INL/EXT-20-61082

Smart Planning Support for Nuclear Power Plant Work Planners

December 2020

Changing the World's Energy Future

Zachary A. Spielman
Johanna H. Oxstrand
Stacey R. Whitmore

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/EXT-20-61082

Smart Planning Support for Nuclear Power Plant Work Planners

Zachary A. Spielman
Johanna H. Oxstrand
Stacey R. Whitmore

December 2020

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Technology Transitions
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Abstract

Operation and maintenance costs of a nuclear power plant account for 60% of overall plant costs due to the nuclear industry's risk-averse culture (World Nuclear Association 2020). The industry relies on highly conservative estimates to avoid risk and brute-force reactions to manage the unexpected and keep a plant running safely. This approach has kept plants operating more safely than in any other power source available over the last six decades (Ritchie 2020). However, these conservative methods have cost the nuclear industry in market competitiveness. The solution is to transform the conservative approaches to accurate, efficient, and still-safe data-driven approaches that leverage advanced technologies available in the digital age. This project endeavored to identify two key aspects to successfully incorporate historical work-execution data: first, the work-management process to which that information is most pertinent, and second, the key variables to inform the best strategy for organizing the upcoming work. The smart planner uses data collected by dynamic work instructions to provide a basis for suggesting requirements of similar, upcoming work packages. Further, it curbs inefficiencies of the work-management process by analyzing the likelihood of discovery work and offering suggestions to build a contingency package. All this takes place as the work planner builds work packages that meet the predetermined scope of work to be performed.

CONTENTS

FIGURES

TABLES

ACRONYMS

DOE	Department of Energy
IAEA	International Atomic Energy Association
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operation
TCF	technology commercialization fund

Acknowledgements

The authors would like to express special gratitude to Elijah Chang and Steve Kuhlman at Lean Power, a subsidiary of Devbridge, for their input, review, and collaboration during this technology commercialization fund (TCF) effort.

Smart Planning Support for Nuclear Power Plant Work Planners

1. INTRODUCTION

1.1 Background

Idaho National Laboratory (INL) and Devbridge Group, LLC, and its subsidiary Lean Power entered a partnership in 2019 to develop a dynamic work management system. The goal of the partnership was to empower nuclear operation, as well as increase safety and human performance related to work execution in the field by enabling the standardization of work procedures, simplification of task completion, and application of real-time data analytics.

INL and Devbridge submitted a proposal to the Department of Energy (DOE) Office of Technology Transitions and were awarded a 24-month-long commercialization effort, which was initiated in December 2018. This report provides a summary of the overall effort, including individual activities conducted.

In support of DOE's efforts to increase industry engagement and commercial impact of the national laboratories and to fulfill the statutory direction provided in the Energy Policy Act of 2005, the Office of Technology Transitions awards proposals that are funded through the statutorily established technology commercialization fund (TCF). The TCF focuses on supporting the commercialization and deployment of promising energy-related technologies developed at national laboratories that have commercial potential. The TCF is part of a broader set of initiatives designed to foster stronger partnerships between DOE national laboratories, private-sector companies, and other entities involved in bringing energy-related technologies to the marketplace.

The TCF is a funding opportunity that leverages the research and development funding in applied energy programs to mature promising energy technologies with the potential for high impact. These funds are matched with funds from private partners to promote promising energy technologies for commercial purposes. The goals of the TCF are 1) to increase the number of energy technologies developed at the national laboratories that graduate to commercial development and achieve commercial impact and 2) to enhance the department's technology-transitions system with a forward-looking and competitive approach to lab and industry partnerships.

The TCF effort described in this report has the project number identifier TCF-18-15696.

1.2 Industry Opportunities and Challenges

Operation and maintenance costs of a nuclear power plant account for 60% of overall plant costs due to the nuclear industry's risk-averse culture (World Nuclear Association, 2020). The industry relies on highly conservative estimates to avoid risk and brute-force reactions to manage the unexpected and keep a plant running safely. This approach has kept plants operating safer than any other power source available over the last six decades (Ritchie 2020). However, these conservative methods have cost the nuclear industry in market competitiveness. The solution? Transform the conservative approaches to accurate, efficient, and still-safe data-driven approaches that leverage advanced technologies available in the digital age.

Nuclear plant operations rely on highly conservative estimates in their processes to manage risk. Conservative estimates result in costly inefficiencies and serve to add cushion when an unexpected event occurs, rather than proactively to manage risk.

Data-driven processes in nuclear plants are sources of improved efficiency when operating the plant. New technologies like integrated digital control rooms, predictive-maintenance technologies, and dynamic instructions for field work improve plant efficiency in ways that will reduce costs and bolster operational integrity (Lybeck, 2020). These technologies minimize the need for overly conservative actions to manage plant risks at no cost to safety. Integrated digital control rooms present the right information at the right time so operators can readily assess plant health, perform fewer mental calculations, and lower search times for indications before competently responding to plant events (Kovesdi, 2020). Predictive maintenance minimizes the cost burden of routine or scheduled maintenance by consuming labor and resources only when necessary to maintain plant equipment. It also identifies an approaching need that may have otherwise been unexpected. Dynamic instructions provide all the necessary information, just-in-time training, and reduced communication times for the craft to accomplish their work (Oxstrand, 2018). Dynamic instructions have the added benefit of capturing high-resolution data of work performed in the plant. Replacing conservative estimates with data-driven analysis tools allows plants to operate more efficiently and as safely at lower costs.

The work-management process is the circulatory system for all operation and maintenance activities in a plant, accounting for 60% of a plants' operational budget. Other industries that employ tools to increase this process's efficiency have seen 15% reduction in costs (Albright, 2016). As with the other technologies mentioned, the strategy is to minimize the manual estimations inherent in the legacy culture of power plants by employing data-driven strategies that harness advantages of operating in a digital age. The benefits gained include:

- More efficient use of labor, improved approaches for scheduling that reduce costly overtime or subcontracted labor
- Insuring work requirements and craft capability are most appropriately matched
- A tighter schedule fit, with accurate, rather than conservative estimations of work time.

Furthermore, with time, the solution becomes predictive to account for necessary contingencies where discovery work on critical work actions is likely. INL targets the work-planning phase of the work-management process to reduce return work, tackle growing maintenance backlogs, and increase schedule adherence, reliability, and efficiency.

Enhancement of data collection, aggregation, and analysis strategies address other challenges in nuclear, such as the aging workforce and resulting loss of legacy knowledge. Work planners rely on highly experienced craft supervisors as their data sources when building work packages. However, that resource is diminishing as the legacy workforce retires. The result is less-experienced craft personnel promoted to supervisory and work-planning positions earlier in their careers. The loss of legacy knowledge is recuperated in enhanced data-collection and analysis strategies. Work planners face declining efficiencies if experienced personnel resources are not replaced.

