mock-up or a shutdown site to, for example, simulate a hidden danger such as radiation, but physical mock-ups are relatively costly and are rarely intended to be demolished multiple times, so have, in our opinion, a more limited scope for learning how to cope with abnormal situations or learning how the configuration of site will change over time.

In addition to ensuring that the required general skills are available for staffing field teams, general

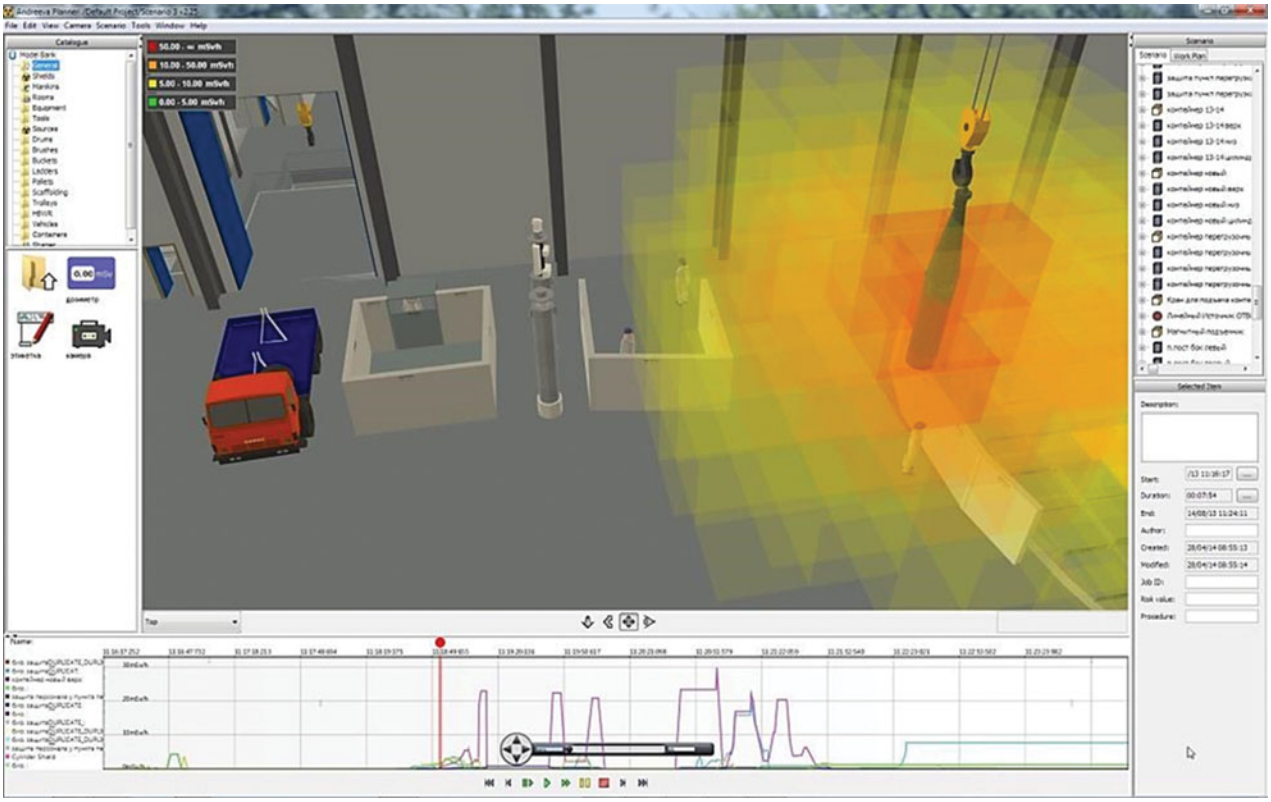

Figure 8. Screenshot of the Andreeva Planner showing simulation of remediation work in the Andreeva Bay (manipulation of aged containers holding spent nuclear fuel – preparation for repackaging and transport). The scenario (simulation) in the figure has been created at the State Research Center Burnasyan Federal Medical Biophysical Center of Federal Medical Biological Agency, RF Ministry of Health and Social Development of Russia.

training for familiarisation with the specific site layout, environment, conditions, protocols, and history would be needed for newly hired team members. For complex jobs, being done for the first time or representing especially high-risk one-off operations, then it may be necessary for the allocated staff to be familiarised with the planned work in good time before the job will be done. For this, the 3D simulations produced during the planning stage are very useful as they can serve as a useful starting point for developing training programmes, reusing data from the previous step's planning stage. The radiological data gathered during characterisation tasks, and the 3D simulations developed during work planning and optimisation, can be applied to produce a VR-based training programme enabling the field team to practice scheduled decommissioning jobs (Figure 7).

