SET-BASED PLANNING IN THE DECOMMISSIONING OF A NUCLEAR POWER PLANT

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ABSTRACT

Decommissioning of nuclear facilities is a rapidly growing field in which construction techniques are applied within a dangerous environment. Radiation and contamination complicate the design of the decommissioning process. The main objectives of decommissioning are to maintain a safe environment for workers and to avoid loosing material. Secondly, the decommissioning process shall minimize the amount of contaminated material that must be stored safely for a long time. Decommissioning processes, as well as construction processes, often consist of several inter-related tasks. During the decommissioning process planning, several feasible procedures for each task must be evaluated within the context of the overall system and regarding delivery of customer value. This paper documents a case-study during which a two staged set-based planning approach was applied to rigorously explore the planning space of a dismantling process at a nuclear power plant in Germany. The result of the planning process was then verified through a survey of experienced practitioners.

KEY WORDS

lean construction, set-based planning, decommissioning, dismantling, nuclear facility, safety, morphological box, Choosing By Advantages.

INTRODUCTION

The subject of this case-study is the planning of a dismantling process that is part of decommissioning of a nuclear power plant. During the dismantling process construction workers remove radioactive parts of the facility. These materials are then stored in a radioactive waste repository.

The number of nuclear power plants that are in decommissioning phase is increasing, due to their age but also due to political circumstances. 19 nuclear power plants have been shut down in Germany so far and 14 of them are currently in

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decommissioning (Kernenergie 2011). Further, the German federal cabinet approved a draft law which entails nuclear power phase-out in Germany until the end of 2022 (Deutscher Bundestag 2011).

Safety is the most important factor during the planning and execution of dismantling processes and is regarded as the major customer value. Specifically, safety concerns the working conditions and choice of procedures for dismantling as well as control, tracking, and containment of radioactive material.

Set-based design application can increase delivery of customer value (Ward et al. 1995) and it has been applied for design problems in several fields (e.g., Sobek et al. 1999, Parrish et al. 2008). Thus, set-based design application seems favourable in order to increase safety in the decommissioning of nuclear power plants. However, set-based design has not been applied in production process planning, to which decommissioning planning seems highly related. The applicability of set-based design depends on the characteristics of the design problem at hand (Terwiesch et al. 2002) and the problem characteristics of nuclear power plant decommissioning seem fitting for the application of set-based production process planning.

First, a literature review describes complexity as a project characteristic and methods for planning. Next, research method and hypotheses are presented. The case-study describes the set-based planning approach and the paper closes with results and conclusions.

LITERATURE REVIEW

COMPLEXITY AS PROJECT CHARACTERISTIC

There is no general agreement on a definition for the term ‘complexity’, rather the context or field of study influences the view on complexity. Pich et al. (2002) define complexity based on the definitions for ambiguity and uncertainty by Schrader et al. (1993). Ambiguity is defined as a lack of knowledge about the structure of a development problem, i.e., one cannot see clearly all parts of the problem and / or their relations with each other. Uncertainty is defined as a lack of information about the parts of a development problem. Uncertainty and ambiguity have a great influence on the management of development processes that are in place to solve a development problem.

MANAGEMENT OF DEVELOPMENT PROCESSES

The purpose of a development process is to find a solution for the development problem at hand. The result of the development process is a product and the goal of the development process is to design the product according the values of the customer of the product. The development of an AEC (Architecture - Engineering - Construction) project is similar to the development of a new product: both consist of design and planning and both can be managed in different ways.

Schrader et al. (1993) argue that a development process should be designed according to the project’s uncertainty and ambiguity. Terwiesch et al. (2002) recommend the use of set-based design for development problems that have high uncertainty and little ambiguity. Sommer et al. (2009) prove the hypothesis of using set-based design when ambiguity is low and uncertainty is high in an empirical study.