1.3 Processes and Procedures in Nuclear

Most tasks conducted at a nuclear power plant have associated standardized procedures. The nuclear industry relies on workers to correctly adhere to and use procedures to complete their tasks. This ensures safe and reliable operations. Procedures have helped the nuclear industry stay safe for decades. However, there are limitations to the current use of procedures. Even though the nuclear industry is moving towards digital technologies, the work-management process and procedures are still mainly paper-based. A document printed on a piece of paper is static. We ask our workers to apply this static documentation to an ever changing and dynamic work environment.

A shift is happening in the industry right now. It started with some utilities' moving to electronic work-management solutions. This move means that procedure writers, planners, and schedulers no longer need to move large stacks of paper from one desk to another during the work-management process. The ability to track review status and potential hold-ups in the process were also enhanced by these solutions. Workers in the field began employing electronic versions of procedures, displayed on hand-held devices.

The electronic copies were mainly portable document format (PDF) files with limited data-capture capabilities.

In the past few years, utilities began to realize that even though electronic work-management solutions greatly improve strictly paper-based processes, and additional important benefits were gained by further expanding these work-management strategies through dynamic work-management solutions and instructions. Vendors such as Lean Power, ATR, Inc., NextAxiom, and DataGlance are now re-designing their products to offer the additional benefits gained by dynamic work-management solutions. The technology provides more-relevant guidance to the worker in the field based on the current task and conditions faced that day. The procedure dynamically adapts to the most-correct path through the instruction. A dynamic instruction also has the capability to ensure that the worker employs the correct equipment, that readings are within acceptable thresholds, and that steps are conducted in the correct sequence.

The main benefits from a dynamic work-management platform are a capability to capture metadata related to work packages, procedures, and procedural steps. Some examples of captured data are time to complete the step, time to complete the task, as-left states for components in the plant, and readings taken by the worker in the field. All this information is valuable, both in providing a real-time or near-real-time update on plant conditions and health of components and for planning and scheduling future work activities.

1.4 Work-Management Process

The work-management process coordinates all work carried out in the plant to keep it running safely and efficiently. It organizes and manages all surveillance and maintenance activities by prioritizing work, designating timelines for work completion and ensuring all qualifications, trainings, and resources will be available. The process requires coordination of all plant personnel. The Institute of Nuclear Power Operations (INPO) has laid out the objectives of an effective work-management process that, if achieved, would lead to safe, effective, and efficient plant operation (INPO 2017):

- Optimize safety system and refueling outage durations
- Support effective station backlog management
- Increase productivity through efficient use of resources
- Improve schedule credibility and stability
- Reduce costs
- Improve equipment performance and system health
- Promote nuclear safety
- Improve radiological safety performance
- Improve industrial safety performance.

These objectives orient the plant towards a mindset that works to prevent or minimize emergencies or encourage contingencies when the original plan becomes insufficient. The stated objectives also have an implied goal of always improving. A defined endpoint is not stated to promote a continuous-improvement process. An effective way of continuously improving towards these objectives is enacting a continual feedback loop capturing how work is performed, the characteristics of the work, what is required, what is successful, and what can be improved. The International Atomic Energy Agency (IAEA) emphasizes the importance of having mechanisms in place to monitor planning, preparation, and execution (IAEA 2007). Most plants subscribe to the six-phase work-management process diagramed in Figure 1.

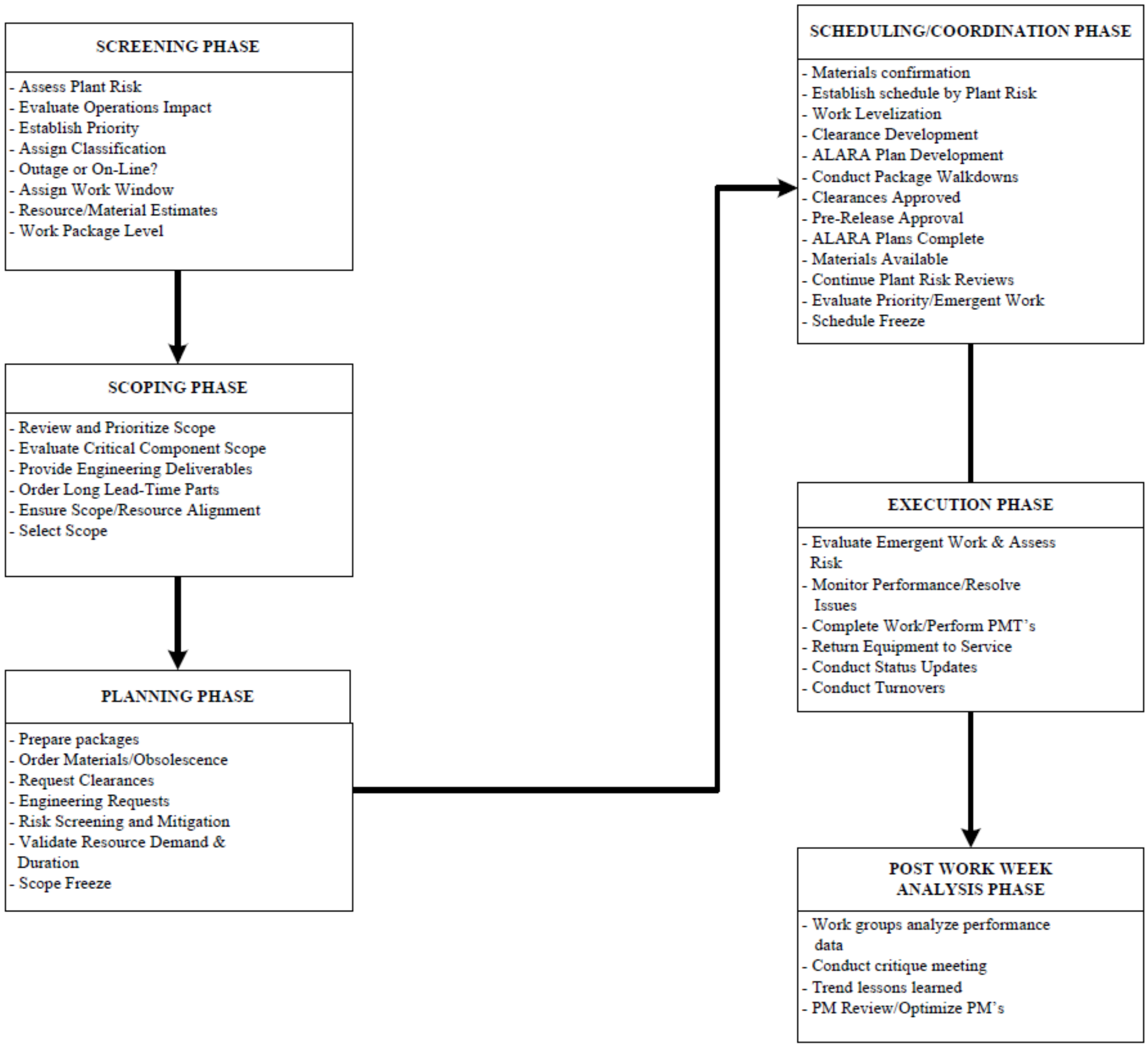

Figure 1. Generic work management process flow diagram taken from AP-928 "Online Work Management Process Description."