A significant advantage of simulator-based training is that it offers an effective way of preparing field operators to handle possible emergency situations [20]. Emulating radiological emergency situations for training in physical environments can be either difficult to do realistically or, as is often the case, impossible to do for safety reasons or because the physical environment that the scenario is associated with is inaccessible or does not exist yet. While a virtual environment typically lacks a physical feel, it provides a sense of presence and immersion that, even on a desktop computer, is nevertheless effective for preparing workers to cope with a range of emergency situations. Visual simulation of past and possible crisis situations, and enabling workers to observe and practice response tactics, can be an effective method for implementing training for an emergency preparedness strategy. For an example, a customised version of the VRdose system, the Andreeva Planner, has been utilised to simulate planned remediation work (**Figure 8**) and possible emergency situations, develop and teach optimal emergency response tactics, as well as support regulatory compliance as part of the emergency preparedness strategy within the programme for the remediation of legacy sites in the Andreeva Bay in the northwest of Russia [8].

Based on our results, 3D and radiological simulation also has great potential in enhancing knowledge transfer from the operational to the decommissioning phase, by demonstrating radiological conditions, work protocols, and past events (Figure 9) registered using 3D simulation, advanced UI, and portable computing device technologies during the data collection phase.

Furthermore, 3D work and radiological simulation can be used to demonstrate work plans and associated radiation, and other, risks (Figure 9). The technology can be used in various configurations for projected 3D

Figure 9. Briefing concepts based on 3D work and radiological simulation.

stereoscopic and two-dimensional (2D) classroom-type briefing, 3D/2D interactive (discussion type) briefing, individual and remote briefing, and even *in situ* using mobile or wearable displays. Realistic visualisation of the planned work protocols and risks can contribute to establishing appropriate situation awareness and understanding of the assigned tasks for the field operators involved [17,18]. The technology has been found to be superior to paper-based briefing [18], since every work scenario is associated with a physical 3D environment in which human activities, radiation, and other sources of danger have a dynamic 3D nature. The 3D projection technology enables stereoscopic viewing for teams of stakeholders, which typically results in more rapid depth perception than 2D projection, and can therefore be useful for relatively short procedures (less than 30 minutes), while 2D projection is more comfortable to view for longer periods of time [19]. In general, 3D projection is of greatest benefit for visualising things within arms-reach of the operator/viewer, therefore 3D projection is often not necessary for briefing purposes as the benefit is reduced the further away the objects visualised are located relative to the viewer.

5. Implementing plans

Once work starts on implementing a scheduled decommissioning job, the primary objective is to ensure that the work is done as planned and that any issues that arise while the job is in progress are managed effectively. To achieve this objective, efficient monitoring of the work progress and of the radiological and other conditions in the work zone is needed, as well as efficient communication between members of the work team.

During the operation of a nuclear facility, the main control room is used to monitor information critical to nuclear safety. During the transition phase, information important to nuclear safety gradually loses importance with the removal of operational waste and the shutdown of systems that are no longer required. However, as the decommissioning work progresses, the importance of radiological information increases. Radiological and exposure conditions determined by the remaining contamination and activated materials are the primary influencer of the costs and safety of a nuclear decommissioning project. Due to the uncertainties in estimating the expected evolution of radiological conditions beforehand, monitoring of radiological and exposure conditions is therefore very important throughout the project. Monitoring radiological conditions and mitigating risk to field operators during a decommissioning job is challenging because the radiological environment changes, often dramatically, as a result of decontamination and dismantling tasks. Hence, monitoring systems need to have a high "refresh rate" in order to capture the dynamicity of the conditions.

During a decommissioning project, field operators are often expected to perform tasks where the general procedure that they have trained for may be the same, but the conditions within which it is carried out differ each time and the procedure may be slightly different, requiring that the worker to be alert to the situation for the current job and not expect, for example, exclusion zones, and other safety precautions to be the same as the last time the same procedure was followed. While briefing good procedures and requiring verification of safety barriers, during critical stages of a job, are important means for ensuring safety, there is an increased likelihood of a safety-related incident if a worker momentarily forgets the current job's conditions and attempts to apply those recalled from a previous time when a similar procedure was followed. Efficient communication within a team and between field workers and supervising staff contributes to ensuring that the correct procedure is followed.