SET-BASED DESIGN

Ward et al. (1995) distinguish between two strategies for the organization of development processes: point-based design and set-based design. When pursuing a point-based strategy, designers develop one solution for a design problem at a given time in detail. In case information arrives that proves the solution unfeasible or the information shows that the effort for adapting the solution to the new insights is unreasonable, the development process starts over. Thus, point-based design can be regarded as the sequential development of solutions in detail until a feasible solution is found. In set-based design, designers develop several solutions at the same time. They begin the development process by considering the whole design space of a problem and then proceed by gradually narrowing down the set of solutions. Solutions are eliminated from the set according to rules that evaluate solutions at decision gates of the development process. These rules reflect the values of the customer. Looking at the whole design space, delaying decisions about pursuing a solution, and ruling out solutions based on customer values shall help develop a solution that satisfies customer value insofar as possible (Ward et al. 1995).

Ward et al. (1995) first observed the company-wide application of set-based design in Toyota's product development processes (Sobek et al. 1999). In the AEC industry set-based approaches have been applied to construction site layout (Tommelein et al. 1991) and rebar design (Parrish et al. 2008).

MORPHOLOGICAL BOX

Zwicky (1948) defined a morphological box as consisting of rows that show functions and columns that show technical solutions for the respective function. Transferred to production planning the rows can describe tasks and the columns depict alternative procedures for each task. Structured re-combination of procedures helps in mapping the whole design space of the planning process. Decision makers can then build feasible combinations of procedures and evaluate the combinations in the context of the whole system.

CHOOSING BY ADVANTAGES

The quality of decision making during a set-based design process is crucial for its success. Choosing by Advantages (CBA) is a sound decision making system and it demands the use of a strict language to achieve mutual understanding between all persons involved in the decision making process (Suhr 1999). An 'alternative' is a possible result of the decision making process. CBA distinguishes clearly between attribute and advantage: an attribute is the characteristic of an alternative and an advantage is the result of the comparison between attributes of two alternatives. Decision-makers design decision rules which are called criteria. A factor is a container for criteria and other types of data. CBA distinguishes between 'must criteria' and 'want criteria': if an alternative cannot satisfy a must criterion, it is unfeasible, and thus discarded. Want criteria represent preferences of the decision-maker(s). Cost is not a criterion but evaluated separately. CBA uses only advantages for the comparison of alternatives: concurrent consideration of advantages and disadvantages makes decision-making un-sound (Suhr 1999). Parrish & Tommelein (2009) applied CBA successfully in a construction design process.

RESEARCH METHOD

This paper is part of ongoing research at the Institute for Technology and Management in Construction on decommissioning of nuclear facilities. One of the authors of this paper was an active member of the team which planned the dismantling process of the large machine rooms. He researched literature and interviewed members of the decommissioning design team as well as workers on site regarding procedures for dismantling, their attributes, and criteria for their evaluation. The resulting concept for the dismantling process was verified through a survey of 21 members of the project team.

HYPOTHESES

Characteristics of a development problem determine whether the application of set-based design is beneficial (Terwiesch et al. 2002). The task of planning a construction process can draw from knowledge about the project that accumulated during building design and input from experienced construction personnel. This knowledge reduces the ambiguity and uncertainty of the construction process. However, some uncertainty remains, e.g., performance characteristics and weather conditions, which can also affect the decommissioning of nuclear facilities.

The allocation of radiation and radioactive material is highly uncertain and can mostly only be determined during the decommissioning process. Further, the field of nuclear decommissioning is rather young and not very developed. It uses procedures from construction that were not designed for application in potentially radioactive environments. Most influences on the decommissioning process are clear and well understood, but there is a lack of information about their specific values and impact. In summary, ambiguity seems low while uncertainty seems high. Thus follows hypothesis 1: set-based planning is applicable for dismantling process planning of nuclear power plants.

Within the environment of decommissioning of nuclear facilities an improvement of customer value can mean an increase in safety or improved efficiency under equal safety. While set-based planning has the potential to increase the delivery of customer value, its application increases the effort needed in the design process. A structured development and analysis of all applicable planning alternatives adds a considerable amount of coordination and work to the process. Nevertheless, set-based planning may be beneficial and it is the goal of this case-study to show applicability and benefit of set-based planning. Thus follows hypothesis 2: application of set-based planning increases delivery of customer value.