The final phase is evaluating how well the process worked for a given work timeline. Lessons learned are applied at the next available opportunity. The circular process ensures plants are always working towards INPO's stated objectives. However, there remain limits to the granularity and quality of the data collected to inform future work-management efforts. While legacy plants have been using more software packages to help store data and connect databases, the act of recording still relies heavily on manual input and word of mouth. Forms are filled out following work executed. Paper procedures are usually submitted to track what was done for manual review later, and supervisors are responsible for communicating how well work packages served the actual work performed. The work planner then incorporates these lessons learned to build more-suitable, accurate work packages next time in hopes of improving work-management process efficiency.

1.5 Work Planning

The work planner aims to build a work package that accurately accounts for the reality of a project. The planner takes actions to ensure the success of the work packages they build. Planners rely on varied data sources regarding the work package at hand. These range from reviewing previous, similar work packages to consulting those experienced at carrying out the work. After planning, a walk-down of the work site confirms the package is accurate, and the estimated resource (e.g., time) expectations are realistic. Neither of these two efforts are perfect. Scope creep still occurs; it erodes the work-management process (see Figure 2.) and requires more effort from everyone, but specifically work planners because they must rebuild the original work package. Instead of using precise estimates of work duration, work planners create work packages with conservative estimates. Work schedulers, the next phase in work management, make the decision to shorten those conservative estimates when scheduling the work or not. While not the most efficient course, the conservative estimate approach helps reduce the work returned to planners.

However, a prime cause of scope creep, which is difficult to anticipate, is discovery work. Discovery work means unanticipated work within a work package that was discovered only after work began and that requires more resources or different qualifications to be performed. Scope creeps by the extended duration the work requires, and this has cascading effects on upcoming scheduled work that is delayed until the project at hand is successfully completed. Work walk-downs are the first means to detect discovery work. However, walk-down reports are given by word of mouth or emails, both of which can be misinterpreted or never received by the planner. Also, walk-downs cannot identify everything. For instance, if a pump or valve must be disassembled for routine maintenance, a walk-down can only view the state of the equipment's exterior. Once the part is opened, more extensive repair or replacement may be warranted. The second defense is discussing work with experienced craftsmen. They may have insight on potentially problematic equipment that would help a planner anticipate common culprits of scope creep. It is the work planner's responsibility to account for possibilities using available information to build work packages to account for these contingencies.

Often, work planners are hired out of the craft labor pool because of their earned expertise, which helps them plan related packages with understanding. Building from a prioritized list and conservative resources-to-complete estimates, the work scope is set and frozen at this phase. The process is manually intensive and not perfect. Occasionally, the planner must rely on inadequate information, little historical information, or unplanned complications with work.

Contingencies referred to as fluff or dummy packages are one workaround planners employ for such eventualities. It is a tool to build conservatism into a work schedule and it softens the blow of scope creep when it occurs. When a planner anticipates the common causes of scope creep, an additional package is written and scheduled immediately following the original work request. That way, discovery work has a dummy work-package placeholder to prevent discovery work from impinging on downstream work alignment and schedule adherence. If work is not discovered, the dummy package is discarded, and following work continues. This method is less disruptive and avoids negative impacts to schedule evaluations. However, discovery work still gets routed back to the planner for approvals and work authoring. The same manual process to determine resources and requirements is carried out. Furthermore, building in contingencies reduces the work-management process efficiency. Using dummy packages everywhere discovery work might be a possibility means sacrificing other needed work in the timeframe available to accomplish maintenance goals.

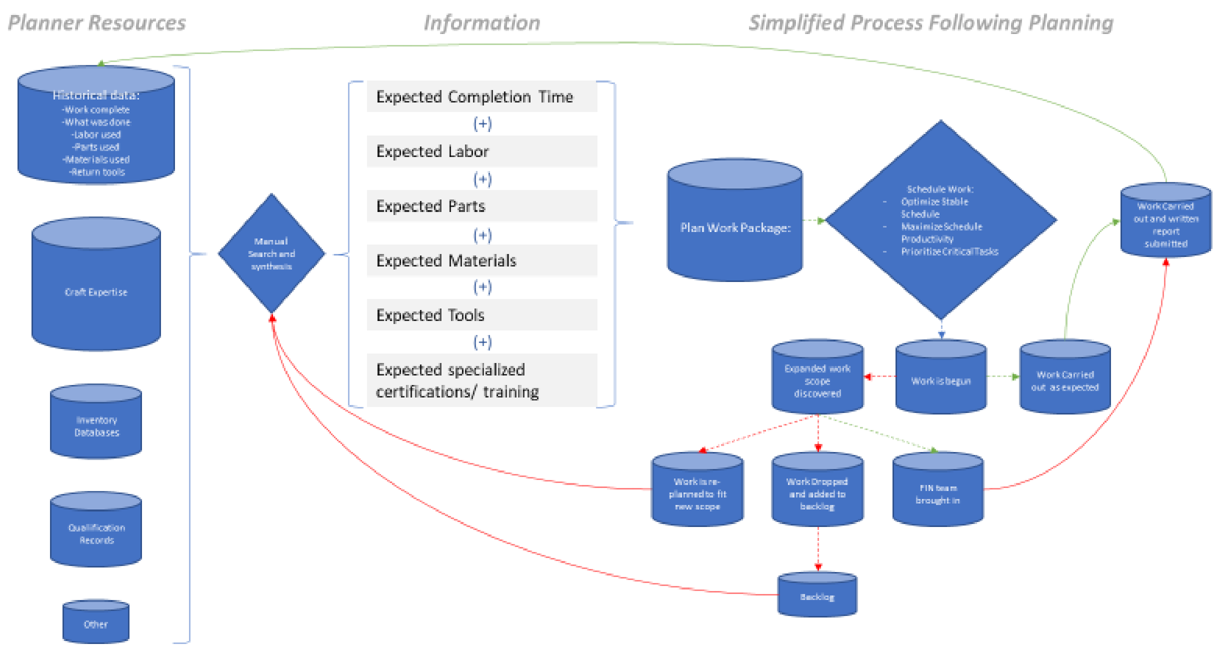

Figure 2. Simplified flow diagram to illustrate how work can be rerouted back to planning if a work package is not adequate for the work needed.