A complicating factor for a team of workers doing a decommissioning job is that there are typically multiple teams doing multiple jobs simultaneously. Hence, a safety incident that may in fact have been contained effectively to protect the workers doing the job in which it occurred may pose increased risk for workers doing other jobs in the vicinity. Effective monitoring, coordination, and communication are therefore important if multi-team work is to be done both safely and efficiently. Communicating dynamic 3D information on conditions and risks is very challenging through traditional techniques, such as procedures, briefings, and job descriptions on paper.

In this work, the authors of this paper have also conducted research into the potential of using mobile and ubiquitous computing technologies to facilitate work progress monitoring and team communication during work in decommissioning environments.

When monitoring the execution of a decommissioning job, the detection of minor deviances from estimates in the plan in terms of exposure of the workers, the population, and the environment are quite common due to the imprecision of impact estimates. Since impact assessments are always performed in a strongly conservative manner, deviances are often positive, with a job done more quickly and with less exposure than budgeted for. A negative deviance does not usually lead to a crisis situation unless the cause was a serious mishap or accident during the execution of the job. When planning a job, the associated safety case normally covers the conceivable eventualities that need to be prepared for, but when multiple safety barriers are breached in an unanticipated manner, as is typically the case in a serious accident, the consequences are often unexpected and require rapid development and execution of a well-informed emergency management strategy [21]. As past events have shown, the results of a serious accident may not be confined within a nuclear installation. Hence, a deliberated emergency response strategy must also take into account the possible impact on the general public and environment.

Figure 10. Monitoring of work progress from a control room of a nuclear installation supported by 3D simulation.

In this work, we have also investigated the potential for applying 3D simulation and mobile computing technologies for supporting crisis management in nuclear decommissioning projects.

5.1. Results and discussion

Based on our results, virtual plant models and 3D simulation could be efficiently used to monitor work progress (status of scheduled tasks), team and field operator locations, and radiological risks from a control room (**Figure 10**). Such information would greatly contribute to avoiding increased exposure due to unplanned events and conditions. It could also contribute to increasing efficiency (e.g. avoiding delays) by enabling rapid rescheduling and reassignment of workers in accordance with actual progress.

In addition to supporting monitoring work progress from the control room, 3D simulation can also be exploited to facilitate two-way communication within the whole decommissioning team (i.e. among members of a

Figure 11. *In situ* information for field operators showing task list (left-hand panel) and 3D simulation (right-hand panel).

field team, across different field teams working in parallel, and between field teams and the control room). **Figure 11** illustrates how 3D simulation based *in situ* information can complement task list based information to field operators. The technology can be applied to visualise pending tasks and tasks in progress using VR or augmented reality techniques [22], while also indicating locations targeted by the tasks (i.e. team and worker positions), task status, and associated risks to the field operators (personal doses and ambient dose distribution, i.e. radiation visualisation). In addition to the planned situation, actual locations, exposure levels, and progress can be visualised based on regular manual input from the workers, and/or automated data registration by sensors [1]. With the help of suitable interpolation techniques, data from sensors measuring radiation dose or activity concentrations can be applied for dynamic monitoring (mapping) of the environment in terms of radiation risk. This information combined with live data on team locations and work progress enables monitoring and projection of risks to field operators. By comparing the expected situation from the plan with the actual situation and projections, deviations can be detected relatively early, and workers can be alerted to ensure that they are aware of the deviation and can respond to it appropriately before any significant safety limits are breached.

In addition to supporting emergency preparedness and the production of well-founded response procedures, the technologies presented in this paper could also be used to support an emergency response team during conceivable crisis situations and emergency conditions that were not prepared for. During first response, the situation may change rapidly in an unexpected manner. It is very important that the response team performs prompt but deliberated actions. Hence, it is imperative that there is efficient communication within the response team, and that team members have the best information possible available to them. 3D simulation technologies can be an efficient means for presenting dynamic (real-time) situation information to response team members in a manner that facilitates rapid visual perception and comprehension [20]. The concept illustrated in Figure 1 can be used to enable rapid registration and sharing of radiological and other data required for assessing the situation (Figure 2). The methodology shown in Figure 10 can be utilised to present dynamic situation information and impact estimates (e.g. distribution of ambient dose levels) to decision-makers. The technology demonstrated in Figure 11 can facilitate communication between team members in order to ensure common understanding of the situation and the chosen response strategy.