CASE-STUDY

BACKGROUND

The nuclear power plant went into service in the 1970’s and its pressurized water reactor produces a net output of 630 MW. Since 1984 it produces an additional 7.7 MW of district heat that is supplied through water steam. In 2003 the plant was shutdown and in 2005 decommissioning was permitted by the regulatory agencies. According to current plans, the demolition of the plant will be complete by the end of 2014.

This case-study focuses on the dismantling process of the large machine rooms. During plant operation, these rooms contained the steam generators and the main cooling fluid ducts of the plant. Thus, the large machine rooms are placed close-by the reactor pressure vessel.

Radioactivity in the large machine rooms

During nuclear power plant operations, areas of the large machine rooms can be exposed to radioactive materials. These materials have two effects on the installations and structures of the rooms: (1) the radiation emitted by radioactive materials activates installations and structures, which means that these become radioactive themselves and start sending out radiation. (2) Installations and structures can incorporate disseminated radioactive materials, thus becoming contaminated. Active material emanates radiation; contaminated material itself does not emanate radiation but it holds radioactive material (Chhatwal 1998).

The dismantling process goes through several phases and this case-study focuses on the phase of dismantling the activated structures. In the preceding phase of the project all installations were removed from the large machine rooms. Structures of the large machine rooms may or may not be activated, contaminated, or both. As a rule of thumb, activation and contamination increases in areas closer to the locations of steam generators and cooling fluid ducts due to their connections to the reactor pressure vessel. Also, the saturation of structures with activation and contamination must not be not evenly, the values of activation and contamination rather vary.

The design of the large machine rooms includes a measure to lessen the saturation of structures with contamination. A 3-4 mm layer of epoxide resin covers all concrete surfaces to avoid contamination by binding radioactive materials before they can reach the concrete.

Safety risks caused by radiation during decommissioning

A decommissioning project faces numerous risks. The two most significant risks involved in the work researched in this case-study are the health and safety risks to construction workers that dismantle structures of the facility and the risk of dissemination of radioactive materials into the environment.

Specifically, workers face the risk of absorbing radiating material through their lungs, mucous membranes, and skin. Thus, workers wear protective suits that shield them from radiation as well as breathing masks and safety goggles. All demolished materials are stored in coverable containers to reduce the risk of material loss. Containers are booked in a database for tracking of materials. Only covered containers leave the large machine rooms.

Dismantling process of the large machine rooms

The German Radiation Protection Ordinance (StrlSchV 2001) is binding for this project; as such it influences the dismantling process. One of its important principles is avoidance of mixing materials. For the work in the large machine rooms it demands that activated must be separated from contaminated material, because they are disposed in different ways.

Thus, avoidance of mixing imposes the separation of four kinds of materials in this phase of the project: (1) surface protection, (2) activated reinforced concrete, (3) contaminated reinforced concrete, and (4) reinforced concrete that is activated and contaminated at the same time. As mentioned, the goal of this phase of the project is the dismantling of all activated material. Material that is contaminated but not activated shall remain in the facility and will be dealt with in a later phase of the project. Nevertheless, it is sometimes necessary to remove contaminated material in order to access activated material. 'White concrete' refers to reinforced concrete that is only activated and 'black' concrete refers to reinforced concrete that is contaminated, regardless of whether it is activated. This nomenclature is used in this paper from this point.

The process of dismantling is iterative. It starts with taking samples of the area under demolition. These samples show how deeply surface protection and reinforced concrete are activated and contaminated. Next, workers remove surface protection and then the reinforced concrete to depth that the material is assumed to be contaminated and/or activated. After removing the concrete, a worker takes another sample that either proves that all activated reinforced concrete is removed or indicates the need for further removal. This process may iterate many times due to the high uncertainty about actual activation of the reinforced concrete. Sampling also helps to distinguish between white and black concrete, which must be handled separately.

In addition to the requirements stated above, the planning of dismantling processes is influenced by the following principles for waste reduction:

- Avoidance of cross-contamination: interaction with contaminated material can mobilize radioactive matter that was sitting on the surface. Contaminated matter must not reach contamination-free material and in turn contaminate it.
- Avoidance of secondary waste: material brought into the large machine rooms will likely be contaminated and thus become secondary waste. The amount of secondary waste shall be minimized.