1.6 INL and Lean Power are Strategic

A collaboration between INL and Lean Power, a dynamic instruction and work-authoring platform, developed a methodology to streamline the work-planning phase of the work-management process. Lean Power's platform has the added capability to unify plant databases and incorporate all historical metadata tracked during work execution. Taking advantage of their dynamic instruction platform, more-granular data describing work practices and execution can be aggregated to perform a decision-making tool for work planners.

The Smart Planner tool will capture the characteristics of a successful planner and the data used to support every work planner and create accurate, data-driven work packages. Furthermore, the Smart Planner can recommend contingency plans when they are likely needed. However, instead of building a dummy work package, the contingency will have all the recommended resources required for review. The planner can thereby build the contingency on the spot, allowing any work that encounters the anticipated contingency to continue without interruption and requiring no extra work from the work planner.

The Smart Planner circumvents the planner's reliance on word-of-mouth work reports, manual database reviews, scouring old work packages, or tracking down experts to build a work package. It also builds packages with more precise resource estimates, allowing schedulers down the line to assemble more-tightly packed timelines to fit in more work. The work packages are resilient to scope creep because they have, built into them, fully formed contingencies in the event of discovery work, building schedule adherence and accuracy. The work backlog grows more slowly as a result of getting more work done as planned, without reorganizing or ditching low-priority work due to scope creep. Four of INPO's stated objectives for a successful work-management process are directly impacted by the Smart Planner (Table 1).

Table 1. Right column lists the INPO AP-928 "Objectives of a successful work management system," and the left column shows how the smart planner impacts the listed objectives.

<table>
<tr><td colspan="2">Effective Work Management Process Objects as Stated in INPO's AP-928 Document</td></tr>
<tr><td rowspan="4">Directly Impacted by Smart Planner</td><td>Optimize safety system and refueling outage durations</td></tr>
<tr><td>Support effective station backlog management</td></tr>
<tr><td>Increase productivity through efficient use of resources</td></tr>
<tr><td>Improve schedule credibility and stability</td></tr>
<tr><td rowspan="5">Indirectly Impacted by Smart Planner</td><td>Reduce costs</td></tr>
<tr><td>Improve equipment performance and system health</td></tr>
<tr><td>Promote nuclear safety</td></tr>
<tr><td>Improve radiological safety performance</td></tr>
<tr><td>Improve industrial safety performance</td></tr>
</table>

2. CONCEPTION OF A SMART PLANNER

The quality of information available to work planners directly impacts the quality of the work package they build. As keyholders who ensure that all resources, clearances, long-lead orders, and work durations are accounted for in the work package, accurate information is of paramount importance to them. They evaluate their efficacy by monitoring key performance indicators, such as schedule adherence, resource loading, and schedule stability. Schedule adherence compares the original work plan to what happened. Resource loading is how evenly work was distributed over time. For instance, poor resource loading might include scheduling excessive overtime or subcontracted work (expensive) on one day while the little work is achieved (inefficient) the next. Schedule stability measures how often work scope is changed, whether adding emergent work or dropping lower-priority work due to scope creep. While some changes are required to handle the unexpected, access to comprehensive, accurate information helps work planners maintain an evenly loaded, stable schedule that is entirely achievable within the work timeframe. Using the metadata collected by dynamic work instructions, plants can prompt planners with quality information that translates to quality work packages. This project focuses on supporting the planning phase of work by preprocessing higher-quality data to improve work-package creation.

Fortunately, alternatives to current archaic data-entry systems and the heuristic determinations of experienced crafts exist. Dynamic work-instruction platforms such as Lean Power's work authoring and execution tool provide the capability to capture rich metadata about every work activity performed. Historical data brought to the planner in an actionable way could replace the need for meetings, research, and experience to plan properly. Translating that historical data into planning insights is the next step toward precision resource loading of accurate and comprehensive work packages to support schedule stability and adherence. Perhaps most improved is a statistical analysis suggesting strategic contingencies. The work, and what can be expected in the contingency, can be predicted. The implication being that an entire contingency can be built simultaneously with the associated work package. That way, work can continue despite discovery work (see Figure 3) illustrating how predicted contingencies can streamline the work process). This solution aligns with countermeasures against outage extensions in IAEA's report suggesting planners use feedback and plant history to inform their work, and to, "proactively plan and schedule by predicting and considering possible problems" (IAEA 2007). These improvements also drive planning performances towards the INPO stated objectives of a successful work-management process (Table 1), that is, making the most of the resources and materials for a given time frame. The improvement is expected to impact the work-management process by minimizing work returned to the planner and keeping work execution flowing, as illustrated in Figure 3.