The GIS-based technology presented earlier also has strong potential for enabling efficient comprehension of environmental impact information (Figure 4) by decision-makers involved in developing environmental remediation and site monitoring strategies, as well as, supporting the regulator's final survey before site release. In addition, the technology can be applied during emergency response to visualise conditions in real time, along with predictions based on the progression of the situation. Systems based on GIS data standards are able to integrate multiple types of geographical data; therefore, in addition to visualising radiation measurements, they can integrate meteorological data, the location of emergency responders, points of interest, cordoned areas, evacuation routes, and so forth, depending on what data is available from fixed measuring stations and emergency first responders and monitors in the field (**Figure 12**).

6. Evaluating, preserving, and transferring experience

After completing a scheduled decommissioning activity, there should be a learning step, where the job is reviewed with respect to the plan and any important

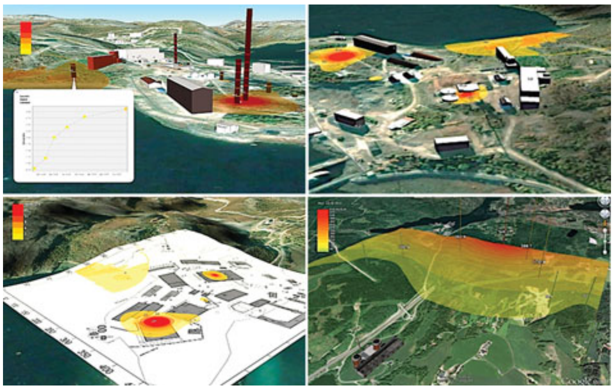

Figure 12. GIS-based environmental radiological monitoring.

lessons learned, extracted, recorded, and shared. The technologies presently employed for many decommissioning tasks do not apply the latest methods. Better exchange of information and lessons learned would facilitate adaptation of new techniques facilitating more efficient and safer decommissioning [12].

In this work, we evaluated the potential for using 3D simulation technology to support advanced knowledge management, facilitating improved preservation and transfer of experience in nuclear decommissioning.

6.1. Results and discussion

The 3D simulation used to prepare the plan is useful for this as it can be applied, for example, to demonstrate success or inefficiency in applying new technology or exiting technology under new conditions. The simulation can also be annotated with actual data collected when the job was done and used to explain deviations or discuss ideas for how the job could have been done even more efficiently. Clearly, if a serious mishap took place then using the 3D simulation tool to model what happened can aid understanding of the consequences or determining what could (or should) have been done to prevent or contain the event. In any case, the simulations and data collected provide a comprehensive documentation of the on-site project activities and experience. This data can be applied to promote organisational learning and contribute to improving safety through greater understanding of the nature of risks, facilitate exchange of experience between decommissioning projects across the border, and educate future decommissioning personnel (e.g. e-learning materials). In addition, the data can also be used to produce statistics useful for planning similar jobs in future, thus providing a more accurate basis for the estimation of costs and risks.

Management of knowledge presents special challenges in the field of nuclear decommissioning. Many experts and international organisations (e.g. the International Atomic Energy Agency) predict that more efficient knowledge management culture, including support by emerging sematic and 3D simulation technologies, will revolutionise future international strategy in nuclear decommissioning [23].

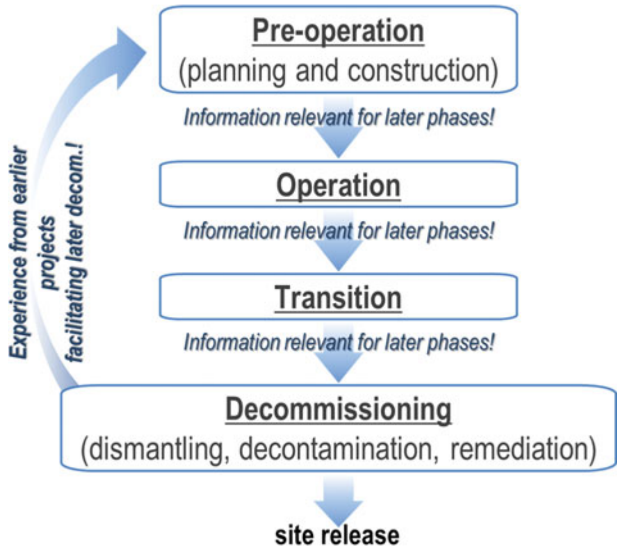

Figure 13. Life-time support concept based on 3D simulation and advanced user interface technology.