Following the removal procedure, workers fill the dismantled material into containers and register the container in the database for tracking. Next, workers transport the containers to their respective destinations. All reinforced concrete is first transported to the crusher, which conditions the concrete to desired granularity and separates the rebar. Black and white concrete must be crushed separately and the crusher must be de-contaminated between loads. Surface protection material and concrete grains stemming from black concrete are filled into radioactive waste containers. Concrete grains stemming from white concrete are measured for radioactivity and, if radiation free, disposed in a landfill. Rebar stemming from black and white concrete is dispatched for melting.

PLANNING OF DISMANTLING PROCESS

The planning process consists of three steps: define the problem, structure the planning process, and choose by advantages.

Define the problem

Modelling of the system helped understand its characteristics. Tasks and dependencies between them were documented in a flowchart and then translated into a force directed graph (figure 2). Dismantling of the large machine rooms is one of several phases within the decommissioning process of the nuclear power plant. A Crusher, a filling station for radioactive waste containers, and other machines as well as the logistics routes between these machines are used during several phases of the project. Thus, the planning of these facilities is not part of this case-study. Nevertheless, their existing design must be considered when evaluating the dismantling process of the large machine rooms. Further, design of sampling procedures and design of the analysis of samples is not within the scope of this case-study. The focus of this case-study is planning of the tasks ‘surface removal’ (circled red), ‘concrete dismantling’ (circled orange), and ‘logistic routing’ (circled green) within the overall system (figure 1). Complexity of the dismantling process becomes visible through the highly interconnected cluster of tasks on the centre left hand: interdependencies between tasks show the iterative nature of the process.

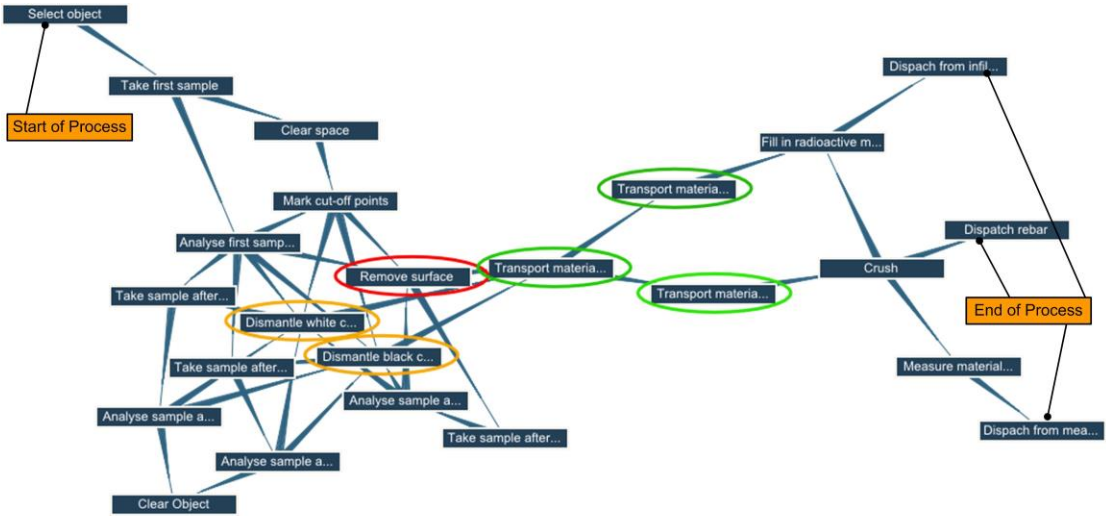

Figure 1: Structure of dismantling process with colour-marked planning scope

Structure the planning process

Following Sobek et al.’s (1999) framework the planning space of the dismantling process was mapped. Interviews with engineers as well as foremen and literature research revealed existing procedures for the three different tasks. Overall 19 procedures for surface removal, 6 procedures for concrete dismantling, and 3 logistics routes were identified. Permutation of the different procedures for the three tasks resulted in 342 combinations that needed to be compared in order to find the ‘best’ process.

The overwhelming number of combinations warranted a two-staged planning process consisting of a branch stage and a system stage (Figure 3). First, the procedures for the tasks of each branch were evaluated based on ‘must criteria’. In case they did not fulfil these, they were discarded from the planning process. After application of the ‘must criteria’ 13 alternatives remained for surface removal, 4 alternatives for concrete dismantling, and 2 alternatives for logistics routing. In the next step, the remaining procedures were evaluated based on the ‘want criteria’ and sorted in order of their advantageousness.

Next, procedures of each branch (branch level alternatives) moved into re-combination. The most advantageous procedures of each branch were chosen, but the question remained how many procedures should be transferred. The number of procedures brought into re-combination determines the effort needed in the system stage. In this case-study the best two alternatives from each branch moved into re-combination. In re-combination planners built combinations of procedures using the morphological box in order to find combinations of procedures for evaluation in the context of the whole system.

In the system stage, combinations of procedures are evaluated based on ‘must’ and ‘want criteria’ (figure 2). Here, no additional ‘must criteria’ were found for the system stage, thus all combinations were only evaluated based on ‘want criteria’. The want criteria consist of the want criteria from each branch plus two new system wide criteria: ‘Maximum number of workers on site at the same time’ and ‘system performance’. The attributes of the latter originate from a performance analysis of the system.

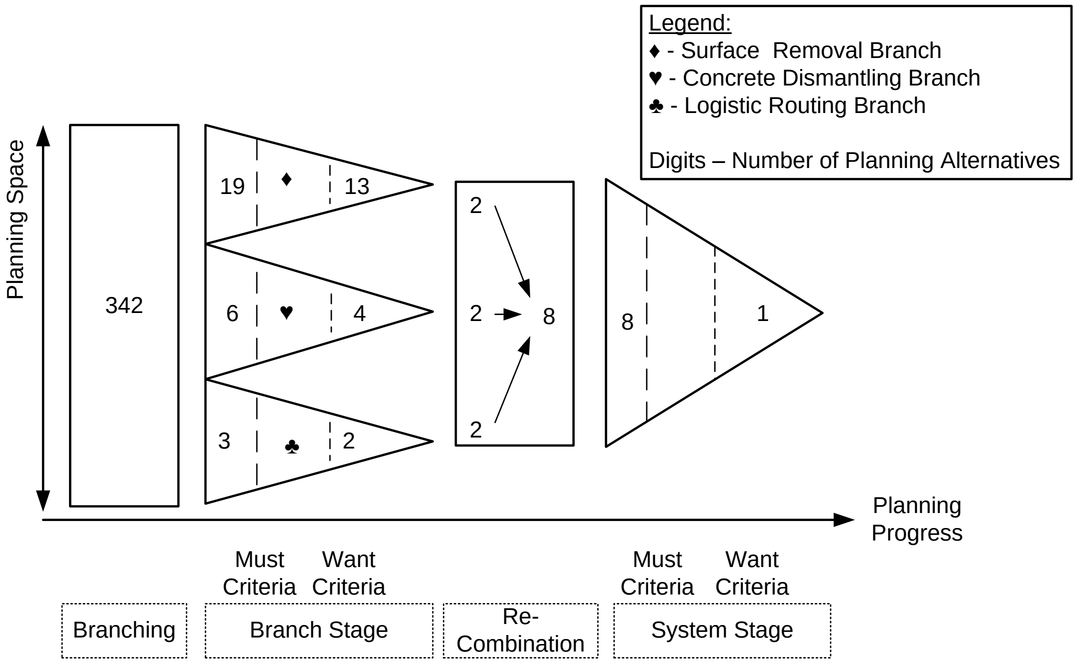

Figure 2: Structure of the 2-stage planning process

Choose by Advantages

Safety is the most important factor in the evaluation of the dismantling process. However, when comparing two equally safe dismantling processes, the German Radiation Protection Ordinance (StrlSchV 2001) stipulates the use of the more efficient process.

Table 1 presents an excerpt of the findings; advantageousness and cost estimates are substituted for symbols. Interviews with engineers and foremen revealed factors, criteria, and advantages for the CBA process. Performance and cost estimates were taken from literature or developed through interviews with experienced machine operators. As a result, system level alternative 5 is most advantageous for the dismantling process of the large machine rooms and has also the least investment cost. Advantageousness is shown on scale ranging from ‘ ‘ to ‘+++’. All factors in this table are want criteria, because no new must criteria were found for the system stage. Only planning alternatives that fulfil the must criteria of the branch stage moved into system stage, i.e., planning alternatives that do not fulfil must-criteria had already been sorted out during the branch stage.

Table 1: Excerpt from results of CBA application on system stage

System Level Alternative 5		
Surface removal procedure:	Scraper & bush hammer	
Concrete removal procedure	Air hammer & rope saw	
Logistic routing procedure:	Route 1	
Want-Criteria	**Attributes**	**Advantages**
Factor: Mixing of material **Criterion:** Less is better	Precise methods prevent mixing of contaminated und not contaminated material.	++
Factor: Cross contamination **Criterion:** Less is better	Rope saw produces only a small amount of dust which can mobilize contamination.	+
Factor: Secondary waste **Criterion:** Less is better	No use of water or acid for removal reduces secondary waste.	+
Factor: Risk of failure **Criterion:** Less is better	Rope saw control requires medium level of concentration which improves worker safety.	+
Factor: Exposure of rebar **Criterion:** Less is better	Concrete acts as shielding when reinforced concrete is cut out in blocks.	+
Factor: Crossings of transport routes **Criterion:** Less is better	No crossing of other routings improves worker safety.	++
Factor: Workers on site **Criterion:** Less is better	Transport: 4, work: 4, supervision: 2 Less personnel leads to more safety.	
Factor: System performance **Criterion:** More is better		++
Sum of advantages		9
Investment costs		+++
Variable costs		+

CONCLUSIONS

The planned dismantling process was verified through a survey of the planning team which supports hypothesis 1: a 2 staged set-based planning process was successfully applied in the dismantling planning of a part of a nuclear power plant.

Hypothesis 2 cannot be rejected nor supported. There is no frame of reference whether a point based, iterative planning approach would have yielded a less valuable outcome. Also, it cannot be shown whether the increased effort, that set-based planning may have needed, pays off through an increase in safety during decommissioning. However, development of the flowchart showed that engineers have a clear understanding about the structure of the process, because they were able to define dependencies between tasks easily. But great uncertainty about the values of the tasks remains, i.e., planners could hardly estimate the amount of concrete to be moved from the large machine rooms. Consequently, the planning problem is highly uncertain and little ambiguous and set-based planning should be beneficial (Terwiesch et al. 2002).

Uncertainty about the facility can resolve as the decommissioning process progresses, because new information on activation, contamination, and the performance of procedures becomes available. Existing documentation of other applicable procedures can be useful to make quick decisions. Set-based planning delivers exactly that through early exploration of the different applicable procedures and it is rather inexpensive compared to the costs that may incur, if the decommissioning process must be stopped, because a change of procedures must be prepared. The accumulated knowledge may be useful later in the project; however, more research is necessary on the benefits of set-based planning.

Further, the relation between customer value and decision making during the planning process needs attention in future research. The decision of how many alternatives move to the next stage of a set-based planning process depends on how much effort the customer wants to invest into the planning process. This decision highly determines the outcome of the planning process: taking only the most advantageous alternative of each branch into the system stage results in not considering the system level criteria. Taking all applicable alternatives of each branch may result in a lot of work.

In the arena of planning decommissioning processes, interaction between the planning and assessing teams needs to be reviewed and possibly arranged more collaboratively. As a consequence more persons would become involved in the planning process and their knowledge could help in planning a better process. However, the additional investment in planning effort must be justified through better results regarding safety and performance. Tools that make set-based planning more cost-effective could help, for example software agents for decision making support (Engelmann et al. 2008).

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