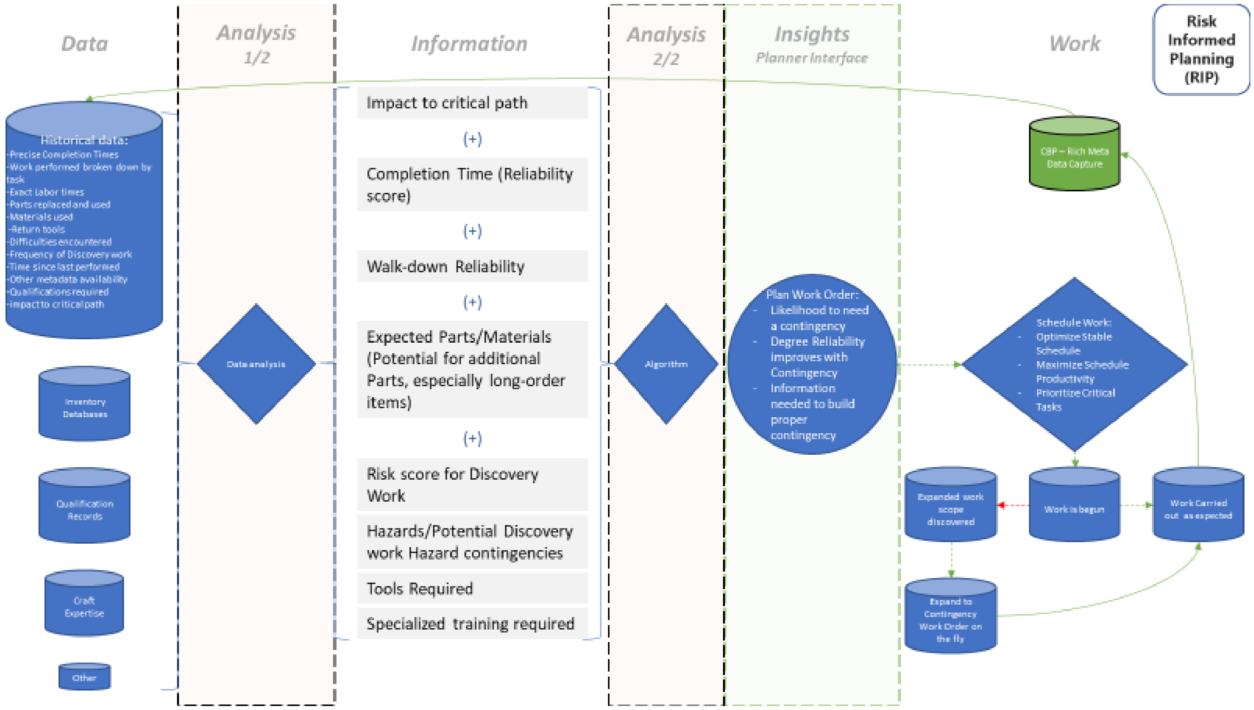

Figure 3. The improved work-management process when work packages are built with comprehensive contingencies only when needed. Compare with Figure 2. to see the how work is less disrupted.

This project endeavored to identify two key aspects to successfully incorporating historical work-execution data. First, where in the work-management process would that information be most pertinent? Second, what variables are key to informing the best strategy for organizing the upcoming work? Different avenues to streamlining the work-management process are iterated, taking advantage of a connected plant by meeting with industry work planners, schedulers, and work-management supervisors. Their input helped identify the pain points, provide insight, and determine the impact and feasibility of the solution described here.

2.1.1 Lean Power Interface Design Review

INL's Human Factors organization reviewed Lean Power's work-authoring tool as part of the effort to determine the tool's appropriateness as a work-scheduling solution. A report, titled "Lean Power Work Authoring Tool Interface Design Review," was delivered to Lean Power. The report details the methodology used to review the work-authoring tool and why these methods were appropriate. A fully detailed account of the results is enumerated in the report for use at Lean Power's discretion. The most-critical issue found scored as a medium-level critical issue for which a potential solution was provided. Based on the review, no highly critical issues were discovered. However, the expert heuristic review methodology, a great formative review method, should be augmented with more-formal end-user studies to finalize the product.

2.2 Developing the Smart Scheduler

2.2.1 Background Research

INL's collaboration with Lean Power began after identifying the data-scarcity obstacle to thorough data collection and dissemination. Using Lean Power's platform to unify disparate data sources creates an opportunity to fill the growing knowledge gap. A planner can now rely less on those around him or the sparsely annotated previous work packages and more on hard information provided by these software tools. To better understand the data needs and the most-effective phase in the work-management process during which to provide it, INL reached out to industry experts.

2.2.2 Expert Interview

Six experts from four companies confirmed the value of the proposed solution. Experts cited pain points in their work potentially assuaged by data-driven scheduling support, such as:

- Failure to review the work ahead of time causes planning inadequacies
- Poor adherence to checks and requirements can result from inadequate work walk-downs
- Less-frequent performance of some work schedules commonly make schedule prediction less reliable
- Jobs that cannot be fully assessed during a walk-down can negatively impact scheduled timelines and milestones
- Manually sifting through previous work accomplished to gain accurate expectations of a current work request is labor intensive
- Poor usability of current software tools is prohibitive to using full capabilities that could reduce labor-intensive efforts to research work.

The common thread in these pain points is inadequate information available to best plan work packages. These inadequacies trickle down and negatively impact later phases—work scheduling and execution—when work to be performed encounters an unexpected issue. The new tasking loops back to work planners as high-priority discovery or emergent work. Planners daily tasks are interrupted to handle the new work. Effectively, due to inadequate information, the work planner has done twice the work for the same job. Avoiding this doubling of effort is achievable by providing adequate, historical information beforehand so that contingencies or expanded work scopes can be worked into the original plan. More advanced than using dummy contingencies, these expanded plans are built to anticipate extra effort, allowing work to continue without the interruption and doubled work-planner effort. The result is a streamlined, linear work process that minimizes the degradation of work (Figure 3).

To ensure the proposed solution captures current strengths, experts were questioned on qualities and capabilities sought after in their profession. These included:

- Diligent communication with the work-management team, including craft supervisors, work planners, plant management, engineers, and schedulers
- Experienced background in at least one craft to support good decision-making
- The ability to aggregate previous work-order history to accurately plan work orders.

The commonly sought-after strengths correspond to pain points. Currently, solutions are sought in highly experienced personnel with historical knowledge and a strong peer network that allows them to plan work efficiently. However, it is well recognized in the nuclear industry that legacy plant knowledge is diminishing as the most highly experienced personnel retire. The remaining personnel are equally skilled, but less exposed to the long-term experience currently sought in work planners. The proposed solution fills this gap by providing historical knowledge to the work planner regardless of experience.

2.2.3 Smart Planner

The smart planning solution was developed in two parallel efforts: 1) the development of a graphical user interface to be used by the work planners and 2) definition of parameters for the algorithm used to moderate the interface to communicate the most useful path forward for the work planner.

2.2.3.1 Interface Development

The smart-planner application is designed to support work planners and the decisions they must make in the work-management process. The user interface will initially augment the existing process, but the end goal is to revise the part of the process specific to the work planner and have the user interface support this new process. The source of information the planner uses will transition from the current practice of discussions with experienced craft and detective work, incorporating disparate databanks to use historical data collected via the dynamic-instruction solution. This transition is noted in the differences between Figure 2 and Figure 3.

The initial step in interface development was to identify the phase in the work-management process where additional support would be most beneficial. As part of this activity, other user needs and goals were identified. Based on these insights, the user interaction with the needed information was designed and developed. In short, the smart-scheduler application must communicate the risk of discovery work for the specific work activity of interest. In addition, the application must provide the resources needed for the potential work discovery so the planner can respond accordingly.

Some requirements identified were the ability to provide user feedback to the system and the need of a transparent risk threshold for suggesting contingent work packages. By providing user feedback on the usefulness and accuracy of the smart planner's suggestions, the work planners can help curate the smart planner's quality during the transition period. A transparent risk threshold keeps planners informed of how decisions are made based on available evidence. As the smart planner is used, confidence in its suggestions should increase and require less curation. However, novel situations are always possible and would require planners to act with little information from the smart planner. Therefore, keeping human planners informed and part of the smart planner's development process assists in keeping them capable of adapting to the novel situation.