7. Conclusion

Results of the research within the OECD Halden Reactor Project [6] into evaluation of 3D simulation, VR, advanced UI, and emerging mobile computing technologies for supporting work in the nuclear industry demonstrate that these technologies have huge potential for improving safety, efficiency, and transparency of nuclear decommissioning projects. Our results show that these technologies can contribute to solving important tasks relevant for decommissioning during the entire lifecycle of a nuclear installation.

During the so-called "transition phase", these technologies can be applied to support planning final removal of operational waste, surveying historical data, planning additional radiological surveys, managing and analysing survey and activation calculation data, initial worker safety assessments and protection design, environmental impact assessments, preparing final decommissioning plans (scheduling and resource allocation, detailed planning of specific jobs), communication (with authorities, advisors and the public), and training workers for decommissioning tasks.

Similarly, during the decommissioning phase itself, these technologies can be used to support communication (with and between staff), carrying out new radiological surveys, updating worker safety assessments and protection, updating decommissioning plans (overall schedule, detailed plans for specific jobs), waste classification (dose-based clearance and release), final survey of end state, development of long-term safety assessment/monitoring strategy, and the regulator's confirmatory survey.

Finally, after completing a decommissioning project, the technologies described here can continue to be useful by providing valuable support for evaluating, preserving, and transferring experience, in order to improve future practice and regulation.

Furthermore, these technologies can be applied during the operational phase to support registration and preservation data that will be useful later for decommissioning, e.g. online monitoring and regular survey data, radiological data about incidents, and development of preliminary decommissioning plans. These technologies could also be employed during the pre-operational phases of planning and construction, to preserve data on the radiological background, site configuration, material properties, natural radioactivity content, to produce decommissioning plans required for licensing new build, and document the initial state of the facility environment.

Results of research in earlier studies at the OECD Halden Reactor Project, into the applicability of 3D simulation, VR, advanced UIs, and mobile computing technologies for supporting pre-operational and operational phases of nuclear installations also provide useful guidance on applying emerging technologies for

(1) development of initial work plans for operation (maintenance, outage),
  (a) refining design for optimal worker safety,
  (b) training workers, even before operation starts, and
(2) planning for implementing an emergency preparedness system during the pre-operational phase, and
(3) planning and training for maintenance and outage work,
  (a) including planning of radiological surveys,
  (b) environmental surveillance (online and offline surveillance of the installation and surrounding area),
  (c) registering and analysing radiological data from regular surveys and after incidents,
  (d) implementing an efficient emergency preparedness system, and
  (e) communication (within field teams, with the control room, advisors, and regulators) during the operational phase.

Figure 13 summarises how 3D simulation, VR, advanced UI, and emerging mobile computing technologies can be applied to support tasks within each phase of a nuclear installation and facilitating information transfer between different phases and projects. In addition, utilisation of such technologies will facilitate adoption of new instrumentation (for cutting, decontamination, packaging, etc.) by supporting evaluation of new tools in the planning phase, and training workers for application of new technology. The results of use in industry projects [1,8,15,24,25] proved that these technologies are very useful for improving planning and optimisation of jobs, team communication and regulatory surveillance, as well as briefing and training of field operators. This is conditional, however, on the technological solution used being a good match with the specific needs of the decommissioning project, and being easy to use, to minimising deployment costs such as training staff. This generally means that the software needs to be designed or adapted specifically to meet the nuclear industry requirements in order to support an acceptable workflow.

At present, practical experience from deployment of such 3D-based decommissioning support systems is relatively scarce. However, there is consensus among experts in that, based on experience so far and projections for the future, the costs entailed by adoption of such technology are definitely worth it compared to the increased safety and financial benefits enabled by the technology [23]. Unfortunately, open literature underpinning this statement is poor and is expected to bloom in the next few years.

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