The development effort faced challenges, such as limited user interactions and access to the planner tools currently used in nuclear power plants. This made the identification of which gaps or specific user needs to address and resolve with the smart planner application difficult. It was also challenging to access a representative dataset to feed the analytics portion of the tool. These kinds of datasets would have helped developers to understand and incorporate existing plant data to provide additional user support in the smart-planner application. Future work must address these challenges by collaborating with utilities and vendors alike to develop a front-facing solution.

2.2.3.2 Data Analytics

A regression model is the right tool analysis for the smart planner because it is a relatively simple algorithm that is flexible and fast to train with a small, well-defined data set containing few outliers. Also, it is optimal in generating a quick initial benchmark. Due to the binary nature of the dependent variable (if or if not, a contingency plan is needed) a logistic regression algorithm was used.

Logistic regressions are suited for smaller data sets. While enormous amounts of data can be collected for maintenance practices in general, a single piece of equipment for a specific type of maintenance performed is likely to be a very small subset of that data. To demonstrate the concept, a data set describing passengers of the titanic (Donges 2018) was relabeled to match the maintenance context in which this regression is expected to perform. The data set is appropriate because the intended prediction is also binary; did the passenger survive or not? Here that output was reappropriated to whether a contingency was needed or not, and passengers were changed to equipment ID labels. The data were then matched by units of measure to line up continuous and categorical variables. Unused data columns were removed. This method is purely intended to demonstrate the concept with a data set and is not appropriate to validate the variables selected to predict a contingency.

As is typical with statistical models, as data collected from work performed and equipment maintenance specifications accumulates, the model produces more accurate predictions. In other words, the longer a plant uses dynamic work instructions that collect high-resolution metadata, the better the planning capabilities will become. Initial efforts may require a heuristic model stand while data are sparse. As data availability grows, the heuristic model can be replaced by the logistic regression explained here. The predictive analytics developed fits a regression model to data collected about a work activity and its associated equipment. This model can later be used to predict when a contingency work package is needed for a given piece of equipment from its associated data.

The analysis is a three-phase process. The first phase involves aggregating plant databases that include inventory, previous work packages, metadata of previous work executed (e.g., duration, personnel required, etc.), and anything else relevant to planning a work package. One challenge to aggregating these data is connecting the disparate data sources. However, some plants have begun using software packages designed to pull together various databases into a single source. Lean Power offers this capability. Also, INL is developing a platform called Deep Lynx, designed as an aggregated warehouse for all digitally available plant information.

The second phase is transforming the data into actionable information. This function replaces the heuristic capabilities of seasoned craft to identify likelihood of discovery work with statistical models based on historical and equipment data available from within the plant. Work characteristics defined during screening and scoping phases and historical data relevant to work being planned are used to inform the statistical model and optimize its prognostic value to the work planner. The variables used in this proof of concept are derived from the information that planners referenced when building their work packages. The set of variables in Table 2 serve as a starting place, but as more is learned about their predictive power, the table should be adjusted to maximize the prognostic capability of the smart planner tool.

Once the data have been collected and analyzed, the data are cleaned by removing unused variables, such as equipment name and identification (ID), that have no effect on the final output. Null and unused values are also removed. The data are then split into train and test subsets to avoid overfitting the data. A model is built on the extracted train data, and output is predicted on the test data. All methods used for splitting, testing, and training data and for generating regression models for making predictions are contained in the scikit-learn (Pedregosa 2011), pandas (McKinney 2010), and Numpy (Harris 2020) Python libraries.

Table 2. A list and description of the variables used to inform the logistic regression model.

Variable Type	Variable Name	Variable Description
Categorical	Critical Path	Critical path is a highly weighted variable indicating the work activity is of high priority due to the negative impact on a plant's safety basis possible keeping a plant from producing energy.
	Logic Ties	If an activity contains logic ties, then cancelling or delaying this work will have cascading impacts on other activities.
Continuous	Work Duration Variation	Work duration variation is measured in minutes and describes how long the activity takes to complete.
	Frequency of Discovery Work	Frequency of discovery work describes how often discovery work is found when servicing this equipment.
	Time Since Last Routine Maintenance Should Have Been Performed	Time since routine maintenance should have been performed indicates how many days have passed since routine maintenance should have been performed.
	Frequency of Discovery Work	Walk-down success in discovery work is measured in three tiers: Low, Medium, or High.

A simple graphical user interface was created using the PySimpleGUI library (PySimpleGUI Organization 2020) to allow the user to select equipment from a list and input whether the selected equipment is on critical path and has logic ties (with development, compensating for logic ties is expected to become more complex). The software references data from the test set for the selected equipment and sums the values for the continuous variables, calculating a mean and standard deviation for each. It then uses the best fit model, extracted by a k-fold cross validation, to make a prediction based on the values selected by the user and calculated values. The results of the prediction and calculation are then displayed at the bottom of the interface to assist the planner in building a proactive work package (Figure 4).

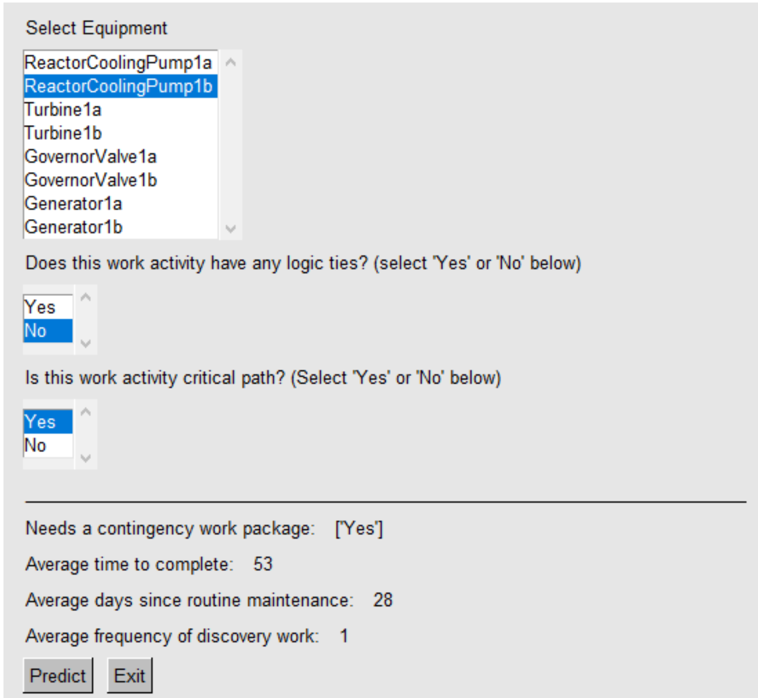

Figure 4. A user selects equipment through a graphical user interface and makes a prediction regarding the need for a contingency work packet. Prediction results and other related information are displayed at the bottom.

The five-fold cross validation algorithm takes in data to fit a model on four (k-1) subsets. When the training phase is finished, the remaining (fifth) subset of data is used to test the regression's goodness-of-fit. Separating the dummy data in this way demonstrates the predictive quality of the regression. This also replicates how historical data are used to train the model immediately prior to predicting the needs of the current work. This method ensures the work planner is given the most up-to-date information.

The model achieved 68% accuracy when predicting the need for a contingency work package. The model is expected to reliably achieve this accuracy level given the current data due to a 1.0 C regularization parameter indicating a tight fit of the model to the data. This outcome is encouraging because it supports the predictive-analytics capability to perform the above predictions with 146 true positives and 101 true negatives. The model accuracy is expected to improve with additional data and curating of the variable input to increase prognostic capabilities.

Still, the accuracy was not perfect. Fifty-five false negatives and 61 false positives were recorded in the predictions, translating to a rate of 15% false negatives. False negatives are the worst error because they put the same burden on the work planner as discovery work would without the smart planner. Except, in this case, the planner may lose trust in the smart planner's ability to support planning efforts and rely on the predictions less. Some considerations to solve this issue include:

- Using a larger data set will reduce the number of false negatives
- Improving the quality of the data set (using real plant data in place of dummy data set)
- Adjusting the type of variables in the regression model.

Addressing any one of these three considerations is expected to improve the regression model. The next step to enhance this regression model is accessing actual plant data to get a sense of the variables and their power to predict the need for a contingency work package. Additionally, the descriptive metrics outputted at the bottom of Figure 4 can be refined and enhanced with iterative input from the work planners to reduce their current efforts to collect relevant information in building their work packages.

2.2.4 Result

The smart planner uses data collected by dynamic work instructions to provide a basis for suggesting requirements of similar, upcoming work packages. Further, it curbs inefficiencies of the work management process by analyzing the likelihood of discovery work and offering suggestions to build a contingency package. All this takes place as the work planner builds work packages that meet the predetermined scope of work to be performed.

A strength of this solution is its improvement as more data is collected. During the transition period, planners can confirm smart-planner insights with the resources already used and available within the plant. As work is performed, data are captured, and user feedback is provided, the analysis process is improved. Through this process, current expertise is captured rather than lost when the highly experienced retire. In the place of experienced personnel is an informed planning assistant that can evaluate work-package planning needs. Successfully implementing a smart planner directly supports the following objectives from INPO (AP-928):

- Optimize safety system- and refueling-outage durations
- Support effective station-backlog management
- Increase productivity through efficient use of resources
- Improve schedule credibility and stability
- Reduce costs
- Promote nuclear safety
- Improve industrial-safety performance
- Improve radiological-safety performance
- Improve equipment performance and system health.

Refueling outage durations, productivity, and schedule credibility and stability will be improved when planners use the insights provided by the smart planner. Incorporating the smart planner’s insights into work packages leads to comprehensive and adaptable work packages able to flex with dynamic work scenarios. The capability to flex as work is carried out reduces the strain on the work-management process that unexpected scenarios typically cause. The doubling of efforts for nearly all phases and cascading effects on later work reliant on completion of the currently afflicted work are minimized using the premeditated work contingencies already equipped with the approvals and resource requirements. Hence, schedules are more resilient to discovery work and less susceptible to communication breakdowns.

Increased productivity and resiliency in the face of adversity leads to fewer project delays or projects relegated to the backlog. One result is that equipment would be maintained more frequently. Use of the smart planner may also lead to earlier detection of serious defects or other discovery work, which can minimize negative impacts to plant operation.

The manually intensive information-seeking portion of an effective work planner is now supported by the smart planner. The work planner can evaluate the insights provided by reviewing all relevant and historical information available regarding the work package at hand. Bringing together the available information minimizes the most time-consuming portion of a planner’s workday. Removing this large portion of the effort frees the planner to generate more work packages or attend to more backlogged items. Furthermore, the planner’s being interrupted by discovery work becomes increasingly less likely, continually improving the time available to a planner to perform other work.

2.3 Industry Benefit

The nuclear industry's work-management process keeps a plant running smoothly. The surveillance and maintenance of all plant equipment and safety systems are coordinated through that work-management process. The process is improved by collecting data and using them to inform process improvements on a continuous basis. However, the process is eroded when communication breaks down, only a paucity of information is available, or excess emergent or discovery work becomes disruptive. Legacy plants are realizing the loss of legacy knowledge available from their retiring work force requires adopting new tools to help minimize the loss of knowledge. Advanced plants are seizing on the opportunities of a digital, connected plant. These opportunities exist for legacy plants as dynamic procedures and digital work-authoring tools become more ubiquitous.

The smart planner is born of the advantages available with digital tools. Capturing an abundance of data is automatic and descriptive of the actual work performed. It is no longer an abstraction captured in a form, through oral descriptions of the process, or from half-scribbled notes awaiting later interpretation. Comments made, trends discovered, and alterations to a work procedure are not subject to the inevitable deterioration found when passing information through multiple checkpoints. Using data from past work performed can fill the gap left by retiring legacy knowledge and experience to further streamline the work-management process.

The smart planner is built to continually improve as more work is performed. As more data are collected, the tool can provide more-detailed recommendations to the planner. The planner is also part of the feedback process to improve the smart planner. Especially in early iterations, the tool will need work-planner input when available information is inadequate.

3. LESSONS LEARNED DURING THIS EFFORT

Typically, to engage end users, become educated in the work management process, and watch the process as it is currently performed in industry requires physical presence at the locations where the work is being carried out. The presence of COVID-19 and travel restrictions hampered the usual avenues to engage industry. The team adapted to online or over-the-phone meetings. Unfortunately, the latter method restricts the ability to see how the work-management process is carried out. Documents, software, and tools used to perform jobs cannot be viewed, and sharing images or data is difficult due to security precautions.

4. FUTURE ACTIONS

4.1 Development

Next steps to bring this solution to utilities are:

- Identify a utility collaborator with some implementation of dynamic work instructions
- Use the data collected by the work-instruction tool to train the smart-planner analytics
- Evaluate capabilities and limits of the analytics to build an interface curated for work planners
- Integrate the smart planner in the existing work planning software tools.

Utilities already using dynamic work instructions are important because the smart planner capitalizes on the new availability of high-quality, granular information regarding all work performed in the plant. Its success lies in training the tool on the data captured in the digital dynamic work instructions. It is likely that additional data captures and close-out entries may help the smart planner to function. Those needs can be identified with a utility using a digital platform already.

As the smart planner is fed additional data, it becomes more accurate. The limitations and capabilities of its accuracy will be addressed in the interface designed for it. An interface with the right transparency and the most-reliable prescriptions will have the greatest success. The tangible impact of supporting the human planners in their work directly results in improved work-management efficiency. Equally as important is the trust a work planner will have in the smart planner's efficacy. A tool not trusted or accessible by the user gets shelved. In fact, those we interviewed mentioned knowing of greater analytic capabilities in their software tools, but they found it easier to perform work manually than use the tools' complex and difficult-to-learn functions. That lesson speaks to the importance of curating the right interface for work planners.

On a similar note, the smart planner needs a capability to integrate with the planning software used at plants. Through interviews, we found that plants use different software tools to help schedule, archive, measure, and perform work. A new addition to the complex suite of tools is unproductive. Developing an integration pathway to work in synchrony with current tools can minimize the disruption of deploying the smart planner. Less disruption can mean faster adoption and increased use of the solution leading to more-potent results.

4.2 Impact Assessment

Once a trial smart planner is implemented at a plant, researchers and industry collaborators should assess the extent to which the two major needs—operations efficiency and archiving rich historical data—are being met.

Operating-efficiency metrics are already in place at most utilities. In fact, these helped identify the need for the smart planner. Using current measures along with benchmarking the objectives directly impacted by the smart planner (laid out in Table 1) for before and after comparisons will help assess the impact a smart planner has on work-management process efficiency. Over time, the smart planner is expected have improved impact as it learns about plant work activities and the provides feedback to improve analytics.

Understanding the impact on work planner's reliance on traditional communication methods is more difficult because direct measures are not traditionally available. However, Figure 3 offers some insight by tracking the pathway's work activities after implementing the smart planner. For instance, measuring backlog growth after implementation, compared to before implementation, is an indicator of impact. Also, having conversations with work planners and schedulers about the accuracy and completeness of work packages is another indicator. For a clearer picture, assess the level of effort work planners exert to build their work packages using the smart planner compared to their current, manual efforts. Quantitative measures such as the National Aeronautics and Space Administration (NASA) Task Load Index (The NASA TLX Tool 2019) offer clear numerical benchmarks for comparison. Multiple administrations of measures or conversations can offer insight to the smart planner's progress as more data are made available to enable its capabilities.

4.3 Adoption

The final phase is disseminating this strategy industrywide. Once successfully demonstrated, a path forward and realized gains would become clear to other utilities and vendors alike. The value of dynamic work instructions would increase as well. At that point, two phases of the work-management process would benefit and demonstrate accuracy and efficiency gains in plant processes. Continuing to improve the utility circulatory system accounting for 60% of operations costs (World Nuclear Association 2020) would improve nuclear power-generation competitiveness in the power-generation industry. Though this solution was developed targeting nuclear power, any process industry with complex work-management processes stands to benefit in the same way. Leveraging advanced technologies in industry allows plants to leave manual, labor-intensive, and costly conservative estimations behind with data-driven, accurate, and precise actions with no loss of safety and with cost-savings to operations.

5. REFERENCES

Albright, B. (2016, March). Scheduling software investment pays off in increased productivity. Field Technologies Online - route scheduling, workforce management software. Retrieved October 26, 2020, from https://www.fieldtechnologiesonline.com/doc/scheduling-software-investment-pays-off-in-increased-productivity-0001

Donges, N. (2018, May 15). Predicting the survival of Titanic passengers. Medium. https://towardsdatascience.com/predicting-the-survival-of-titanic-passengers-30870ccc7e8

Harris ,Charles R., K. Jarrod Millman, Stéfan J. van der Walt, Ralf Gommers, Pauli Virtanen, David Cournapeau, Eric Wieser, Julian Taylor, Sebastian Berg, Nathaniel J. Smith, Robert Kern, Matti Picus, Stephan Hoyer, Marten H. van Kerkwijk, Matthew Brett, Allan Haldane, Jaime Fernández del Río, Mark Wiebe, Pearu Peterson, Pierre Gérard-Marchant, Kevin Sheppard, Tyler Reddy, Warren Weckesser, Hameer Abbasi, Christoph Gohlke & Travis E. Oliphant. Array programming with NumPy, Nature, 585, 357–362 (2020), DOI:10.1038/s41586-020-2649-2 (publisher link)

International Atomic Energy Agency, Management Strategies for Nuclear Power Plant Outages, Technical Reports Series No. 449, IAEA, Vienna (2007).

Kovesdi, C., Spielman, Z. A., Hill, R., Li, R., Mohon, J., & Le Blanc, K. (2020). Demonstration and Evaluation of an Advanced Integrated Operations Concept for Hybrid Control Rooms (INL/EXT-20-58538). Idaho National Laboratory.

Lybeck, N. J., Thomas, K. D., & Primer, C. A. (2020, September 29). Light water reactor sustainability program plant modernization technical program plan for FY 2021 (Program document). OSTI.GOV. https://www.osti.gov/biblio/1669362-light-water-reactor-sustainability-program-plant-modernization-technical-program-plan-fy

McKinney, Wes. Data Structures for Statistical Computing in Python, Proceedings of the 9th Python in Science Conference, 51-56 (2010) (publisher link)

Oxstrand, J., Le Blanc, K. L., & Hill, R. (2018, April 1). Human performance benefits gained by dynamic instructions compared to smart PDFs (INL/CON-17-43985-Rev000). Idaho National Laboratory. https://www.osti.gov/biblio/1478768-human-performance-benefits-gained-dynamic-instructions-compared-smart-pdfs

Pedregosa, Fabian, Gaël Varoquaux, Alexandre Gramfort, Vincent Michel, Bertrand Thirion, Olivier Grisel, Mathieu Blondel, Peter Prettenhofer, Ron Weiss, Vincent Dubourg, Jake Vanderplas, Alexandre Passos, David Cournapeau, Matthieu Brucher, Matthieu Perrot, Édouard Duchesnay. Scikit-learn: Machine Learning in Python, Journal of Machine Learning Research, 12, 2825-2830 (2011) (publisher link)

PySimpleGUI Organization. (2020). PySimpleGUI. PySimpleGUI. Retrieved December 8, 2020, from https://pysimplegui.readthedocs.io/en/latest/

Ritchie, H. (2020, February 10). What are the safest sources of energy? Retrieved October 20, 2020, from https://ourworldindata.org/safest-sources-of-energy

NASA. The NASA TLX Tool: Task Load Index. (2019, August 15). TLX @ NASA Ames - Home. Human Systems Integration Division @ NASA Ames. Retrieved November 10, 2020, from https://humansystems.arc.nasa.gov/groups/TLX/

United States, Institute of Nuclear Plant Operations. (2017). *Online Work Management Process Description AP-928* (Revision 5 ed., pp. 1-54).

World Nuclear Association. (2020, March). Economics of Nuclear Power. Retrieved October 20, 2020, from https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx