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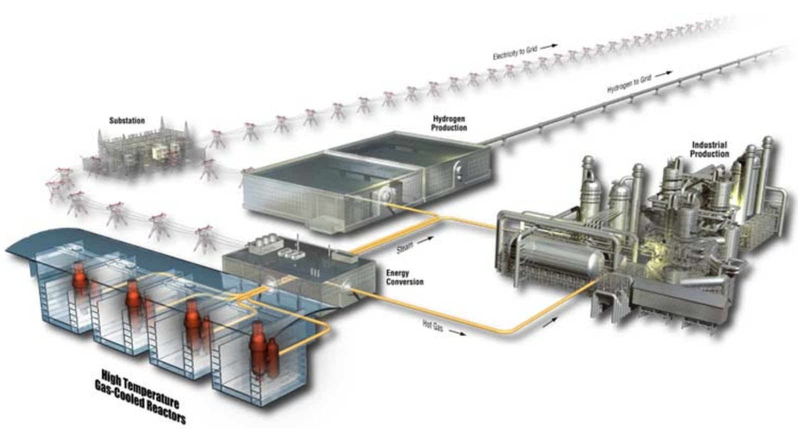
Work Domain Analysis Methodology for Development of Operational Concepts for Advanced Reactors

Jacques Hugo

May 2015



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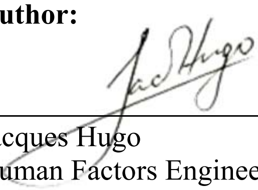

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ABSTRACT

This report describes a methodology to conduct a work domain analysis in preparation for the development of operational concepts for new plants. This method has been adapted from the classical method described in the literature in order to better deal with the uncertainty and incomplete information typical of first-of-a-kind designs. This report outlines the strategy for undertaking a work domain wnalysis of a new nuclear power plant and the methods to be used in the development of the various phases of the analysis. Basic principles are described to the extent necessary to explain why and how the classical method was adapted to make it suitable as a tool for the preparation of operational concepts for a new nuclear power plant. Practical examples of the systematic application of the method and the various presentation formats in the operational analysis of advanced reactors are provided.

NOTE: *For additional information, readers are referred to previous reports listed in the Reference section of this report.*

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ACRONYMS

ADS	abstraction-decomposition space
AdvNPP	advanced nuclear power plant
AH	abstraction hierarchy
AOO	anticipated operational occurrences
CAA	contextual activity analysis
CAT	contextual activity template
CWA	cognitive work analysis
EBR-II	Experimental Breeder Reactor-II
FAF	functional abstraction framework
FOAK	first-of-a-kind
FRA	functional requirements analysis
HFE	human factors engineering
HSI	human-system interface
I&C	instrumentation and control
INCOSE	International Council on Systems Engineering
INL	Idaho National Laboratory
MOE	measures of effectiveness
MOP	measures of performance
NIOSH	National Institute for Safety and Health
NPP	nuclear power plant
OpsCon	operational concept
OCD	operational concept document
OSHA	Occupational Safety and Health Administration
SFR	sodium fast reactor
SME	subject matter expert
SSC	structures, systems, and components
StrAn	strategies analysis
WDA	work domain analysis

Work Domain Analysis Methodology for Development of Operational Concepts for Advanced Reactors

1. BACKGROUND AND INTRODUCTION

Currently designed advanced nuclear power plants (AdvNPPs) differ in important respects from the previous generation of light water reactors. Typical advanced features include their ability to load-follow, produce different product streams with reconfigurable balance-of-plant systems, high levels of automation with humans in supervisory roles, integration of advanced human-system interface (HSI) technologies, computerized procedures, new challenges for staffing and training, online maintenance for multiple reactor units, and many more. Because of these unique design characteristics, AdvNPPs will require definition of nontraditional operational concepts. However, the implications of new operational concepts have not been evaluated in detail. Operational concepts will require detailed examination of system, functional and operational requirements, the impact of unique operational conditions and scenarios, and various economic, technical, regulatory, organizational, and human constraints that will influence future operational strategies.

The results from the research and development in the Operational Concept project will make an important contribution to the nuclear industry's ability of the nuclear industry to prepare for a new generation of AdvNPPs. The availability of well-defined operational concepts early in the project life cycle is important for traceability of design decisions and will help to align all engineering disciplines to ensure that system designs meet operational requirements, which includes the role of human operators. Failure to develop well-defined operational concept documents may lead to system design errors, serious operational inefficiencies, operator error, equipment damage, or other unsafe conditions.

Previous project work focused on three specific topics:

1. Identification of the unique characteristics of AdvNPPs that would influence decisions regarding the role and function of operating staff. This included an analysis of the requirements for allocation of functions to humans or systems in a highly-automated operating environment.
2. Identification of the human performance requirements in AdvNPPs. This included considerations of the impact of unconventional structures, systems, and components (SSC) on human performance.
3. Identification and description of the unique characteristics of a predecessor sodium fast reactor (SFR) and how this could be used to inform the development of operational concepts for more advanced reactor designs.

The results from these three topics led to the formulation of a framework within which the operational characteristics and associated human factors requirements for an AdvNPP could be analyzed and defined. This framework leveraged the results from the experimental application of the work domain analysis (WDA) method to the analysis of the Experimental Breeder Reactor-II (EBR-II). This framework was subsequently applied to the development of an example WDA for a generic SFR.

This report provides a detailed description of a modified WDA method that was developed specifically to serve as guidance for developers of AdvNPPs. It presents the WDA methodology as a system of broad principles and guiding rules from which specific methods or procedures may be derived to analyze or interpret multidimensional requirements and constraints within the scope of AdvNPP operations. The practical application of the derived methods forms a generic framework that can be broken down into subprocesses that may be combined or performed in different sequences.

This report outlines the strategy for undertaking a WDA during the design phase of a new AdvNPP and the methods to use in the development of the various phases of the analysis. The purpose of this document is not to rewrite the many excellent textbooks on cognitive work analysis (CWA) or WDA, but rather to present a practical methodology based upon the key principles described in the literature. This report will describe those basic principles only to the extent necessary to explain why and how the classical method was adapted to make it suitable as a tool for the preparation of operational concepts for a new AdvNPP.

Since the report contains terminology and concepts that may be unfamiliar to many readers, the following document map is provided as a guide to specific sections of interest:

Section	Description
Theoretical Background and Literature Review	The section covers the origin of the Cognitive Work Analysis and Work Domain method as described by the most prominent authors in the field.
Basic Concepts and Terminology	This section provides an alphabetical list of definitions and explanations of the key terms used in this methodology.
Work Domain Analysis Method Guidelines	This section describes the basic principles that govern the application of Work Domain Analysis to the development of operational concepts for a new plant.
Work Domain Analysis Procedure	This section provides guidance for readers who are interested in the practical development of abstraction hierarchies, analysis of operational conditions, and development of operationsl strategies.
Operational Concept Definition	This is a brief explanation of what an Operational Concept Document is.
References	The reference section of this report contains a bibliography of resources on theoretical background, practical application, and case studies. Every attempt is made in this document to provide self-explanatory methodology and application guidance, but reference is made in the body of the report to specific literature sources, where necessary.

For on-screen reading, hyperlinks *(blue underlined italic text)* have been provided throughout the document to facilitate easy cross-referencing of related material.

2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction to Cognitive Work Analysis Theory

Human-centered approaches to the analysis of incidents at nuclear power plants (NPPs) started soon after the Three Mile Island incident in 1979. This was mainly an effort to improve not only the reliability of human-machine interaction, but also to ensure attention to human cognitive processes in the design of HSIs). An example of this approach is seen in this guideline in NUREG-0700 (HSI Design Guide): “The support provided by the [computer-based operator support system] should be consistent in content and format with the cognitive strategies and mental models employed by the user” (p. 437). Another outcome of the intense Three Mile Island investigations was the recognition by the U.S. nuclear industry of the usefulness of work analysis and abstraction hierarchies in NPP functional analysis. The method was later adopted by the Japanese nuclear industry in the conceptual development of a new generation of control rooms (Vicente, 1999).

Lind (2003) provides a concise history of how CWA and its various phases came to play such an important role in certain industries. He explains that the AH was originally developed in the context of supervisory control of power plants, which has contributed to the general acceptance of the principles by systems engineers. He points out that the AH does more than just represent hierarchical structures in the domain. It also reflects tacit knowledge about engineering practices in the broader domain of process control that also has contributed to its application. Lind believes this explains the common-sense appeal of the AH and its success in the nuclear power industry.

However, Lind created the impression that application of the method is widespread in the nuclear power industry. Our research indicates that this is not the case. The majority of literature on WDA in the nuclear industry describes only small-scale studies of specific NPP systems, and all of them were focused on the supervisory function of the operator and representation of that function in some kind of interface design (Bisantz et al., 2003; Bisantz & Burns, 2008; Naikar, 2013). Lind emphasizes that the common-sense nature of WDA has “...led to the perception that the AH is without problems and ready to use.” This may be true for the kind of studies described in the literature, but is less applicable for large-scale analyses. To date, there has been no attention to the challenges of developing a WDA for a whole NPP and certainly not for any new NPP design.

The applications of WDA described by Lind and others are based on the premise that WDA and the AH would be used in the development of some kind of representation of a NPP operator’s work processes. This perspective is very different from the application of WDA described in this report. Lind has also described conceptual and methodological problems with the application of WDA. These problems relate to serious constraints when analysts attempt rigorous implementation of the principles. These are specifically methodology problems (knowledge acquisition, analysis boundary definition, and model validation), conceptual problems (identification of goals and objectives, level of breakdown, clear definition of the SSC hierarchy, roles of agents, distinction between values, measures, purposes, functions, processes, etc.). In other words, this is an example of a theory that cannot readily be translated to the real world without adaptation.

Partly motivated by the industry interest, a significant amount of work has been done in academia and systems engineering to develop the foundations and applications of WDA for analysis and modeling of complex work domains. In studies reported by authors like Naikar (2013), Jamieson et al. (2007), and Bisantz et al. (2003; 2008), it was found to be a valid approach to definition of NPP operator strategies for fault finding, and has offered a reliable basis for the analysis of operational strategies and eventually the design of operator interfaces.

However, several authors (e.g., Hajdukiewicz et al., 2001; Miller, 2004; Naikar, 2013; Sanderson, 1998) have found that in spite of the general acceptance of the principles, it has actually proven difficult to apply WDA in practice. Some of the difficulties could be ascribed to the lack of fully worked-out and validated examples from the industry. Most of the examples available from literature are limited in scope and are hard to translate to full-scope industrial applications. In addition, there is a significant lack of practical experience among practitioners in the nuclear industry, especially with regard to the opportunity to apply the method to new designs, because this is where the lack of operating experience or prior design information most severely challenges the skills of the analyst.

This report will describe an adaptation of the classical WDA method to form a pragmatic approach specifically designed to analyze NPP work domains and to develop operational concepts for new reactor designs.

The rest of this section provides a short overview of the contributions of some of the leading authors in CWA and why their contributions are relevant for the nuclear power industry.

2.2 Jens Rasmussen

Jens Rasmussen's work (1986; 1990; 1994) on cognitive engineering was years ahead of its time. From the beginning he has set out to develop a framework for the analysis and description of human-machine interaction and the design of user interface systems. However, his work is much more than that; he touches upon every aspect of the shape and function of a stratified sociotechnical system. This includes a thorough discussion on the nature of human tasks and performance in technical environments, the human as a component of the sociotechnical system, human error, and even such arcane topics as the design of supervisory control systems.

Much of subsequent cognitive engineering research relies on his legacy and many experimental projects have validated the basic concepts. However, many of his groundbreaking concepts have only recently started to be implemented in industry. One of his most important contributions, from a nuclear industry perspective, was probably the emphasis on the human as component within the system. This, linked to the increasing emphasis on avoiding human error that could lead to nuclear incidents, has created a paradigm shift in traditional engineering perspectives that often considered human abilities and limitations only late in a project when human-machine interfaces needed to be provided.

Rasmussen's most significant contribution (for the purpose of this report) is the discussion on the stratified nature of the technical enterprise, its goals, functions, and systems, and how this can be analyzed and represented in an AH framework. He explains that the way in which the functional properties of a system are perceived by workers and decisionmakers depends to a great extent upon their goals and intentions in relation to those of the enterprise. For that reason, it is important to provide a structured representation of the functional as well as physical properties of the system as it appears to a worker (e.g., NPP control room operator). A structured representation will also be a suitable framework for describing human-system interactions. This framework derives higher-level principles from the purpose of the system (i.e., reasons why the system exists in its various configurations at the specific level of abstraction considered). The hierarchical framework provides top-down as well as bottom-up logic in the form of a corresponding level of information detail required to characterize the function, process, or system.

Rasmussen further explains how the AH maps to the actual structure of the enterprise. For example, at low levels of abstraction, the AH provides information about a specific physical world that serves several purposes. More specifically, the bottom level of the AH is dealing with physical objects. In contrast, the higher levels of abstraction are closely related to a specific purpose or abstract goal that can be met by several physical arrangements of physical objects at the low levels.

It is clear that this arrangement makes the functional AH useful for a systematic representation of the many-to-many mappings in the purpose/function/equipment relationships, which is the basis of supervisory decisionmaking. These relationships are expressed in terms of the “what-why-how” links between levels: information on why a function is needed is obtained from the level above and information about the “how” (i.e., resources and their limitations required for the function, is obtained from the level below).

This information will ultimately be incorporated into a device or interface (e.g., HSIs in the control room) that will allow a decisionmaker to interrogate the state of a physical system or component in order to formulate the actual control task required to achieve the goal of the enterprise.

2.3 Kim Vicente

Kim Vicente’s work (1999; 2004) is widely regarded as the foundation for the practical application of CWA and all its derivative methods. Vicente has added great value to the original work by Jens Rasmussen (1986) and others by putting it all together in a coherent theoretical framework, supported by case studies from various domains. This work is also a systematic and disciplined attempt to clarify the semantics, and despite several adaptations by other authors and practitioners, this remains the benchmark for defining relevant concepts.

Table 1 represents Vicente’s description of how CWA can be broken down into five defined phases, (each with a defined outcome) that serves as input to the next phase (see also Hugo et al., 2013).

Table 1. The CWA Phases and their Products.

Phase	Product
Work Domain Analysis	Abstraction-Decomposition Framework and System Decomposition
Control Task Analysis	Decision Ladders
Strategies Analysis	Course of Action, Information Flow Map
Social Organization and Cooperation Analysis	Combination of previous
Worker Competencies Analysis	Skills, Rules, Knowledge Inventory, high-level function allocations

As shown above, WDA is a part of CWA and is used to analyze and define the task environment. The following diagram (Figure 1) explains the relationship between the five phases.

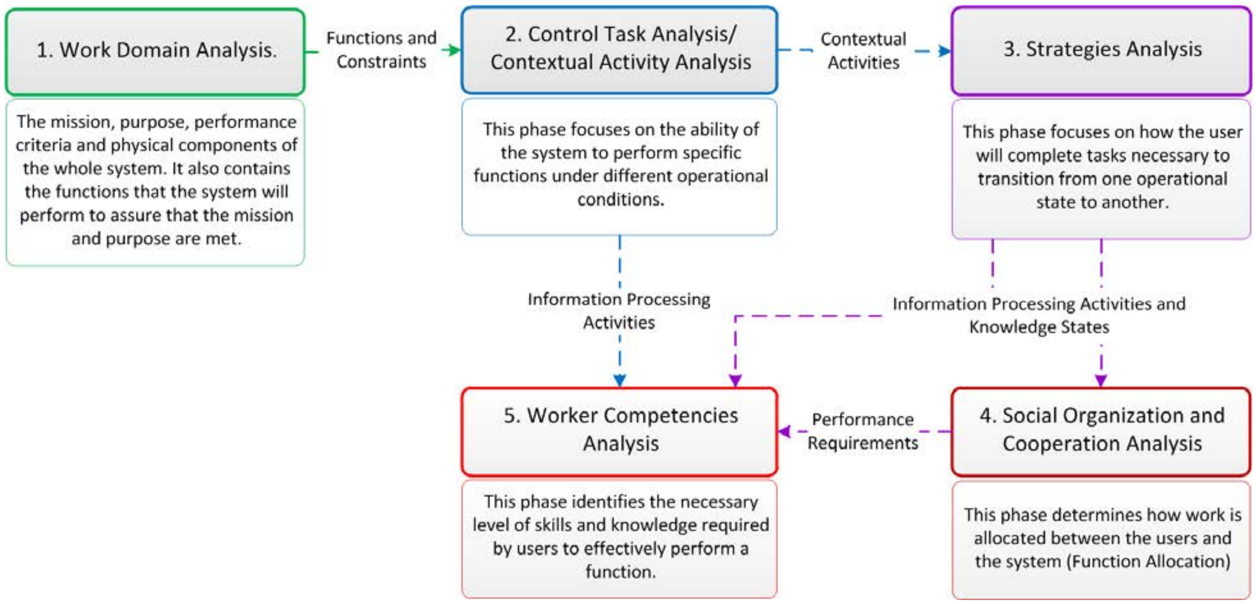


Figure 1. The five phases of cognitive work analysis.

WDA identifies a fundamental set of constraints on the actions of any actor, thus providing a solid foundation for subsequent analysis and design phases. The goals and functions of the work domain impose constraints on workers by specifying the purposes that the work system must fulfill, the values and priorities that the work system must satisfy, and the functions that the work system must perform. Therefore, because the environment that the task is conducted in has the potential to significantly affect the task conducted and ultimately the entire plant operation, CWA, and specifically WDA, is particularly suitable as an organizing framework for analysis of the key principles of AdvNPPs.

Vicente further describes three possible approaches to CWA:

1. The **normative** approach, which relies on the analysis of tasks that need to be performed in order to achieve a specific goal. It includes assumptions about human behavior and available resources. This approach aims to establish rational benchmarks or performance criteria for how work should be performed.
2. The **descriptive** approach seeks to understand how workers actually behave in practice. This goal is accomplished by studying actual work in the field and documenting the practical challenges that workers face on the job and to identify opportunities for new designs.
3. The **formative** approach focuses on identifying technological, functional, and organizational requirements to support work effectively.

As Vicente describes, the normative as well as the descriptive approach have limitations. The normative approach attempts to legislate work, while the descriptive approach attempts to portray existing work. Neither approach is suitable when requirements for a new design or system need to be identified.

More recent literature (i.e., Bisantz, Naikar, Jamieson, Sanderson, Naikar, Lintern, and others) has demonstrated that it is often necessary to deviate in some respects from Vicente’s baseline. This is expected and practical experience has shown that different work domains and different analytical goals require slightly different treatments. This is especially true for complex sociotechnical systems that would employ new, first-of-a-kind (FOAK) technologies and work methods described later in this report.

An important aspect of CWA that emerges from Vicente's work is the ecological approach. This means that the analysis of work should also consider the constraints imposed by the environment within which the sociotechnical system is situated and within which work is performed. This approach matches several perspectives that make CWA unlike any other traditional systems engineering approach, for example: the five phases of CWA represent a continuum from ecological at the highest level (the work domain), to cognitive at the lowest level (social organization and cooperation, and worker competencies). Similarly, this stratified approach also matches the ontological approach, where the highest level of WDA abstraction (goals and purposes) matches the upper, formal ontological level that is rationally derived and represents general, abstract categories of the sociotechnical system. The lower levels of the AH match the domain-specific levels of the ontology that is empirically derived from expert knowledge about the domain.

2.4 Neelam Naikar

In her work on CWA, Naikar (2005; 2006; 2013) describes the work domain as an intentional-functional-physical space in which work can be accomplished. As its name implies, WDA is a method for identifying the intentional, functional, and physical properties of a workspace and for mapping the relationships between those properties. WDA is the best-known and most pragmatic stage within the framework of CWA. With its emphasis on activity-independent, structural properties of a work domain, it is unique within behavioral and technical disciplines.

Naikar's work has added significantly to the classical models and frameworks of WDA that describe all facets of the methodology and its application to real-world environments, systems or operations. In practice, the models of WDA describe the product of an analyst's thinking about a problem, and essentially represent how the analyst is "framing" the problem, system or condition that is being analyzed. Often, these "analytical models" represent a conjecture or a supposition of how the analyst believes the relationships between abstract and concrete artifacts or events are organized. This is why, for many people, WDA seems obscure and difficult.

It could be argued that many other human factors methods of analysis are more straightforward. However, throughout her work Naikar forwards a persuasive argument that WDA offers unique and valuable contributions that approach the problem of design in a fundamentally different way. Her treatment of WDA is by far the most thorough and systematic now available. She has assembled an impressive array of research in explaining why it is useful and how it is typically accomplished. Rather than breaking new ground, she explains the fundamentals in clear, practical terms and provides examples of how the method can be applied to good effect.

On the question of why CWA and WDA are appropriate for the nuclear domain, Naikar explains the differences between normative, descriptive, and formative approached first described by Vicente:

- Normative approaches prescribe how work should be done in a system. Task analysis techniques that specify sequences or timelines of tasks for workers to follow belong in this category (e.g., Kirwan & Ainsworth, 1992).
- Descriptive techniques focus on describing how work is done in a system. Cognitive task analysis techniques, which are intended for studying the cognitive nature of work, are of this type (e.g., Klein & Militello, 2001). These techniques are most appropriate for investigating systems in which workers' responsibilities are characterized predominantly by cognitive, rather than manual tasks.
- In the formative approach, CWA focuses on revealing how work can be done in a system. This framework recognizes that workers in complex sociotechnical systems have many possibilities for action, including what to do, when to do it, and how to do it. Furthermore, these workers have to contend with novel or unanticipated events, which may pose serious threats to a system's effectiveness or safety. WDA focuses on the constraints that are placed on actors by the functional and also the physical structure of the work environment. This approach will promote safety, productivity and workers' health. Naiker states that this approach to design is necessary for complex

sociotechnical systems because of the impact that novel events can have on their effectiveness. Since events like beyond-design basis events or severe accidents cannot be specified in advance, workers cannot be provided with detailed preplanned solutions for handling them. Instead, when such events occur, workers must use their expertise and ingenuity to address high-level strategies to improvise a solution in real time. By identifying the constraints that the work environment and the system will impose on workers, it becomes possible to design systems, processes, and facilities that incorporate novel and flexible functionality that will support workers in unpredictable conditions. Therefore, instead of prescribing or describing how work should be done or is done in a system in conditions that are known or predictable, this framework focuses on identifying the constraints on actors. Within these constraints workers can form a variety of work patterns, which is why CWA is most accurately described as formative.

Naikar further addresses an array of issues. For example, "should we always use five levels of abstraction? What should those levels be named? Is it always necessary to develop the decomposition dimension?" These are common questions asked even by experienced practitioners of WDA. Her description of several variations of models that can be traced back to the work of Rasmussen, Vicente, Woods, Hollnagel, and others, contrasts different strategies for dealing with these issues. She explains the rationale behind the different strategies and argues that the variations are typically consistent with the foundational assumptions of WDA with each of the variations offering something of value to the analyst. Possibly Naikar's most valuable message is that while there may be incorrect ways to build an AH or an abstraction-decomposition space (ADS), there are at least several valid variations.

The major limitation of Naikar's latest work is that it lacks industrial examples. For example, NPP operations receive only a cursory mention in a reference to the previous work by authors such as Rasmussen, Vicente, Bisantz, Roth, and Burns. A fully worked-out example of an industrial system would have been especially helpful. One of the primary constraints for analysts working in industrial domains is the shortage of proof-of-concept examples of WDA at the scale and complexity of large sociotechnical systems such as a NPP.

Naikar describes how WDA could be a valuable analytical method to generate functional requirements, but this is especially challenging when the system being designed is a FOAK that has no predecessor. Her examples of AH and ADS based on a home are useful in that they help to make abstract concepts more concrete. However, it is still a major cognitive leap from an everyday artifact to a complex industrial system. This is where complete work domain analyses of one or two complex industrial systems would have been extremely valuable. Nevertheless, Naikar's templates and her model descriptions go a long way towards filling some of the gaps previously evident in the literature on WDA.

In spite of its shortcomings, the 2013 publication is regarded as a practitioner's handbook and the most valuable guideline to date for the development of WDA for operational concepts. The book does not overwhelm the reader with a huge amount of theory but rather demystifies obscure concepts from older sources and provides step-by-step directions for turning the theoretical foundations of WDA into practice. The book provides useful hints and tips for the less experienced practitioner on how to conduct specific aspects of the methodology. It offers practical guidance, for example, on sources of information for an analysis, typical content of models, questions to ask, formats for results, and much more.

The conclusion reached from Naikar's work is that WDA is particularly suited to analysis of a sociotechnical system that is immature or in the early phases of development. For that reason, it is largely technology-independent, focusing on environmental constraints and functions, instead of systems and hardware. This also means that any statements made about the involvement of humans will be on a high level only for example, identifying the conceptual roles of humans in relation to the high-level purposes and missions of the sociotechnical system. This is also why it is particularly suitable for creating the early framework of operational concepts. The analysis becomes more specific only when the design matures sufficiently to allow analysis of operational contexts and subsequently, courses of action strategies that arise for specific operational scenarios, organizational coordination and teamwork, and worker competencies.

2.5 Amy Pritchett, So Kim, and Karen Feigh

In Amy Pritchett's collaboration with Karen Feigh and So Young Kim, (2013), she explains how WDA provides an explicit description of the work domain in the AH. This AH model qualitatively provides a structural means–end decomposition of the intrinsic constraints and information requirements in the work environment. This structured framework has proven very valuable in identifying the work activities required to regulate inherent dynamics in the work environment. In her PhD thesis, Kim (2011) emphasizes the stratified nature of abstraction and decomposition in WDA and how the multilevel modeling provides analysts with a mechanism for managing not only the complexity of the model, but also the systematic approach of deriving means-ends relationships. In theory, work could be described only at the lowest level of abstraction (i.e., by using only action and resource constructs). However, for complex work domains, the number of actions and their inter-relationships can become unmanageable without an organizing structure. By using the multi-level modeling technique, the analyst is forced to reason about the structure of the work and, as a side benefit, is fostered in estimating the abstractions an agent may employ when performing the work. Specifically, the progression from abstract to concrete helps to reveal the different levels of operational information required by human and system, ranging, for example, from detailed descriptions of specific work activities to succinct descriptions of higher-level functions and their relationship to mission goals.

Pritchett et al. (2011) summarizes as follows: "Established work analysis methods such as CWA and contextual design qualitatively highlight several important aspects of work. However, the ability to also simulate the collective work situated in a detailed model of the dynamics of the environment can extend the designer's ability to predict and compare crucial aspects of function allocation relative to the requirements."

2.6 Morten Lind

Lind (2003) criticizes WDA and argues that it suffers from both methodological and conceptual problems. He argues that the ADS developed through WDA is incoherent and cannot perform the role promoted for it by Rasmussen, Vicente, and many others (including Lintern), either in principle or in practice.

One might agree with Lind, especially if his argument is based on the classical definition of the AH and ADS. As noted in other reports for this project, the classical method is clearly too generic and needs to be adapted to the characteristics of the particular domain. This was also Naikar's (2013) opinion. The methodology is not carved in stone and is meant to be adapted to the requirements of the analysis. Although semantics can be a source of confusion, Lind's arguments deal with more than just semantics, as claimed by Lintern. The real difficulty lies in the general lack of understanding that different domains, different projects and different analysis objectives require different treatments of the method. This principle validates the Idaho National Laboratory (INL) decision to adapt the classical method to the needs of the operational concept project, as will be explained later.

2.7 Gavan Lintern

Lintern (2006) has taken exception to Lind's criticism of WDA. Lintern admits that Lind is not alone in voicing his disapproval of WDA, but he believes that in contrast to many others whose critiques are little more than expressions of discontent, Lind has developed an explicit argument. Lintern believes that Lind's views are sufficiently cogent to be addressed and, given that they are devastating, if valid, need to be addressed by those who rely on this analysis. Lintern also claims that the criticism is mostly based on semantic problems. This may indeed be the source of much misinterpretation in CWA. However, as other authors (e.g., Naikar, Bisantz, or Hollnagel) have explained, CWA is not meant to be a rigid method that can only be applied in a fixed linear fashion. This method is meant to be flexible and adaptable to the needs of specific kinds of analysis.

It is our belief that Lintern is correct in his explanation of the semantic difficulties: "Work Domain Analysis [is represented] as an Abstraction-Decomposition Space but it is also known as an Abstraction Hierarchy or an Abstraction-Decomposition model. The term Abstraction Hierarchy is unsatisfactory because it encourages neglect of the decomposition dimension, which is essential to this analysis. I dislike characterizing this as a model because to many the word model implies properties that the result of this analysis does not capture, for example properties of causality and activity. That is not to argue that 'model' is incorrect when used in this sense but only that it introduces avoidable ambiguity."

This ambiguity is one of reasons why the classical WDA method has to be adapted to the needs of operational concept development for new NPP designs. This is where Lintern's disambiguation of many aspects of WDA becomes very useful, in spite of his rebuttal to Lind's criticism. For example, he explains what is meant by abstraction and hierarchy and how the terms should be treated in WDA: "A hierarchy is a system of ranking and organizing things in terms of a relationship, such as is superior to, is part of, or is taller than." Although he does not define abstraction precisely, his overall approach conforms to the "standard" definition (i.e., a process of taking away or removing characteristics from something in order to reduce it to a set of essential characteristics). From this perspective, he emphasizes that hierarchies that are based purely on the containment principle (i.e., consisting solely of subordinate nodes nested within superior nodes) are not compatible with the abstraction principle of WDA that is focused on understanding the means-ends dependencies of the whole sociotechnical system and not just the physical structures. WDA is primarily about functional abstraction and functional decomposition and although the term functional is often left implicit to avoid the repetition of a long and clumsy designation, it should not be forgotten.

Finally, Lintern regards the potential of WDA to be generalized across work domains one of its key strengths, but he also notes that there is much confusion and inconsistent use of the terms originally defined by Vicente. Particularly the terms "goal and purpose" and "function and process" are often used interchangeably. In the INL operational concept method, these terms adhere to the meaning intended by Vicente, and later also Naikar and Lintern, but defined specifically within the context of the requirements of operational contexts. (These definitions are included in Section 3, BASIC CONCEPTS AND TERMINOLOGY).

2.8 Adapted Cognitive Work Analysis Method

The five phases of the classical CWA method as defined by Vicente (1999) consist of WDA, Control Task Analysis, Strategies Analysis (StrAn), Social Organization and Cooperation Analysis, and Worker Competencies Analysis. These phases are meant to guide the analyst through the process of answering the question of why the system exists, what activities are conducted within the domain, how the activities are achieved and who performs it. The method also focuses on identifying properties of the work environment and of the compentencies of the workers themselves that determine possible constraints on the ways that humans might interact with systems in the environment, without explicitly identifying specific sequences of actions.

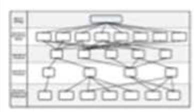
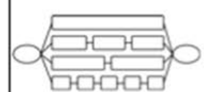
As indicated in the *Introduction to Cognitive Work Analysis Theory*, the primary objective of the classical CWA method is to inform design, or to lead to an actual system design of some kind. However, Naikar has demonstrated the application of WDA in non-design applications (e.g., for training of pilots) (Naikar 2013, p. 249). In addition, Sanderson et al. (1999) claim that "...there has been a tendency to overlook the use of CWA for other purposes than interface design and they emphasize the usefulness of CWA at all points in the system life-cycle, from requirements to decommissioning."

It is impractical to use the classical WDA method for a new NPP design, especially where information from predecessor plants is limited or nonexistent. The method has to be adapted for the development of operational concept documents to accommodate the many uncertainties that exist early in a new engineering project. Based on the experience during the development of the WDA for a generic SFR, a slightly modified version was developed as a framework for the analysis and development of Operational concepts. The adapted method combines the basic principles of WDA with specific aspects of the second and third phases of CWA. The resulting hybrid method places particular emphasis on WDA, but also includes contextual activities analysis (CAA) and StrAn, as will be described later. These have been found to be the most useful phases of CWA when plant design information is still immature. Because operational concepts need to be developed for a new plant during the very early phases of design, it was found more beneficial to focus on the mission of the plant, its primary functions, and the main systems required for those functions.

The modified WDA process follows the basic approach described by Vicente (1999) but some terminology and definitions were adopted from Jenkins et al. (2009), Lintern (2006, 2010), Walker et al. (2014) and Naikar (2006, 2013).

The importance of including CAA and StrAn in the adapted method is illustrated by the following table (Table 2) derived from Sanderson et al. (1999):

Table 2. Cognitive work analysis in the system life cycle.

			
Phases of CWA:	**WDA**	**Contextual Activity Analysis**	**Strategies Analysis**
Content of phase:	*Purpose and Structure*	*Operational conditions in context*	*Course of action*
Requirements	Develop		
Specifications	Develop	Develop	
Design			
Hardware, software	Define		
Control Tasks	Given	Define	
Dialog support		Given	Define
Actor roles			Given
Interface formats			
Simulation	means/ends	activities	options
Design Evaluation	characterize/ evaluate/ compare	characterize/ evaluate/ compare	characterize/ evaluate/ compare
Implementation	guide		
Test	judge match	judge performance	judge process
Operator selection			
Operator training	guide	guide	guide
Routine use	describe	describe	describe
Non-routine use	describe	describe	describe
Maintenance	describe		
Upgrades & modifications	model effects	model effects	model effects
Decommissioning	judge shortfall	judge shortfall	

The contribution of CWA the difference project phases has been summarized by Sanderson et al. (1999) as follows (Table 3):

Table 3. Contribution of cognitive work analysis to project phases.

Project Phase	Value added
ncept Definition	High
Requirements Analysis	High
Function Analysis	High
Function Allocation	High
Task Analysis & Design	High
Interface Development	High
Performance, Workload, and Training Estimation	Moderate
Requirements Review	High
Personnel Selection	Moderate
Training Development	Moderate
Performance Assurance	Moderate
Problem Investigation	Moderate

This shows that CWA is particularly important during the early phases of the project where it can add significant value in terms of integration of the human elements of the system.

The emergent properties of the system as a whole will be revealed through the remaining two phases of CWA: social organization and cooperation analysis, and worker competencies analysis. These phases can be postponed until the plant design is mature enough to allow more detailed analysis of function allocations, automation requirements, and operator tasks. This approach does not eliminate the other phases of CWA, but postpones their analysis until the plant design has sufficiently matured to enable the identification and analysis of lower-level systems and their functions.

The basic principles of the remaining two phases required for the analysis and allocation of tasks and the design of HSIs are described briefly below.

2.8.1 Social Organization and Cooperation Analysis

This phase of CWA focuses on the constraints that are placed on operational staff by the allocation of functions to agents (humans or systems), or shared between them, and the need for coordination of work in a system. The emphasis is on identifying and defining possible ways that the organization can be structured to best support the mission and goals of the enterprise. This requires defining the criteria that may shape or govern how the functions defined in the WDA are allocated and distributed across the human and system agents. These criteria may include competency, information requirements, communication requirements, workload, and safety and reliability. All of these criteria will influence the final phase, worker competencies analysis.

2.8.2 Worker Competencies Analysis

The analysis of worker competencies identifies the mental and physical requirements for members of the operational team to effectively accomplish the domain's numerous control tasks, with the ultimate goal of identifying constraints that might affect systems design. As the final phase of CWA, the worker competencies analysis inherits all of the constraints identified through the previous four analytical phases. Although this does not form part of WDA, it is important to note that the products of all five phases of CWA are used in the development of information requirements to feed subsequent interface design activities. As such, it is critical for all phases of WDA to effectively organize and represent all the nested constraints of the work domain.

It is easy to see how similar the last two phases are to classical function allocation and task analysis. However, it is not suggested that CWA should replace classical functional requirements analysis (FRA), function allocation, or task analysis methods. All these methods are complementary and it is up to the analyst to determine which method is the most economical and will produce the most useful and reliable results.

3. BASIC CONCEPTS AND TERMINOLOGY

This section contains (in alphabetical order) the most important terms and concepts associated with CWA in general and WDA in particular.

3.1 Abstraction

The textbook definition of abstraction describes it simply as the process of taking away or removing characteristics from something in order to reduce it to a set of essential characteristics. The word is used either as a noun or as a verb; in the latter instance abstraction is the product of this process and it can be represented in many different forms, including verbal or graphical descriptions.

In the context of the functional and physical structure of a NPP, an abstraction would be the result of reducing the information content of this structure and related observable phenomena to a set of categories ranging from general and abstract, to specific and concrete. In this way only information is retained that is relevant for a particular purpose, that is, the analysis of the work domain. The process of abstraction results in a hierarchy of five interdependent levels: power plant mission and purpose, operational principles and values, general operational functions, operational processes, and physical SSC. Together the categories (i.e., levels of abstraction) form a structural totality of the work domain and its supporting processes.

3.2 Abstraction Hierarchy

AH is a general-purpose modeling and analysis method that decomposes the work domain of complex sociotechnical systems in terms of its functional and physical structure and relationships between functions and dependent entities.

AH describes a system at different levels of abstraction using *what*, *how*, and *why* relationships. Moving down the model levels answers how certain elements in the system are achieved, whereas moving up reveals why certain elements exist. Elements at the highest level of the model define the purposes and goals of the system. Elements at the lowest levels of the model indicate and describe the physical components (i.e., equipment) of the system. The how and why relationships and dependencies are shown on the AH as Means-Ends Links. AH is typically developed following a systematic approach known as a WDA. It is not uncommon for a WDA to yield multiple AH models, each examining the system at a different level of physical detail defined using another model called the part-whole Hierarchy (Burns & Hajdukiewicz, 2004) or ADS. A unique feature of WDA is that each level in the AH is a complete description of the work domain from the perspective of that particular level.

One of the advantages of the AH model is that it can be used to explore the impact of new technology on the system values and purposes. Additional technologies can be modeled at the base of the model and their impact assessed through the mean-ends links to the top of the diagram. However, the true value of the AH framework is in the way it acts as a guide to acquiring the knowledge necessary to understand the domain. The framework helps to direct the search for deep knowledge, providing structure to the information analysis process, particularly for the domain novice. While the output may initially appear abstract or theoretical, its value to the analysis cannot be overstated. The AH defines the systemic constraints at the highest level. The AH can thus be regarded as a formal ontological framework for understanding the work domain. It also provides a rigorous theoretical foundation for understanding the categorical decomposition of the part-whole relations (Little, 2009).

(Note that in the Advanced Reactor Technology (ART) project work the term "functional abstraction framework" was adopted to emphasize that this is a framework within which the functional relationships and dependencies of the sociotechnical system may be analyzed.)

The classical AH consists of five levels of abstraction, ranging from the most abstract level "functional purpose", to the most concrete level, "physical form" (Vicente, 1999). (Note that the labels used for each of the levels of the hierarchy may differ, depending on the aims of the analysis):

3.2.1 Level 1: Functional Purpose

This level of abstraction deals with the high-level mission and goals of the enterprise, or the sociotechnical system overall. The typical functional purposes of a NPP are to generate electrical power, to ensure nuclear safety, and to protect workers, the public, and the environment.

3.2.2 Level 2: Abstract Function (principles, values, and measures)

This abstraction level of the NPP is typically described in terms of the value added by the various operational processes of the main systems and how the successful achievement of the next level, generalized functions, could be measured. This level therefore describes the performance parameters required for the system to meet its intended purpose such as rated electrical power output generation, decay heat removal, habitability maintained, etc.

3.2.3 Level 3: Generalized Function

This abstraction level explains the general, high-level functions required to support the principles, values and measures and found at the abstract function level such as maintain equipment integrity, optimize fuel burnup, manage grid interfaces, etc.

3.2.4 Level 4: Physical Functions and Processes

The level defines the processes performed by equipment, tools, resources, and/or physical objects available for the system such as reactivity control, coolant circulation, plant control and automation, etc. Physical connections between components could also be indicated within this abstraction level by means of *topological links* to explain the relationships and dependencies between thermal-hydraulic, electrical, pneumatic, fluidic, or mechanical processes. (An example of topological links is shown in the bottom two levels of Figure 2).

3.2.5 Level 5: Physical Form

The Physical Form level describes the condition, location, and physical appearance of the SSCs required to perform the physical functions such as the reactor, primary coolant system, steam generation system, etc.

It must be emphasized that, while objects indicated at this level may appear to be a reflection of the real world, the level is still conceptual and not meant to suggest the type of technology needed in the actual design. One way to avoid prejudging technology choices and also to minimize the complexity of the analysis would be to constrain the list of components to those that are likely to be directly involved in a specific operational condition.

3.3 Abstraction-Decomposition

Bisantz and Burns (2008) describe the ADS as a two-dimensional orthogonal model of the abstraction levels, coupled with the decomposition of the SSC. The two orthogonal dimensions of the ADS represent the means-ends and part-whole relations.

The top two levels of the ADS are epistemically-driven, (i.e., based on theoretical knowledge of methods, validity, and scope of the items identified). The bottom three are ontologically-driven, (i.e., based on the representation of the means-ends relationships). The top two levels serve as inputs to the ontology as overall goals of the system. Conversely, the ontology informs the epistemic levels of the ADS about the formal structure of the underlying functions, processes, SSCs and means-ends relationships. Together these levels provide a sufficient granular decomposition of all items of interest in the work domain. (Little, in Bisantz & Burns, 2008; Little, in Borgo & Lesmo, 2008; Little, 2009).

Although Little regards ontologies and AH as distinctly different, the AH can actually be regarded as a sophisticated ontology in itself because it provides a significant amount of knowledge about a sociotechnical system through "...decomposition of reality into structured sets of categories that are relationally linked to one another. The categories should correspond to most abstract, somewhat abstract, and least abstract understandings of reality" (2009). Therefore, as an ontology, the AH provides a representation of a formal structure, in terms of:

- Hierarchical structure of physical entities (environments, power plant SSC)
- Structure of abstract or nonphysical entities, such as goals, principles, values, measurements, functions and processes
- Relations between individual objects and their attributes
- Relations between individual objects and their aggregations
- Relations between functions and processes
- Relations between causal and intentional phenomena and attributes
- Distinctions between spatial and temporal functions and processes.

It is usually very difficult to develop the ADS for a complex system and it also of relatively little value when the new plant design is still in a conceptual phase. This is mainly due to the lack of a stable system and functional breakdown. For this reason, the ADS may be postponed until the design is more mature and has at a minimum the main systems identified to support operations.

3.4 Cognitive Work

"Cognitive" in this term refers to the process of cognition that deals with logic, as opposed to emotions. Cognitive functions are those functions carried out by the human brain.

When we refer to cognitive work, the (often unstated) implication is that a system meant to support a task can either support or inhibit human performance, depending on how well it has been adapted to human requirements. Cognitive work involves the cognitive activities of knowing, understanding, planning, deciding, problem solving, integrating, analyzing, synthesizing, assessing, and judging. Cognitive work is notoriously difficult to assess, for obvious reasons – cognitive tasks are difficult to observe, difficult to measure and difficult to describe. There is also a lot of variability within and between cognitive tasks, because of different external and internal influences such as environment, organization, time of day and many more.

As described above, "cognitive" is a useful term to describe a particular mental function of the human brain. However, it is also part of a common taxonomic imprecision in psychological concepts. This apparently stems from psychology's "cognitive revolution" of the 1970s. According to Segal & Lachman (1972), the computer metaphor "information processing" was taken into psychology in a kind of paradigm shift and the term was then used to describe cognitive (and, indeed, much of psychological) functioning. This has caused so much confusion that some writers refer to life skills such as dependability, persistence, reliability and self-discipline as "non-cognitive"! (Heckman & Krueger, 2005).

For the human factors analyst, any distinction between cognitive and "non-cognitive" in human tasks is artificial. All work has cognitive and physical elements, albeit in different proportions. The idea of work without thought, or thought without work, is inconceivable. All human actions require perception, even if information processing is only at a subconscious level (Hollnagel, 2003).

3.5 Cognitive Work Analysis

Pritchett et al. (2013) summarize CWA as follows: "Established work analysis methods such as CWA and contextual design qualitatively highlight several important aspects of work. However, the ability to also simulate the collective work situated in a detailed model of the dynamics of the environment can extend the designer's ability to predict and compare crucial aspects of function allocation relative to the requirements..."

There is little doubt that CWA and WDA are appropriate for the nuclear power domain, but a distinction should be made between normative and descriptive techniques. Normative approaches prescribe how work *should be done* in a system and task analysis techniques that specify sequences or timelines of tasks for workers to follow belong in this category (Naikar, 2013). Examples of this are found in Kirwan & Ainsworth, 1992.

In contrast, descriptive techniques focus on describing how work *is* done in a system. Cognitive task analysis techniques, which are intended for studying the cognitive nature of work, are of this type (e.g., Klein & Militello, 2001, etc.). These techniques are most appropriate for investigating systems in which workers' responsibilities are characterized predominantly by cognitive, rather than manual tasks.

In essence, CWA focuses on revealing how work *can be done* in a system. This framework recognizes that workers in complex sociotechnical systems have many possibilities for action, including what to do, when to do it, and how to do it. Furthermore, these workers have to contend with novel or unanticipated events, which pose immense threats to a system's effectiveness, safety or efficiency. Therefore, instead of prescribing or describing how work *should* be done or *is* done in a system in conditions that are known or predictable, the CWA framework focuses on identifying the operational conditions and the constraints on actors or agents. Within these constraints workers can form a variety of work patterns, which is why CWA is described as formative.

There are three reasons why the formative approach is especially important for FOAK designs:

1. Work demands within complex, modern sociotechnical systems are primarily cognitive and social in nature, rather than physical or manual. Although the initial purpose of WDA for a new NPP is not to produce, for example, a control room or HSI design, it is important to identify the potential human factors aspects of the domain as early as possible, as well as systemic constraints at the highest level, and the impact of introducing new technology on the system values and purpose.
2. It is not feasible at the time of design to describe or prescribe all of the possibilities for action available to workers. To prescribe how work should be done in a system, analysts must have information about the properties of components and systems used to perform the work. This information becomes available only when the design is more mature.
3. Descriptions of operational strategies (i.e., ways to achieve certain performance outcomes) are likely to reflect the properties of the systems required to support those outcomes as well as the effect of certain constraints and the intended roles of human or automation agents.

Rasmussen et al. (1990) extend this perspective by emphasizing that the systems we study are goal directed, which means they have to serve specific purposes in a specific domain in order to survive. The reason for the existence of the sociotechnical system is found in the way the system and the environment share certain goals. Modern technology tends to be particularly influential in creating dynamic, turbulent environments. As a result, the goals may change, requirements and opportunities in the environment change, and the means and tools to pursue goals and adapt to changes tend to vary. A prime example of this in the commercial nuclear power industry is the impact the Fukushima event in Japan has had on the industry. Previous goals related to severe accident response and beyond design basis events did not exist because they were not considered probable; Fukishima has placed the commercial nuclear industry in a position to institutionalize dramatic changes such as new training, equipment, and strategies.

3.6 Constraints

The NPP and its functional and structural characteristics are associated with specific constraints placed upon the actions of any human or system agent. The goals and functions of the work domain impose constraints on workers by specifying the purposes that the work system must fulfill, the values and priorities that the work system must satisfy, and the functions that the work system must perform. Therefore, the work system environment within which the task is conducted has the potential to significantly affect the task and ultimately the entire plant operation. In combination, the goals and purposes of the work domain define the fundamental problem space of workers and include the values, priorities, and functions that must be achieved by a work system with a given set of physical resources. However, within these constraints, workers have many options or possibilities for action in the work domain. This becomes the basis for the allocation of functions to humans or systems, the analysis of tasks, determination of skills, rules and knowledge involved in those tasks, the definition of operating principles and requirements, and ultimately the design of HSI tools to enable operators to perform the identified tasks effectively, efficiently and safely.

As described in Section 2.2.3 of the January 2015 milestone report section 2.2.3 (Hugo & Oxstrand, 2015) one of the most important applications of the results from the WDA is the development of operational strategies, which can be defined as a sequence of short-term and long-term operations that transform goals, plans, decisions, policy, rules, and procedures into the technical processes necessary for humans and systems to produce the defined production outcomes of the enterprise. The success and quality of the output will be influenced by the constraints that are imposed upon the sociotechnical system as a whole.

Constraints could be any one or a combination of technical, physical, environmental, psychological, organizational, political, or regulatory conditions. A previous report (Hugo et al., 2014), explained that constraints could be either *causal* (that is, determined by physical or natural laws), or *intentional* (determined by social laws, conventions, policies, or values). For example, the structure, functions and dependencies of a complex sociotechnical system like an NPP are influenced by the *causal* properties of the thermal-hydraulic processes, as well as materials and specific technologies. It is also influenced by *intentional* regulations, company policy, market requirements, design conventions, and many other intangible constraints. The analysis of a system is therefore determined by the degree to which the behavior of the human and system agents within the system is influenced by the relationship and interaction between causal and intentional constraints. The analysis of the functional abstraction framework (FAF) will help all stakeholders to understand the functional and physical context (that is, the work domain) within which the NPP staff will perform their tasks. For example, the environmental, physical, and functional requirements of the plant will impose physical as well as social and psychological constraints on NPP workers.

Most industrial processes are influenced by situation and resource, and the operational strategy is thus also influenced by the extent to which the enterprise succeeds in mobilizing the available resources under the conditions imposed by the constraints on either humans or systems agents, or both:

- *Effect on humans*– typically causal and intentional constraints identified in complex systems include constraints imposed upon the behavior or activities of people due to:
    - Purpose or mission of a system (*causal* as well as *intentional*)
    - Physical situation, including environmental conditions (*causal*)
    - Specific operational situations, such as operator response time, accuracy, or situation awareness (*causal*)
    - Available means by which activities can be performed (*causal* and *intentional*)
    - Organizational structures, specific agent roles, and definitions (*intentional*)

- Human capabilities and limitations, such as physical strength, mental workload, or fatigue (*causal*).

- *Effect on systems* –causal as well as intentional constraints may also be imposed upon the ability of systems to perform a function due to:
    - Physical limitations imposed by material properties (*causal*)
    - Reliability limits under adverse operational conditions, such as temperature, pressure, speed, etc. (primarily *causal,* due to characteristics safety-related systems, but also *intentional*, due to regulatory or policy requirements)
    - Ability of operators to act quickly enough to either initiate or stop a function (*causal*)
    - Spatial limitations in plant layout, preventing systems to be located in optimal positions (*causal*)
    - Limits in production capacity of a system or component, such as flow rate, volume, tolerance, heat conductivity or dissipation, speed, etc. (*causal* and *intentional*)
    - Limits in the control capability of the automation system (*causal* and *intentional*)
    - Limits imposed by industry codes or regulations for reliability, safety, or quality (*intentional*).

The key constraints that are likely to influence specific operational design decisions for a typical SFR are summarized in Table 4 (copied from Hugo and Oxstrand 2015 for easy reference):

Table 4. Constraints and their effects.

Constraint	Effect
Environmental	Environmental constraints include all external physical conditions that may influence human or system performance. This includes temperature, humidity, air quality, wind, vibration, radiation, lighting, etc. All of these conditions could be very hazardous to human health and good performance and may require various means to protect personnel health and safety. Many of these measures will be mandated by National Institute for Safety and Health (NIOSH) or Occupational Safety and Health Administration (OSHA) regulations.
Human Factors	Human abilities and limitations vary along many dimensions. The design of the main control room and HSI of the AdvNPP must consider basic physical and sensory capacities, including vision, hearing, manual dexterity, strength, and reach. Cognitive functions, such as attention, memory, information processing, appreciation and understanding of hazards can influence the safety, effectiveness and productivity of the work environment. The resulting design will have an impact on operators' ability to interact with systems, equipment, and each other, and also to execute procedures.
Organizational	The guiding principle for the AdvNPP organization is to ensure that the physical assets and organizational resources in the operations domain are aligned with the direction set out in their corporate strategy. This would include development of policies and guidelines for specific constraints, such as work hours, staffing, safety, environmental protection, asset protection, security, and/or communication.

Constraint	Effect
Regulatory	There are many regulations that influence the operation of a NPP. These include the industrial and occupational safety regulations mentioned above, but the most significant regulations during the design phase of a new plant are those dealing with licensing. The most direct regulatory basis for the human factors aspects of plant operations can be found in 10 CFR 50.52: *Licenses, Certifications, and Approvals for Nuclear Power Plants*. This part governs the issuance of early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power facilities. This regulation includes reference to various aspects of human factors engineering (HFE), for example, HSI, procedures, training and staffing. Specific references emphasize the importance of early establishment of a HFE program that would help to inform the development of Operational concepts, such as 10 CFR 50.34(f)(2).
Technical or physical	Technical and physical constraints are found in system characteristics and performance parameters such as size of equipment, speed, accuracy, location, material, tolerances (temperature, pressure, and strength), etc. These constraints will influence the design, selection or placement of equipment. The constraints will ultimately also have a significant effect on human performance and ultimately on the design of HSIs and workspaces.

Constraints will influence the functional capabilities and limitations of systems and will also determine capabilities of the physical objects, tools or other resources that must be available to the operators to perform their tasks.

3.7 Contextual Activity Analysis

The constraints associated with what needs to be accomplished in a system are modeled by the CAA. Where WDA is used in Operational concepts development, CAA is used synonymously with **Error! Reference source not found.** except that the focus is on contextual activities (or events) instead of tasks. The contextual constraints can be specific operational conditions within a defined scenario, such as an upset or transient condition. A table format is typically used to identify the intersections between plant functions and operational conditions. Since most operational conditions will influence the development of Operational concepts, a high-level analysis of the link between functions and specific operational conditions will serve as preparation for the next phase, strategies analysis. In particular, the CAA provides the "course of action" basis for many subsequent decisions regarding operating practices and procedures and the associated control and monitoring artifacts.

3.8 Control Task Analysis

Control task analysis is part of the second phase of CWA. It forms part of this adapted WDA methodology because of the focus on Operational concepts. It should be noted, however, that when WDA is used to define operational concepts, the term "task" is inaccurate because no specific operator actions are known yet. Since this stage of the analysis is *event-dependent* (see Naikar, 2013, p. 267), the emphasis is on how or why functions would be influenced by specific operational conditions or events, that is, "contexts." This is why the term CAA is more appropriate.

3.9 Ecological Approach

The term "ecological" originates from a school of psychology developed by James J. Gibson (1966) known as ecological psychology, which was further elaborated by Urie Bonfenbrenner (1981). This approach focuses on human-environment relationships, in particular in relation to how human behavior is shaped by perception of, and interaction with artifacts in real-world environments. WDA borrows from ecological psychology in that the constraints and relationships of the work environment in a complex system are observable by an operator for example, through various concrete and abstract representations of the domain, such as HSIs. The perception of these relationships and constraints will shape the behavior of individuals and ultimately the whole enterprise. In this way WDA is considered an ecological approach to understanding a sociotechnical system because it conforms to the basic precepts of Bronfenbrenner's (1981) ecological systems theory. This means that analogous to ecological systems theory, five systems (or levels) can also be identified in the AdvNPP sociotechnical system:

- *Microsystem*: This refers to the discrete artifacts (SSC) that most immediately and directly impact the mission and goals of the power plant in particular and the enterprise in general. This is analogous to the physical objects level of the AH.
- *Mesosystem*: This represents the interconnections between the microsystems, the processes that they perform, and the functions required to achieve the goals of the enterprise. (This can be interpreted as the means-ends links between the levels of the WDA).
- *Macrosystem*: This describes the power plant as a whole and all the supporting organizational, technological, economical, political, and regulatory structures that are needed for it to achieve the defined mission and goals. The macrosystem typically evolves over time, because of environmental, technological, political, etc. changes, each of which may change the macrosystem.
- *Exosystem*: This represents the broader sociotechnical system on the outside boundaries of the macrosystem. It involves links between the AdvNPP enterprise, the power utility, the consumers, service providers, vendors, international partners, educational institutions, researchers, and more.
- *Chronosystem*: This system represents the patterning of environmental events and transitions over the life cycle of the sociotechnical system. A NPP typically goes through several short-term and long-term transitions during its life cycle, for example, design, construction, commissioning, first fueling, start-up, normal operations, shutdown, refueling, decommissioning, and also various incidents during its operating life. Most of the known transitions can be plotted on a timeline and incorporated in the plant's operational strategy.

Although these five levels do not map precisely to the AH, the principle is very similar. In the ecological approach to the development of Operational concepts, the aim is to apply WDA principles (levels of abstraction, means-ends links, dependencies, constraints, etc.) to a new system to reduce the complexity of the functional and physical architecture of the system prior to design.

3.10 Functional Abstraction Framework

When a WDA is developed to inform a new plant's Operational concepts, the emphasis is on high-level functions and it is largely technology-independent. Because of the need to establish a framework for further detailed analyses like function allocation and task analysis, the term functional abstraction framework (FAF) is adopted as the first product of the WDA, instead of abstract hierarchy.

Like the AH, the FAF is a framework that decomposes the sociotechnical system in terms of the missions, goals, functions, processes, and systems described in this report, and also the relationship between the entities in the various levels that are identified for conceptual operational conditions. Relationships between entities in the FAF are mapped by Means-Ends Links.

This FAF adheres to Rasmussen's original description: "... the functional abstraction hierarchy is useful for a systematic representation of the many-to-many mapping in the purpose/function/equipment relationship, which is the context of supervisory decision making. An important use of the AH is as a framework for description of the control tasks required to maintain optimal safe system operation. States can only be defined as errors or faults with reference to the intended functional purpose. Causes of improper functions depend upon changes in the physical or material world. Thus, they are explained "bottom-up" in the levels of abstraction. In contrast, reasons for proper function are derived "top-down" from the functional purpose." (1986, p. 21)

With reference to the generic definition of AH in Section 3.2, the five levels of abstraction in the FAF are briefly described in Table 5 below.

Table 5. Levels of the functional abstraction framework.

Abstraction Level	Description
Domain purpose (nuclear power plant ission and objectives)	The domain purpose, displayed at the very top of the diagram, represents the reason why the work system exists. This purpose is independent of any specific situation, it is also independent of time – the system purpose exists as long as the system does.
Domain values (operational principles and values)	This level of the hierarchy is used to capture the key values that can be used to assess how well the work system is performing its domain purpose(s).
Domain functions (general operational functions)	The middle layer of hierarchy lists the functions that can be performed by the combined work system. These functions are expressed in the context of the domain under investigation.
Physical functions (operational processes)	This level identifies the physical functions that the physical objects (SSC) can perform.
Physical objects (SSC)	The key physical objects within the work system are identified at the base of the hierarchy. These objects represent the minimal physical architecture necessary to perform the physical functions. Judgement is required to limit the object list to a manageable size and the most appropriate set of objects will usually be determined by the selected boundaries of the analysis. (It must be emphasized however that during the early stages of the design, most of these SSC will be generic and no specific type of technology is assumed yet).

In previous work, the traditional graphical representation of an AH was used to illustrate the result of the FAF (see example in Figure 2 below). This diagram illustrates how the different levels of the WDA can be populated and how the links between the entities in each level provide information about the "why, what, how" dependencies and relationships. For example, the links between operational processes and SSC indicate that often more than one system is required for a process and that several processes may require the same systems.

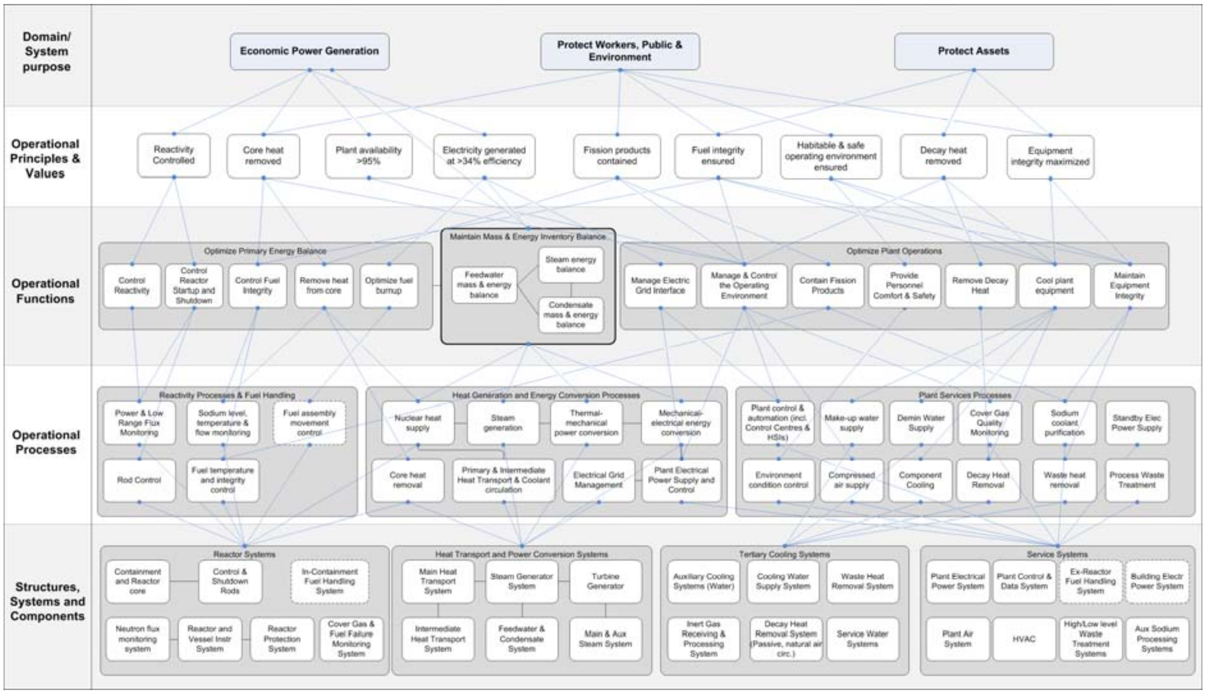


Figure 2. Graphical functional abstraction framework example

3.11 Functions

According to NUREG-0711, the term *function* refers to "…high-level plant functions, such as safety functions, or to a lower-level description of the purpose of an individual piece of equipment, such as a valve or display system. Plants have a hierarchical structure of functions, processes, systems, and components. High-level functions are usually accomplished through some combination of lower-level system actuations such as reactor trip, safety injection, or accumulators. Often plant systems are used in combination to achieve a high-level function. The combination of systems used to achieve a high-level function is called a process. There may be more than one possible process that can achieve a given high-level function."

This definition applies directly to the identification of higher- and lower-level functions as well as operational processes for the WDA.

3.12 Goal

The term "goal" in the AH is adopted from Vicente's original definition: "a state to be achieved, or maintained, by an actor at a particular time. Note that goals are attributes of actors, not domains, and that they are dynamic."

The dynamic nature of goals (i.e., their tendency to change over time) is related to the "chronosystem" described in the *Ecological Approach*.

3.13 Hierarchy

A hierarchy is an arrangement of items (e.g., objects, names, values, and categories) in which the items are represented as being "above," "below," or "at the same level as" one another.

In WDA, a hierarchy results from the abstraction of the functional and physical structure of the NPP. This AH is an arrangement and classification of principles, functions, processes and artifacts according to their relative importance or inclusiveness. The relationship between the levels of abstraction and the items within each level is represented through Means-Ends Links.

3.14 Means-Ends Links

The dependencies and relationships in the FAF are represented by means-ends links. Vicente (1999, p. 7) defines the means-ends links as "the relationship between adjacent levels in a means-ends hierarchy. The level below a given level describes the structural means that are available for achieving the level above. The level above a given level describes the ends (or functions) that can be achieved by the level below."

These links are therefore an important epistemic element of the work domain in the sense that they provide information on the what-how-why triadic relationships between the levels of abstraction. The same description is provided by Naikar (2013, p. 30). Considering each level in the hierarchy as the "what" it is seen that the level above answers the question "why is this needed?" while the level below answers the question "how can this be achieved?" One of the main benefits of the means-ends links in the FAF is that it reveals complex mappings among the levels (many-to-one, many-to-many, one-to-many). Most items in all levels will usually have more than one link, for example, multiple links between an operational process and physical SSC will indicate that often more than one system is required for a process and that several processes may require the same systems.

For example, interrogation of the FAF can be done either top down or bottom up by focusing on an element in any level and then determining why that element is needed and what is needed to ensure that it will serve that purpose.

The January 2015 milestone report (Hugo & Oxstrand, 2015) describes the relationships between the five levels of the FAF. These relationships are called means-ends links, which eventually also provide a means to identify constraints.

Means-ends links have traditionally been represented graphically in FAF diagrams by lines between entities in the hierarchy. However, when the FAF for a large and complex sociotechnical system such as a FOAK NPP design is represented graphically, it becomes very difficult to read and follow the links. Therefore, a look-up table is recommended as the format for the FAF with the means-ends links presented as references in the look-up table. An example of this format is shown in Figure 23, page 70.

3.15 Processes

A process is simply defined as a series of actions that produce something or that lead to a particular result. In the WDA, these are the technical processes (thermohydraulic, electrical, mechanical, etc.) performed by one or more systems to satisfy the functional requirements of the NPP.

3.16 Purpose

The term "purpose" in the top level of the FAF is adopted from Vicente's original definition: "Purpose is the overarching intentions the work domain was designed to achieve. Vicente points out that purposes are properties of domains, not of actors, and that they are relatively permanent (this constancy property could be regarded as similar to the "microsystem" and the "mesosystem" levels of the *Ecological Approach*). For the FAF this is regarded as synonymous with "Goal".

3.17 Strategies

A strategy is a high level plan to achieve one or more goals under conditions of uncertainty. In human factors terms, it can be described as a cognitive task procedure that transforms an initial state of knowledge into a final state of knowledge, through, for example, Pattern Recognition, Analytic Search and Hypothesis and Testing. Ideally a strategy is transformed into a course of action which leads to achievement of a specific goal, as illustrated in this diagram (Figure 3):

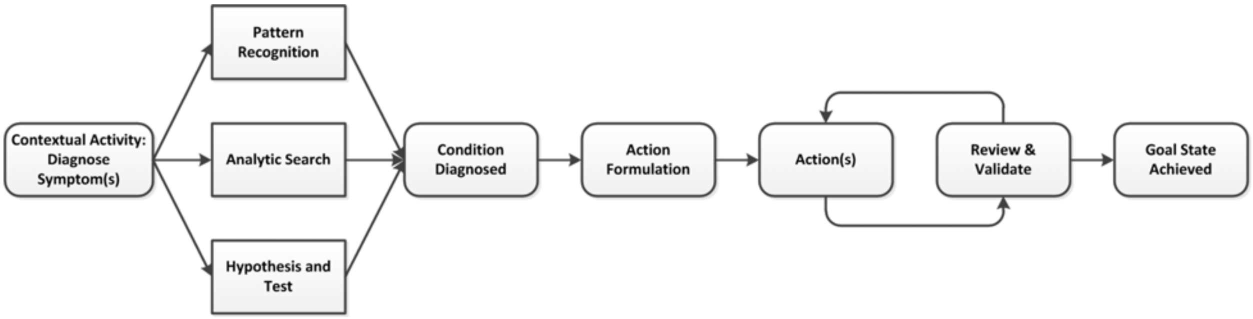


Figure 3. Strategy Formulation Process and Course of Action.

For the AdvNPP, "operational strategies" refers to one or more defined "courses of action" that form part of the enterprise's way of handling the routine processes as well as exceptional conditions of the plant. A well-developed operational strategy is important because the resources available to achieve these goals are usually limited. Strategy generally involves setting goals (for example, production targets, maintenance schedules, material inventories, etc.), determining actions to achieve the goals, and mobilizing resources to execute the actions.

A strategy also describes how the available resources will be leveraged to achieve the goals. Strategies form an intrinsic part of the AdvNPP's operational concept and are best developed early in the life cycle of a new project. This modified WDA process and its outputs help to develop a rational operational concept.

3.18 Systems

The term "system" in WDA is an obvious oversimplification because it can refer to different levels of breakdown. The generic term for the lowest level of the *abstraction hierarchy* is "physical objects", but to conform to the language of an engineering domain, this level of the *Functional Abstraction Framework* is instead called "structures, systems and components" which implicitly refers to different levels of breakdown. For example, generically the AdvNPP can be called a "system", but it is actually a combination of structures, which are made up of systems, which in turn could consist of different components.

3.19 Tasks, Task Analysis, and Work Domain Analysis

A task is an activity that needs to be accomplished by one or more specific persons within a defined period of time. Generically, such activities might be defined as part of a process. When used within a phrase such as "Operational Task" it defines a well documented, controlled, proceduralized, and usually low risk, activity. Most tasks in an NPP are described in procedures that control the manner in which the task is carried out.

Task analysis versus work domain analysis: If task analysis is likened to a set of instructions on how to navigate from point A to point B, then WDA is like having a map of the terrain that includes point A and point B. WDA is therefore broader and includes the environmental constraints and opportunities for behavior, as in Gibsonian ecological psychology and ecological interface design (See *Ecological Approach*).

3.20 Work Domain

The Work Domain is simply defined as the sociotechnical system that is the focus of the analysis. This could be a specific system, for example, a reactor cooling pump, a collection of systems like a main control room, an entire power plant, or even a whole fleet of power plants.

Pritchett, Kim, Kannan, & Feigh (2011) regard this as synonymous with "environment," which they define as "...the aggregation of physical and social/cultural/policy constructs required to describe, constrain, and structure the dynamics of the work".

Determining the scope of the analysis is one of the first challenges facing the analyst. It is very important to define the boundaries of the analysis right in the beginning of the project. In addition to defining the boundaries of the analysis, it is also important to adhere to the underlying premise of WDA: the emphasis is first on WORK, and only second on the DOMAIN. This means that although it is not the purpose of the analysis to analyze and define actions taken by humans, there will always be humans that are eventually affected by the results on the analysis. These two points will be explained in more detail later (see *Define the boundaries of the analysis*).

3.21 Work Domain Analysis

WDA is an analytical framework that provides a description of the physical and functional structure of a work domain and the constraints that govern the purpose and the function of the physical SSC under analysis.

The main tool of the method is the AH (Rasmussen, 1986; Vicente, 1999) which is used to provide a context-independent description of the domain. The analyses and resultant graphical representations diagrams are technology-independent during the early phases of the analysis, but as more detail is developed, specific system characteristics needed to support the higher-level functions may be identified making WDA an iterative process that needs to be refined as the design of the NPP progresses.

The WDA models qualitatively provide a structural means–end decomposition of the intrinsic constraints and information requirements in the work environment and can be used to identify the work activities required to regulate inherent dynamics in the work environment. Where the objective is to collect and structure information that would support the later evaluation of function allocations, the FAF's multilevel approach illustrates how an agent (and also the designer making function allocation decisions) may be able to view work at different levels of abstraction, ranging from detailed descriptions of specific work activities to succinct descriptions of higher-level functions and their relationship to mission goals. As Pritchett et al. (2013) explained (see Subsection 2.5 above), the multilevel FAF model provides a structured mechanism to effectively manage the complexity of the analysis.

The conclusion from this is that WDA is particularly suited to analysis of sociotechnical systems that are immature or in the early phases of development. For that reason it is largely technology-independent, focusing on environmental constraints and functions, instead of systems and hardware. This also means that any statements made about the involvement of humans as agents will be on a high level only, identifying, for example, the conceptual roles of humans in relation to the high-level purposes and missions of the sociotechnical system. This is also why it is particularly suitable for creating the early framework of operational concepts.

The analysis becomes more specific only when the design matures sufficiently to allow analysis of operational contexts and subsequently, courses of action strategies that arise for specific operational scenarios, organizational coordination and teamwork, and finally worker competencies.

WDA focuses on the constraints that are placed on actors by the functional and also the physical structure of the work environment. This will promote safety, productivity and workers' health. Naiker states that this approach to design is necessary for complex sociotechnical systems because of the impact that novel events can have on their effectiveness. Since events like beyond-design basis events or severe accidents cannot be specified with sufficient detail in advance, workers cannot be provided with preplanned solutions (procedures) for handling them. Instead, when such events occur, workers must use high level guidelines and strategies and their expertise and ingenuity to improvise a solution in real time. By identifying the constraints that the work environment and the system will impose on workers, it becomes possible to design facilities that incorporate novel and flexible functionality that will support workers in unpredictable conditions. (Naikar, 2013, p. 16).

4. WORK DOMAIN ANALYSIS METHOD GUIDELINES

This section introduces the basic principles of developing a WDA, including the supplementary phases of CAA and StrAn defined in the previous section. It must be emphasized again that this is not a step-by-step procedure because developing the WDA is not a linear process. The sequence will often be dictated by the availability, maturity and reliability of information. It may also be dictated by the availability of other resources, such as subject matter experts (SMEs). Nevertheless, since the methodology is a guiding framework in itself, it is usually easy, even for people new to the method, to stay on track and develop the analysis incrementally. The sections below are therefore general descriptions and recommendations for the application of the principles. Since it is not the intention of this document to rewrite the available literature, the reader is referred to the resources listed in the *Reference* section for more detail.

4.1 Purpose of the Analysis

Establishing the purpose of the WDA is one of the most important considerations during the early stages of the project. A poorly defined purpose could cause unnecessary rework and inconclusive or invalid results.

The two main considerations are the clear definition of the objectives of the analysis, and how the outcomes will be applied. Both of these considerations will be influenced by a number of factors:

- The relative maturity of the conceptual design.
- The availability of SMEs to support specific parts of the analysis (e.g., knowledge of the intended systems and processes, but also interfaces, dependencies, and constraints).
- Specific regulatory or licensing requirements (e.g., mandatory functions and function allocations, etc.).

4.1.1 Objectives

If the primary purpose of the WDA for a new NPP is to identify and define principles and requirements that would be used in the development of an operational concept document (OCD), then it is important to ensure that the WDA includes the analysis of the functional and physical aspects of the plant that would affect operations.

As indicated before, it is not the purpose of this adapted method to *design* a specific system, but to collect as much information as possible about the characteristics of the intended system, including its purpose, its functions, the artifacts within the given work domain, the relationships among entities, and the constraints that may influence the outcome.

4.1.2 Application of the Outcomes

In spite of the emphasis on the term “ecological”, this phase of the application of the method will not result in an ecological interface design. It will however be able to provide a substantial amount of information that, in combination with the later phases of CWA, (i.e., analysis of function allocation, staffing requirements, and worker competencies), would inform the development of automation schemes and operator interfaces.

Since the focus is rather on understanding the operational requirements during the early projects phases, the intended use of the products of WDA will also influence the scope and focus of the WDA, as described in the *Adapted CWA Method.*

4.1.3 Application in Operational Concept Development

A NPP's operational concept is generally understood to be a high-level description of the plant, its main systems and their functions, and how operating and maintenance personnel will work and interact with system resources to fulfill their roles and responsibilities. While several new NPP designs have emerged in the past few years, the issues and implications of innovative operational concepts that will inevitably result from new technologies employed by advanced NPPs have not been evaluated in detail. These new plants will require definition of non-traditional operational concepts to address unique operational scenarios that are expected to have an effect on plant safety, human performance and reliability, leading to new challenges for system design, staffing and training. A particular operational characteristic of new NPPs is that operators and crews are expected to meet the demands of a highly automated plant. Automation is generally expected to decrease complexity and workload, and improve team coordination. This has led to one of the goals for new NPP operational concepts: addressing the economic advantages of reducing the dependence on large operating crews when possible, thereby reducing operating costs.

Models of function allocation and staffing applied to the existing generation of NPPs will not be optimal for the new generation of plants that will use advanced technologies and materials. The science-based approach to function allocation in the systems engineering processes aims to improve system performance while maintaining or improving safety. Although this should help to provide the confidence needed in the industry that advanced nuclear plants are indeed the answer to cost effective ways to meet future energy needs, many questions remain to be answered. While a set of allocation criteria and conceptual automation principles are useful, they must be translated into operational strategies that would directly support specific phases of the systems engineering process.

Determining optimal function allocations is closely associated with choosing optimal levels of automation and it also affects decisions about control room and plant staffing levels. At present control room staffing is still strictly regulated by 10 CFR 50.54(m)(2)(i), which determines the minimum number of licensed operators required to safely operate a given number of power plant units. While highly automated plant designs offer the opportunity to reduce the number of operators, any deviation from the existing regulatory requirements must be justified in a request for exemption from the requirements of 10 CFR 50.54 (m), as provided in 10 CFR 50.13, following guidance in NUREG-1791. The implication is that plant designers must pay particular attention to the plant's operational concepts and strategies, especially with regard to technology capabilities in relation to human abilities and limitations.

These challenges, many of which are unique to new NPPs, require a systematic approach to FRA, function allocation, and operator task analysis. One of the outcomes of a systematic approach would be a rational operational strategy that would help to inform the development of automation schemes, workplace designs and operational procedures that are based, not on technology capability, but on the ideal combination of human and technology strengths to maximize system performance and safety.

For a new NPP, the implementation of the what, who, when, where, why, and how described by the International Council on Systems Engineering (INCOSE) will produce an OCD that is a collection of a large amount of strategic and high-level technical information that would include, for example:

- A description of the plant's main and subsystems, their purpose and functions.
- A description of the operational modes and states of the plant, including normal transitions, anticipated operating occurrences and transients.
- A description of the staffing strategies for the plant and the high-level roles that are to be assigned to operational and maintenance personnel, including the basis for the allocation of control functions to the main control room and other facilities.
- Operating requirements for facilities such as the control rooms, remote shutdown facility, HSIs, local control stations, communication equipment, and the requirements for monitoring, interacting, and overriding automatic systems.

- An overview of operational procedures, including instrumentation and control (I&C) architectures, automatic and manual operations, outage management, normal and emergency operating procedures, and alarm handling.
- INCOSE recommends the development of an initial operational concept by the users, operators and several specialty engineering experts at the inception of the project who then jointly maintain the Operational conceptthroughout the production, utilization, support and retirement phases of the system life cycle (INCOSE 2012).

In addition to the items above, the OCD should also provide an overall methodology to realize the goals and objectives for the system. It should not be a standalone document but should be linked to a Systems Engineering Management Plan and more detailed plans for all specialty engineering disciplines. One of the latter is the Human Factors Engineering Program Plan that describes how human factors activities and products are to be synchronized with other engineering activities.

4.2 Sources of Information for the Analysis

There are six important sources of information for the WDA that will help to define the scope and content of all the outputs of the method. These sources are described below.

1. **Documents**

   These could include a large variety of information, the most important sources being the following:

   - System design documents of a predecessor or a related design
   - User requirements specification
   - Operating experience reports of predecessor or surrogate designs (a surrogate design could be a system in a non-nuclear industry that applies similar operational strategies or human interaction principles, such as aviation, unmanned aircraft systems, oil refineries, etc.
   - Draft OCDs for a predecessor or surrogate design
   - Operating procedures or a predecessor or surrogate design
   - Off-normal and emergency procedures
   - Technical specifications
   - Regulatory guidance and reports
   - Research reports on the intended system.

2. **Subject Matter Experts**

   For a completely new system the SMEs are typically limited to the engineers or scientists working on the system. Even where a predecessor existed, the SMEs may no longer be available, which makes it very difficult to verify the reliability of the information.

3. **Observation and Site Visits**

   This is often impossible where there is no existing design to observe. However, even if the new design is completely FOAK, it is likely to employ known principles, such a nuclear fission, thermo-hydraulics, or similar processes to convert one type of energy into another. This means that there will be several existing systems that will exhibit behaviors than can be observed. The real challenge is to translate such observations into information that would be useful for the development of operating concepts for the new design.

4. **Surrogate Designs**

   Valuable lessons can be learned from surrogate facilities to gain a fuller understanding of potential HFE issues related to AdvNPPs. A surrogate facility is one whose operation involves any or all of the following: advanced technologies, high levels of automation and/or operational concepts that make similar demands on human performance. Although there are important differences between advanced reactors and these surrogates, there are often many similarities that offer an opportunity to learn from their design, operations, and experience. Refer to NUREG/CR-7126 ("Human-performance Issues Related to the Design and Operation of Small Modular Reactors") for more information.

5. **Simulations and Mockups**

   For smaller-scale designs it may be possible to generate design requirements from simulations, models, and miniature or full scale mockups of the intended system. For example, it is possible to model an entire control room in a combination of software and hardware and then use it to develop and evaluate a specific future operational concept such as operator interaction with an advanced automation system. Although it may be difficult to validate the results from such models before the actual system has been built, it will nevertheless provide valuable information that cannot be obtained in any other way.

6. **Full- or Miniature-Scale Prototypes**

   Fully operational prototypes can replicate a NPP's physics, thermal-hydraulic and support systems' performance under normal operating conditions and most if not all accident conditions. The prototype allows scientists and engineers the opportunity to collect plant performance data and valuable operating experience data. An additional benefit is the opportunity to train staff under various scenarios to help define both normal and emergency procedures.

   Regardless of the sources and their initial perceived value, the main challenge in obtaining or developing reliable information is to have the results of the WDA reviewed as often as possible. This may mean making provision for several iterations in the WDA process, which in turn should be incorporated in the systems engineering process.

4.3 Level of Decomposition

The stratified nature of any sociotechnical system is the basic reason for analyzing it on different levels of detail. The WDA also provides analysts with a mechanism for managing the complexity of the model. Although simpler work domains may need to be described only at the lowest level of abstraction (that is, using only systems and functions), for complex work domains the number of actions and their inter-relationships can become unmanageable without an organizing structure. The FAF guides the analyst to reason about the structure of the work and also the level of system breakdown (i.e., SSC) that a worker may encounter when performing a task.

4.4 Need to Develop Multiple Models

Most analyses for a new plant will require several FAF, CAA, and StrAn models; a single model will only be sufficient to capture the details of fairly simple designs. In addition, the purpose of the analysis and how the results will be used will often dictate the scope of the models that need to be developed.

4.4.1 Different Needs of Different Stakeholders

Different stakeholders have different needs. This is why it is usually necessary to develop several models of the same system is to address the requirements of different stakeholders. As explained before, it is not advisable to try to represent all characteristics of the plant in one model. It would be so complex that it would be extremely difficult to obtain useful information from the model. A more practical approach is to develop a set of models that distinguish the following:

- Plant owners and utilities: Strategic purpose and mission
- Regulators: licensing basis
- Plant managers: operating principles

- Human factors engineers and I&C engineers: automation principles
- System engineers: system and functional characteristics and dependencies.

Some information in these models may overlap, but each provides a unique perspective that would aid in the development of operational concepts that would be extremely valuable in avoiding conceptual and design errors early in the project life cycle.

4.4.2 Scenario- or Condition-Based

The determination of operational conditions or operating scenarios is an invaluable aspect of operational concept development. The analysis of the operational impact of unconventional plant configurations must include, for example, the effect of expected number of units, passive safety systems, core design, different coolants, reactor-to-power conversion ratios, physical plant layout, plant siting, and many more. Highly automated plants in particular are expected to have a significant impact on operational concepts in general and human performance in particular. For example, in the case of advanced automation schemes, a single operator may simultaneously monitor and control multiple units, or switch roles when operational conditions do not require full-time control or monitoring of systems. To support these modes of operation, the modern control room will likely require advanced HSIs that would provide sophisticated operational information visualization, coupled with adaptive automation schemes and operator support systems to reduce complexity. These all have to be mapped to human performance requirements, system efficiency and safety, and economic power production.

Selecting one or more operational conditions is one of the most effective ways of bounding the WDA (see *Define the boundaries of the analysis*). Operational conditions would typically fall into one or more of four classes:

1. Normal power production (normal operation of the reactor at power levels sufficient to produce electricity)
2. Anticipated operational occurrences (AOO) (a condition that deviates from normal operation and which is expected to occur at least once during the plant operating lifetime but does not cause any significant damage to items important to safety or lead to accident conditions).
3. Equipment failure or damage conditions (any condition that takes a system out of service, requires maintenance, or causes production loss, but does not challenge nuclear safety).
4. Nuclear safety challenges (any condition that would normally be classified as a design basis accident or a beyond design basis accident).

5. WORK DOMAIN ANALYSIS PROCEDURE

As explained before, the primary purpose of the WDA for the development of operational concepts is to model the relationships between missions, goals, functions, processes, systems and constraints in such a way that a clear path is developed from high-level requirements to operational strategies.

The analysis typically starts by studying the overall mission and goals of the enterprise. For NPPs, this is usually described in three very clear statements: (1) generate electricity economically, (2) protect workers, the public, and the environment, and (3) protect assets. This is followed by an analysis of the primary and secondary functions required to achieve these goals and how their achievement would be measured in terms of operational or productivity values, such as supply capacity and availability, net generation, thermal performance, coolant inventory, water consumption. Next, the physical processes and effects (for example, produce fission heat, transport heat, and generate electricity), necessary to support the functions are identified, and finally the components (e.g., reactor, pumps, heat exchangers, steam generators, and turbine generators) that are used to produce those physical effects are identified.

The following are the basic steps required in completing the WDA:

1. Identify main goals and mission of the enterprise
2. Define the scope of the analysis, based on considerations in *Boundaries of the analysis*.
3. Identify the operational condition of interest
4. Collect information and develop a system/function breakdown
5. Populate the top level of the FAF with the main goals
6. Identify the systems involved in the selected operational conditions in Step 3
7. Populate the bottom three levels of the FAF with the selected systems, processes and functions (no links)
8. Analyze the main contextual activities:
   - Determine functions for all identified scenario situations
   - Verify against scenarios and review with SMEs
9. Develop the means-ends links
10. Develop the strategies analysis for each condition
11. Finalize the analysis
    - Document all assumptions and constraints
    - Review with SME and rest of the team.

The graphical representation of the process in Figure 4 illustrates the various non-linear ways of populating the FAF, the CAT, and the StrAn.

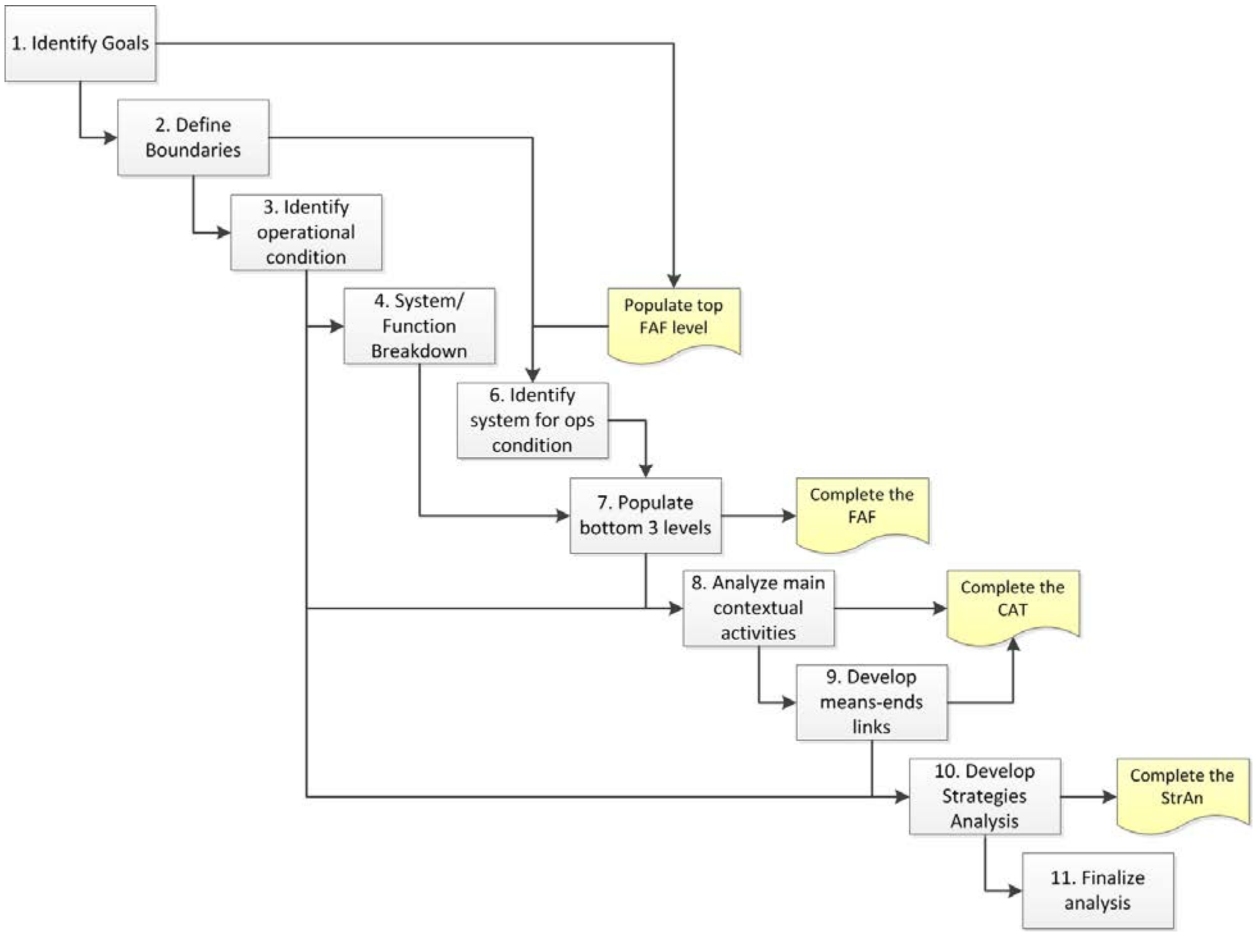


Figure 4. The modified work domain analysis process.

These key steps are described in detail in the following sections.

For more details on the process, refer to Vicente (1999, p. 171) for the basic steps that have been adapted in this report.

5.1 Developing the Functional Abstraction Framework

5.1.1 Development of the Abstraction Hierarchy

The top three levels of the FAF diagrams consider the overall objectives of the domain and what it can achieve, whereas the bottom two levels describe the physical components and their affordances. The means-ends links make it possible to identify and model the impact that characteristics and 8constraints of specific components may have on the overall domain purpose.

The FAF hierarchy is constructed by considering the work system's objectives (top-down) and the work system's capabilities (bottom-up). Moving up through the hierarchy from physical SSC to missions and goals will reveal the reasons for the existence of the system, while moving down from mission and goals to SSC will reveal the means by which overall goal-oriented purposes can be achieved.

The diagram (see Figure 2, Figure 11, and Figure 12) is constructed based upon a range of data collection opportunities. The exact data collection process is dependent on the domain in question and the availability of data. In most cases, the process commences with some form of document analysis. Document analysis allows the analyst to gain a basic domain understanding, forming the basis for semi-structured interviews with domain experts. Wherever possible, observation of the actual work in context is also highly recommended.

5.1.2 Define the Boundaries of the Analysis

Defining the boundaries of the WDA is similar to the process of defining system boundaries in the Systems Engineering Process. The purpose is to determine what elements of the system design and operation may be influenced by the analysis and what elements are needed to ensure internal validity of the WDA. The analysis therefore needs to determine what the inputs and outputs of the analysis will be. This includes sources of information (documents, SMEs, observation, research results, etc.). It is important to remember that much of the WDA process is iterative and therefore it is possible that the system boundaries may change as the analysis and the design of the system progress.

The boundary of the analysis will be determined by abstract as well as concrete elements. For example, a specific economic objective like reducing operating and maintenance cost and the functions required to achieve it forms an abstract boundary, whereas the systems required for those functions comprise the concrete boundary.

Choosing a specific operational condition (state of the plant), such as "normal operations" or "plant startup" helps to bound the initial analysis and avoids the complexity of trying to analyze the whole plant at once. This initial selection of operational conditions is refined progressively as more information becomes available, specifically during the *CAA*, which includes more detailed definitions of specific plant conditions, such as start-up, shutdown, full-power operations, and so on.

Note: *The identification of "analysis boundaries" for normal operations should not be confused with the identification of performance parameters for safety boundaries of critical functions.*

It is advisable to exclude safety-related systems and functions from the initial analysis. Treatment of safety issues in the WDA is important of course, but not necessary to identify the main operational goals and requirements. Complexity is also avoided by not attempting analysis of any safety-related functions until sufficient functional and structural information is available on systems required for plant safety. Safety-related functions should only be analyzed once the physical and functional architecture of the plant for normal operations are well understood.

The key elements required in defining the analysis boundaries are as follows:

1. Focus area
2. Natural demarcations of the focus area
3. Limitations and constraints of the analysis
4. Specific mission and purpose for the focus area
5. Specific systems or functions
6. Any specific objectives.

The elements are described briefly below.

5.1.2.1 Focus Area. The criteria for determining/selecting the focus area could be based upon one or more of these considerations:

- A user requirement specification
- A decision to redesign a previous system
- Introduction of a new design concept or system (e.g., a newly introduced passive safety system)
- Identification of a significant commercial opportunity (e.g., a serious energy shortfall in a specific market segment)
- A decision to develop and deploy a technology innovation
- A request from a government or other authority to develop a solution.

The identification of the focus area should benefit from information on previously designed or built systems or subsystems (e.g., predecessor or analogous plants) for comparison with the system under design. Comparison systems should have objectives or purposes similar to that of the system being designed. The system under design may have multiple comparison systems or a variety of comparison subsystems from different pre-existing systems.

5.1.2.2 Natural Demarcations. Natural demarcations could vary from macro to micro, (e.g., geographical area, plant section) (e.g., control room), a specific system (e.g., primary cooling system), or a specific material (e.g., coolant or fuel). The natural environment within which the system will operate will be one of the most common demarcations. This includes current, future, or anticipated environments. The physical environment will impact system components such as life support, lighting, vibration and noise control, operator exposure or duty limits, and human performance shaping factors.

5.1.2.3 Limitations of the Analysis. Before continuing with the actual analysis it is always useful to consider the limitations of the analysis and how the limitations could affect the execution of the analysis and its outcomes. The following limitations should be identified:

- **Scope** – this is often influenced by available time, space, material, and human and financial resources. This is why it is important to carefully consider the realistic boundaries of the analysis.
- **Quality** - the quality of the analysis may be influenced by the experience and skill of the analysts, how well the planned scope matches the required outcomes, and the quantity, quality, and reliability of information sources.
- **Validity** - this is the most important aspect of the WDA and especially challenging for the analysis of FOAK systems. The reason for this is that, as indicated before, information on predecessor designs is scarce and operating experience may be non-existent. This means that the analyst will have to rely on the judgement of SMEs. However, when there is no alternative this may be an inherent constraint that could only be mitigated or reduced by rigorous review and necessary iterations throughout the project.

5.1.2.4 Specific Mission. Specific missions or purposes related to the focus are likely to have a major influence on the scope of the analysis. This could be operational events anticipated for the system mission (or more than one mission), including operational phases, time scales, and events external to the system. Complete descriptions should be developed of a range of missions from the typical, representative mission to worst-case missions. Scenarios may be in narrative or graphic format. Graphic formats include plots of system activities, functions, and events against time or location. (Note however the exclusion of safety-related events and functions until a thorough understanding of the work domain has been developed is highly recommended).

5.1.2.5 System(s). The selected focus area and its natural demarcations will often also indicate one or more specific systems that should be included in the analysis. The type, size, complexity and number of such systems may have a significant impact on the overall scope as well as quality of the analysis. The emphasis in this selection should be on an analysis that is big enough to produce meaningful results, but small enough to be manageable within the time, funding, and resource constraints.

5.1.2.6 Specific Objective. Another important bounding principle is whether to include automation considerations in the analysis. It is a well-known fact that new I&C technologies make it possible to automate systems in ways not possible with the analog systems of older nuclear plants. One of the objectives of the WDA is to sensitize designers to the importance of keeping operators aware of the state of the automation system(s) at all times. To ensure this, new automation philosophies must be informed by the tasks that operators are required to perform, and their abilities and limitations in performing those tasks under various operational conditions. Making design decisions must be based not only on an understanding of the criteria for allocating functions to humans or to systems, but on the synergistic collaboration between them during the different plant states.

As an outcome of automation decisions, staffing and crew composition may become another important consideration. If information is going to be required for optimal functional allocations and optimizing crew size and composition, a number of approaches may have to be modeled in the WDA once the plant design has matured sufficiently for task analysis and function allocation to start.

5.1.3 Define Mission and Purpose

The purpose of the top level of the FAF is to determine what the proposed system is supposed to accomplish, or to determine the challenge or demand that must be addressed. It will also provide the basis for the operational concept that determines why the system is needed. This may be defined as a gap in current capabilities that must be filled or a current system that needs to be replaced or upgraded. For example, "produce electricity economically" in a remote area and not connected to an electric grid.

The typical mission of a NPP is to generate electricity safely and economically. This is the primary rationale for its construction and operation. All other information generated through the WDA must correspond to and support this concept.

As indicated before, one of the most important ways to determine the boundaries of the WDA is to consider bounding events that may have a significant effect on design and operations. These could include, for example, events like transient overpower, station blackout, loss of heat sink from full power, anticipated transient without scram, steam generator tube rupture and failure to isolate, large sodium leak followed by fire, flow blockage to or from fuel assembly, and external events like tornadoes, fire, flood, seismic, or tsunami.

Operational conditions include changes in the system mission throughout individual missions and the system's life-cycle. This includes identification of modes of operation the application for which the system is being designed and how it will change over time.

5.1.4 Define Values and Measures

Measures of performance (MOP) and measures of effectiveness (MOE) are among the most important pieces of information that the WDA contributes to the new plant's operational concept. Together they determine what constitutes successful operations for the system and they reflect the intended consequences and deliberate outcomes of system operation that can be achieved when a system is properly designed and is maintained in a manner that is consistent with its design.

The MOEs and MOPs comprise the second level of the hierarchy. They define the metrics by which the overall effectiveness of the system will be assessed and how the enterprise will know how effectively the defined functions are achieving the domain purpose.

MOPs are quantifiable system performance measurements that can take any number of forms, depending on the maturity of the design. Examples of quantitative MOPs are:

- A simple count or measure: The duration of reactor startup to reach first criticality.
- An average: The average electrical output of the turbine-generator.
- A rate: The maximum flow rate of primary sodium coolant to the intermediate heat exchanger at full power.
- A percentage: The percentage of failures may result in system shut down.

The MOPs indicate the system's intended level of performance and further elaboration of the analysis in the operational concept will allow engineers to determine what inherent system performance is required to meet the stated operational goals. MOPs do not provide an assessment of what impact that level of performance will have in terms of being able to accomplish the goal the operating organization (e.g., the utility) had in mind. That impact assessment is provided by MOEs.

MOEs may be based on overall system or component performance, or their performance during particular mission phases. Where possible, MOEs should be stated as a declarative statement, but they are generally more complex than MOPs and could cross-reference two or more MOPs. For example, an MOE could be stated in terms of accomplishment gained per cost incurred: the cost of an amount of fuel burned to produce a given unit of electricity.

Generally, during the conceptual design it may be difficult to obtain accurate performance or effectiveness measures, in which case estimates or approximate targets could be indicated. If reliable MOEs and MOPs are not available during the WDA for a conceptual design, it is acceptable to state those values and measures in qualitative terms, for example, it may be stated in general terms that the required power conversion efficiency is more than 40%, or that successful mission accomplishment is achieved when "electricity is generated economically at a plant capacity of 95%." Such vague statements may be acceptable to produce an early understanding of the work domain and its goals, but the MOPs and MOEs should be reviewed and refined as the design matures.

5.1.5 Define Generalized Functions

The purpose of this level of the FAF is to define the basic functions that will be necessary for the system to meet the mission objective or need. Identifying the relevant functions for the selected scenario or operational condition is closely related to the FRA process. In fact, it could be of great benefit to the WDA when there are existing FRA results. Conversely, where this is no existing FRA, it could be regarded as an inherent part of the WDA process.

From the perspective of the WDA, FRA is regarded as a method to analyze the mission requirements of the sociotechnical system and to translate them into discrete operational functions that must be performed or achieved to meet the design objectives of the system. As described in a number of international standards and guidelines (e.g., IEEE 1023-2004, IEEE 1220-2005, and also NUREG-0711), this is regarded as a formal and mandatory phase of any engineering project, especially for mission-critical systems. It can be used as a part of system design development in which it is used to specify the systems and associated subsystems that are needed to accomplish design objectives. It is also used to analyze existing or partially designed systems to verify that functions of the design are implemented.

For the purpose of the FAF, identifying the generalized functions will delineate between the mission-related, function-related, and physical (i.e., electrical, mechanical, chemical, thermal, etc.) SSCs that achieve the design objectives of the system.

The generic functions of a NPP for normal power generation are the following:

1. Reactivity control
2. Core heat removal
3. Heat transport
4. Steam generation
5. Electricity generation
6. Electric power grid interface management.

These functions represent the essential thermal-hydraulic elements employed in converting energy produced through nuclear fission into electricity that is supplied as a commodity to the energy market. Each of these generic functions is essential; any interruption in the performance attributes of these functions disrupts or degrades the system's ability to achieve its mission goals. For example, in order to generate electricity (Function 5), all of the preceding functions (Functions 1-4) and their requirements must be met. Any disruption in preceding functions will disable or degrade subsequent functions. Disruptions can also lead to challenges in the system's ability to ensure safety. For the analysis of an upset condition, the FAF and the following phases (CAA and StrAn) must therefore show that adequate provisions must be made in the design to detect and respond to all potential disruptions.

For the analysis of normal power operations, the CAA and StrAn must show how SSC, processes and functions will support the achievement of the defined MOEs and MOPs.

Depending on the scope and complexity of the selected scenario or operational condition, it may be necessary to identify sub-goals and corresponding subsidiary functions. Because this may make the FAF very complex, it may be necessary to develop one overview FAF and a set of lower-level FAFs for the secondary functions. For example, each of the following six groups of functions may require a separate FAF:

1. Reactivity control
   - Controlled generation of fission heat in the nuclear core
   - Balance reactivity in the nuclear core
   - Adjust power to required level
2. Core heat removal
   - Transfer of fission heat in the nuclear core to reactor coolant
   - Removal of core heat by circulation of reactor coolant
3. Heat transport
   - Transfer of energy in the primary reactor coolant to secondary and other coolants
4. Steam generation
   - Transfer of energy from primary reactor coolant and other coolants to water to produce steam
5. Electricity generation
   - Conversion of steam energy into mechanical energy
   - Conversion of mechanical energy into electrical energy
6. Power grid interface management.
   - Control of voltage and frequency
   - Control and monitor of electrical loads.

In practice, the FAF for Reactivity Control during power operation should show the values and measures, purpose-related functions, processes, and SSC required to control generation of fission heat through controlled nuclear fission in the core, achieve an axial power (i.e., neutron flux) distribution throughout the core that meets design requirements, and the ability to change power level through core system adjustments (e.g., control rods) to meet energy demand.

It must be emphasized again that the analysis at this stage is technology-neutral and also does not identify any human involvement. The potential role of humans and also the potential relationship between humans and automation systems is only identified once conceptual operational strategies emerge from the WDA.

Note that when naming processes, it is a useful convention to consistently use the verb-noun form, (e.g., control reactivity and supply instrument air).

5.1.6 Define Physical Processes

Physical processes are derived primarily from the known characteristics of the related system or component. Most conventional systems have well-defined processes, and conversely, certain processes require specific types of systems. For example, specific types of pumps will support a specific process: pumps are used to transport fluids and they can be classified according to the method they use to move the fluid: direct lift, displacement, and gravity pumps. Centrifugal pumps are used where a constant flow is required, such as for primary coolant circulation.

The bottom two levels of the FAF could be populated in any order, depending on information that is available about processes and dependencies among them. For example, if it is known that the new plant will require valves with pneumatic actuators, it is obvious that air compressors will be required, so the process related to those systems will be something like “air pressurization” and the related function will be “supply high-pressure clean air to air-operated valves”. The same would apply to any other process, such as “heat generation from nuclear fission”, “electric power generation”.

Note that when naming processes, it is a useful convention to consistently use the adjective-verb or adjective-noun format, for example: “pneumatic power control”, or “decay heat removal.”

5.1.7 Develop System and Function Breakdowns

The lowest level of the FAF identifies the SSC that are required to perform the technical processes that are required to support the operational functions. The SSC include physical structures (e.g., reactor pressure vessel, heat exchangers, containment structure, piping, and cables) as well as active electro-mechanical components (e.g., control rod drive mechanisms, pumps, valves, motors, sensors, and actuators). These SSC interact in a number of ways through defined operational configurations to achieve the operational and safety objectives. (Note however, as indicated before, that analysis of safety-related systems and functions should be postponed until a good understanding of the normal operational requirements has been established).

The example in Figure 5 illustrates a system breakdown (based on Experimental Breeder Reactor-2 – EBR-II) that contains several levels that can be collapsed and expanded as needed. System breakdowns can be developed in Excel Spreadsheets or in MindManager maps, see Subsection 5.4.1 Graphical Representations.

Breakdown Level					EBR-II System Breakdown
1	2	3	4	5	System name
X					1. Reactor Building
X					2. Reactor
	X				2.1 Reactor Vessel Assembly
	X				2.2 Neutron Shield
	X				2.3 Primary Tank and Biological Shield
	X				2.4 Air Baffle Tank
	X				2.5 Counters, Chambers and Instrument Thimbles
	X				2.6 Control and Safety Rod Drive Systems
X					3. Primary Sodium Cooling System
	X				3.1 Primary Sodium Pumps (2)
	X				3.7 Intermediate Heat Exchanger (IHX)
	X				3.8 Shutdown Cooling System
	X				3.9 Primary Sodium Purification System
	X				3.10 Silicone Coolant System
	X				3.11 Primary Argon Gas Systems
	X				3.12 Radioactive Sodium Chemistry Loop (RSCL)
	X				3.13 Vacuum Distillation Sampler (RSCL Cell A)
	X				3.14 O-H-T Oxygen-Hydrogen-Tritium Module (RSCL Cell B)
		X			3.14.1 Oxygen Meter
		X			3.14.2 Hydrogen Meter
		X			3.14.3 Tritium Meter
		X			3.14.4 Regenerative Heat Exchanger
		X			3.14.5 Flow Control Valve
		X			3.14.6 Flow Meter
	X				3.15 Equilibration Module (RSCL Cell C)
	X				3.16 Analytical Cold Trap (RSCL Cell D)
X					4. Secondary Sodium System
	X				4.1 Sodium Surge Tank
	X				4.2 Main EM Pump
	X				4.3 Intermediate Heat Exchanger (Tube Side)
	X				4.4 Evaporators (Shell Side)
	X				4.5 Superheaters (Shell Side)
	X				4.6 Tube Leak Detection System (Evaporators and Superheaters)
	X				4.7 Sodium Recirculation
		X			4.7.1 Sodium Recirculation Pumps (2)

Figure 5. Example of a system breakdown.

5.1.8 Means-Ends Links and Dependencies

Developing the means-ends simply involves identifying and describing the relationships and dependencies between entities in the FAF. It is important to define these links as accurately as possible because mistakes at this stage will cause important inaccuracies in the CAA and then cause a ripple effect throughout the remainder of the analysis.

For relatively simple FAFs the graphical format may be used as described in Subsection 5.4.1, but for complex analyses the table format is recommended. This will allow easier tracking and updating of the links. It is also important to avoid links across FAF levels; (i.e., only link Level 5 and 4, Level 4 and 3, and so on).

Figure 5 above is used to illustrate the use of the look-up table format. In this example, Item Number 2.3, "Fuel Efficiency" is a MOE expressed in terms of "breeder effect, actinides burned, and fuel damage mitigated" shown as sub-levels within "Values and Measures." The first reference listed in the means-ends column is 1.1. Following this reference will answer the question of "why is this needed?" in this case to "Generate Electricity Economically". Following the reference from Fuel Efficiency to the level below provides the answer to "how can it be achieved?" in this case, by removal of process heat (reference 3.2). In the same manner all references for the entire FAF can be examined.

This method may seem more elaborate than the graphical representation, but it is more accurate and also easier to modify.

5.1.9 Review and Verify the Funcational Abstration Framework

Once the entire FAF (or set of FAFs) has been populated, it is advisable to review it as thoroughly as possible with stakeholders, especially SMEs. The more accurate the FAF is at this stage the more reliable the WDA end results will be.

5.2 Developing the Contextual Activity Analysis

The constraints associated with what needs to be accomplished in a system are modeled by the CAA. This phase of the WDA provides a better understanding of the relationship between functions and operational conditions and how those relationships could form the basis of specific constraints that will influence subsequent operational decisions. Specifically, CAA allows us to identify the requirements associated with known, recurring classes of situations.

This phase specifies the input and end goal of a specific function, but without identifying how the function would be performed to achieve the required output (Figure 20). This leaves a "black box" that will only be refined in the next phase, *Strategies Analysis*.

Figure 6. Input and end goal of functions.

Naikar et al. (2005) introduced the Contextual Activity Template (CAT) for use in this phase of the CWA. This template was found to be a very practical way of representing the activities, conditions and situations in the work domain. These work situations can be decomposed based on recurring schedules, specific locations, or specific system operational requirements. However, at this stage of the analysis these relationships are still independent of any specific temporal or spatial characteristics.

As shown in the example in Figure 19, the CAT plots the work situations (operational conditions) along the horizontal axis and the work functions are shown along the vertical axis.

1. A check mark indicates a function that can and typically does occur in the corresponding condition. It can also indicate a required or mandatory function for the given condition.
2. A question mark indicates a function that could occur in the corresponding condition, but typically does not, or is optional.
3. A circle-slash symbol indicates a function that is not possible or not allowed in the corresponding condition.
4. Where necessary, annotations could be added to clarify the variable relationship between a function and a specific condition.

The work functions listed in the first column are taken from the generalized functions in the third level of the FAF ("Operational Functions"). These situations are very specific to the selection operating scenario and it is important to make a clear separation between those scenarios. Since the contextual constraints will be different for different scenarios, it is advisable to develop a separate CAT for different scenarios. Typical CAA models would be based on, for example, normal operations, AOO, normal transitions, or transients.

As indicated above, the CAA provides the "course of action" basis for many subsequent decisions regarding operating practices and procedures and the associated control and monitoring artifacts.

The remainder of this section provides an overview of the basic principles that should guide a human-centric perspective on the identification of operational conditions and the subsequent design of plant modes and states and automation schemes.

5.2.1 Identify Operational Conditions

The Example WDA report (Hugo & Oxstrand, 2015) described how the operation of a NPP can be characterized in terms of specific conditions, the evolution of those conditions over time, specific performance parameters involved, start and end states of various systems, and many more. The accurate definition of operational conditions is important in planning the response to normal, abnormal, and emergency conditions where decisions that are made are dependent on availability and comprehensibility of large amounts of data and information. The determination of operational conditions and response strategies is therefore a vital aspect of operational concept development. The analysis of the operational impact of AdvNPP configurations must include, for example, the effect of fuel type and design, different coolants, plant layout, and plant siting. The result from the CAA is a key ingredient of the operational strategy and also forms an essential input to function allocation, task analysis, automation design, operating procedures, and control room design.

5.2.2 List the Functions and Operational Conditions

This step consists of populating the CAT, as described above. The following procedure will help to develop a reliable CAT that can be reviewed by all stakeholders:

1. Start by reviewing the selected operational scenarios. As indicated before, typical scenarios could be normal operations, AOOs, normal transitions, fault conditions or transients, etc.
2. Divide the scenarios into specific operational situations; this will depend on the level of detail required. These situations will be listed horizontally in the top row of the CAT.
3. Identify the functions that are relevant in the selected scenario and list them vertically in the left-hand column.
4. Examine the functions one by one and consider whether the function can be performed in the situation listed in the top row and apply the appropriate marking in the intersecting cell.
5. Add a comments column on the right of the CAT table to provide additional information on contextual conditions for a specific function. Alternatively, some simple text annotations could be added in the cell itself.

See the example in Figure 19 for clarification of this procedure.

5.2.3 Operational Mode and State Analysis

The identification and description of operational conditions requires a clear understanding of the relationship between the given condition and the operating mode of the plant. As described in Subsection 5.1.2 typical operating modes are reactor startup, normal power operations, reduced power operations, reactor shutdown, refueling, maintenance, etc. Normal operations include planned transitions between these modes, but unplanned events and faults could occur within any of those modes. Understanding the nature of events (transients) and transitions is vital for the development of the WDA and the plant's operating concept, because this will ultimately affect the way operators are required to respond to the various plant conditions and thus the effectiveness, efficiency and safety of overall plant operations.

A modern distributed control system is designed to manage the safe and effective operation of a complex system like an advanced NPP. Such a plant can be defined in terms of a collection of discrete-event systems, that is, systems that perform discrete functions in uniquely definable operational modes and states. The key principles of a mode/state-based approach to automation are defined as follows:

- Operational *modes* are defined as groupings of common functions, logic and purpose. They are usually hierarchical in nature and have as goal the systematic reduction of overall plant function to lower-level functions. This means that a specific mode comprises a hierarchy of several lower-level functions. The discrete functions in such a scheme would eventually form the basis for control functions as well as operator tasks. Note that, unlike a state, operational modes are not usually quantified in terms of specific operating parameters. Note, however, that the terms modes and states are often used interchangeably – the actual definition will depend on the context of use, as shown in Figure 7 below. (Ryan & Olver, 2014).
- *States* are plant characteristics or parameters of predetermined value or range. State definitions can be common to many modes of operation, for example, a pump may be in a running, stopped, standby, or failed state in any mode. Predetermined state values would be, for example, the allowable or required operating speed range of 1500 RPM to 1800 RPM of a 1000 MW turbine generator in a mode where electricity is generated. Any deviation from these values would mean either a transition (planned) or a transient (unplanned) that takes the system into another state.
- *Transitions* are normal operational sequences that take the plant or system from one mode or state to the next in a planned manner. A transition takes inputs from a current state, performs the predefined transformation, and produces outputs that would define the next state, along with other outputs that may be needed for related systems. A transition may occur within a mode (e.g., power changes in Mode 1) or between modes (e.g., a planned sequence to shut down systems before a different mode is reached).
- *Transients* result from conditions that force the plant from one state and/or mode to the next in an unplanned manner. A system would be in a transitional state when a process variable has been changed and the system has not yet reached steady-state. Transients result due to faults that arise externally (for example, a loss of off-site power) or internally (for example, a pump trip or generator overspeed) to the plant. A transient can occur in any condition, even during a normal transition. If it occurs within a mode and the system does not recover from the undesirable condition within a predetermined time, it may force the system into a different mode, or, depending upon the nature of the fault condition, into an abnormal mode (see below). Transients are events or conditions that should be avoided, but the plant must still be designed to accommodate these conditions and operating procedures as well as operator support should be provided to ensure effective recovery.
- *Abnormal modes* are entered due to some fault condition in the plant. A specific fault mode transition sequence is associated with abnormal modes, for example, a reactor trip due to a stuck control rod, or loss of generator synchronization. These fault mode transition sequences will be less frequent than transients, and will also be of a more complex nature. The rectification of a fault mode may require operator intervention.
- *Runbacks* are pre-programmed transition sequences within a specific mode that aim to ensure sustainability of operation during sub-system capacity reduction. For example, the turbine generator may go into a runback when one of the steam generator feed pumps fails. The unit will unload to something like 40% or 50% load and then maintain that load until the pump is back in service. Runbacks are similar to transitions but remain inside the current mode.

All of the logical constructs described above could be defined in a “state matrix” where all operating parameters of all relevant systems are defined for all operating modes.

See Hugo et al., 2014 for an example from EBR-II that demonstrates how this approach could form the basis of very detailed specifications for automation.

The following generic state-transition model (Figure 7) illustrates the theoretical basis for the definition of power plant operational modes and transitions.

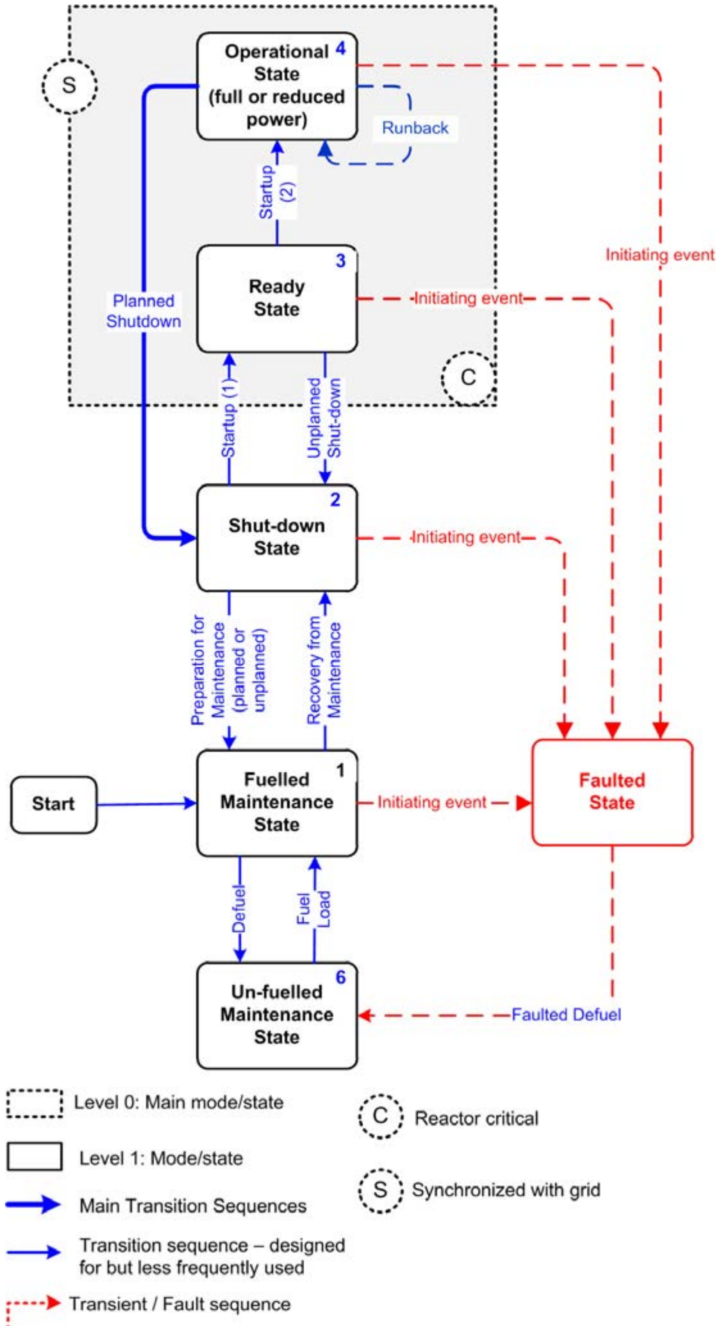


Figure 7. Generic mode/state transition model.

From a human factors perspective, the ultimate aim of a mode/state-based approach is two-fold: (1) to help the operator determine unambiguously what condition the plant is in, is about to enter, or has just exited from, and (2) to ensure coordinated and reliable response to plant conditions.

Correct interaction may be achieved by providing the operator with the full detail of the underlying system behavior. However, in reality the sheer amount of such detail is generally impossible for the operator to absorb and comprehend in the short time required for them to respond to the event. System representations like piping and instrumentation diagrams (P&IDs) and related user manuals provide only an abstract description of the system's behavior. Operators prefer interfaces that are simple and straightforward. This reduces the size of user manuals, training costs, and perceptual and cognitive burden. Providing integral and unambiguous representations of the plant condition at any point in time will help operators to maximize their situation awareness, that is, an understanding of current process parameters and the normal value of those parameters, the difference between current values and normal values, the past state of the process, and the predicted future state of the process.

A mode/state approach in the design of the HSI will help operators maximize situation awareness by integration of this information. This will be critical when the operator is confronted with a complex and changing situation, which is when the operator is required to make correct diagnoses of faults and to identify situations and problems not covered by normal operating procedures.

A more comprehensive discussion on the treatment of operational modes and states will be part of the forthcoming report on a reference operational concept for SFRs, to be published in September 2015.

5.2.4 Identifying Causal-Intentional Constraints

As described in Hugo & Oxstrand (2015), the success and quality of the WDA output will be influenced by the identification of the constraints that are imposed upon the sociotechnical system as a whole. In this phase of the analysis it is necessary to identify and describe the technical or physical, environmental, psychological, organizational, political and regulatory constraints that may affect the development and implementation of the new plant's operational concepts.

Given this definition, system boundaries will determine what constraints are placed on the system by external factors. Constraints include cost and funding (for design as well as operation and maintenance), infrastructure, training constraints, regulatory or legal constraints, human resource availability, etc. Also identify how constraints will change over time (through both life cycle phases and operational phases).

Refer to Section 3.6 and Hugo et al., 2014 for a discussion of causal constraints (that is, determined by physical or natural laws), and intentional constraints (determined by law, regulation, conventions, policies, or values). See also Figure 9 that illustrates how constraints affect all aspects of plant operations and how this is incorporated in the WDA.

5.3 Strategies Analysis

From the definition of "strategy" offered in Subsection 3.17, we can understand that different strategies will impose different demands on resources. For physical resources (SSC), the demands would be primarily in terms of the constraints described earlier. For human resources, the demands would also be in terms of cognitive or physical demands, because the strategies and event scenarios would tap different knowledge and behavioral states and processes. As the WDA progresses toward the final phases and the plant design becomes mature enough to allow transitioning of the analyses to Function Allocation and Task Analysis, we will see that the potential for action by workers in a complex system is influenced to a great extent by behavior-shaping constraints that produce a much clearer definition of the field within which action can take place.

As the final phase of the modified WDA method, operational strategies are derived from the analysis of the operational conditions identified in the CAA. The StrAn models alternative pathways (or strategies) from one system state to another. The strategies adopted under a particular situation may vary depending on the constraints within the given situation. The strategy applied will be influenced by several variables, such as experience, knowledge, training, workload, available tools, and whether it is a human or automated agent that performs the activity or some combination (shared automation) of both agents.

StrAn (also called course of action analysis) looks at filling the ‘black box’ left in CAA (Figure 8). In other words, it examines different ways of carrying out the same function. Wherever the previous phase dealt with the question of *what* needs to be done, this phase addresses *how* it can be done.

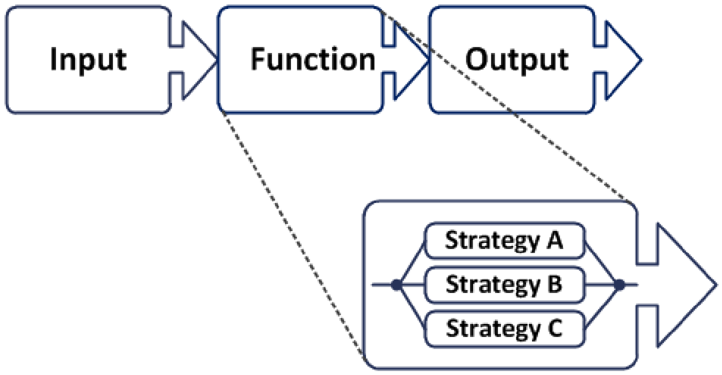


Figure 8. Scheme for strategy analysis per function.

The following diagram (Figure 9) illustrates how strategies evolve progressively and iteratively between the levels of the WDA and how all aspects of plant operations will ultimately be affected by the various constraints:

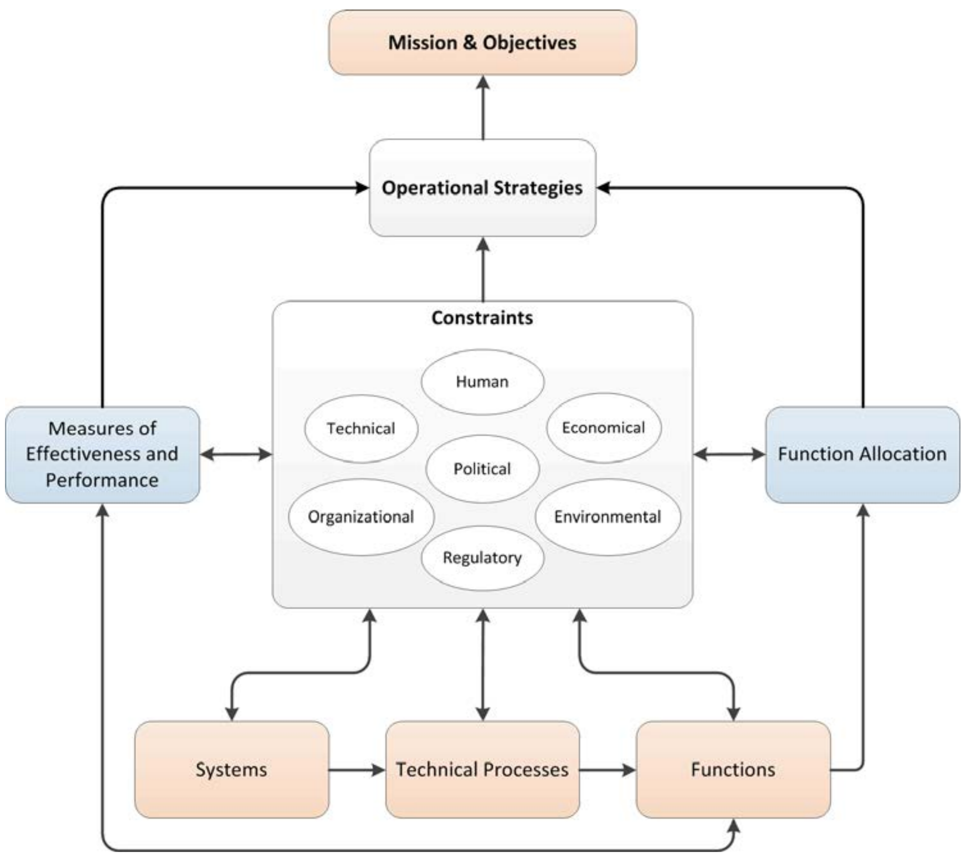


Figure 9. Evolution of strategies and the effect of constraints.

There are a number of ways of achieving the same ends with the SSC described in the FAF. Each of the strategies will use different resources and distribute the workload in different ways.

The example in Figure 10 shows how we can examine different ways of achieving a reactor scram when automatic scram has failed:

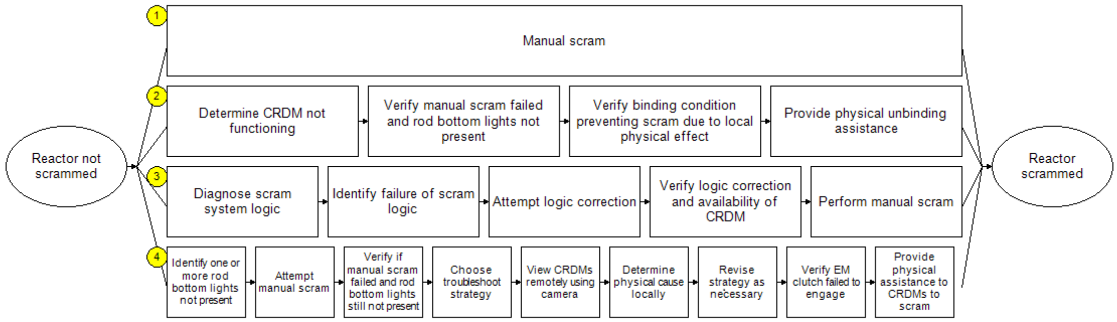


Figure 10. Strategies analysis example for manual scram.

Although the graphical representation provides an easy way to follow the logic of the four alternative strategies, it would also be possible to use a tabular representation.

The operational strategies derived from the analysis of operational conditions will eventually result in decisions about the development of an operating scheme to handle the specific conditions and the transitions between them. Unconventional operational conditions like reduced power operations, novel refueling methods, online maintenance, unplanned shutdowns for sodium or argon leaks, or load following that automatically adjusts power output may the basis for the definition of operational modes and states specific to new reactor technologies. These modes and states will inevitably create complexities and require innovative treatments in the design and use of I&C systems, as well as appropriate HSIs. In order to guide decisions about automation and function allocation, it will be beneficial to define plant operation schemes in terms of a collection of discrete-event systems, that is, systems that perform discrete functions in uniquely definable operational modes and states.

5.4 Selecting Analysis Tools and Formats

A large part of HFE analysis and design activities has to do with the presentation of operational and task information. The current practice is to a large extent influenced by the visual conventions associated with methods like FRA, function allocation, and task analysis, all of which have various possible formats. Conventions like textual, tabular and hierarchical representations have become well established in the human factors community. Since there is little evidence of past attempts to investigate the usability of such conventions, with or without dedicated tools, this section describes practical formats developed and applied successfully during this project.

Experience at INL has confirmed that smaller-scale analyses could be could be done with general purpose tools like spreadsheets or normal text documents. However, most analysts would probably agree that WDA for a new NPP is a non-trivial undertaking and that analysts need all the help they can get. It is certainly not cost effective to simply add more analysts when the task is extensive. This is where tools are needed. The main purpose of a tool should be to enable the analyst to really understand the nature and structure of a task. If the tool requires the user to attend to the complexities and functionality of the software itself, it will detract from the analysis process and this may lead to errors and omissions. Thus, any HFE analysis software should assist the users by enabling them to think about the relationship between different pieces of information without burdening them with needless complexity. For example, if the structure of the information is linear, hierarchical or a network, the tool should make that structure visible. Similarly, if there is a relationship between different pieces of information (for example, precedence, dependency, input to, output from, part of, and so on), then that relationship should not only be visible, but it should also be possible to specify and also interrogate that relationship.

Where software tools are considered, an effective tool must provide the necessary features for representation, interaction and usability. Indeed, experience has shown that there are very specific requirements for a WDA tool. In order to support key processes like development of functional and system breakdowns, CAA, and StrAn, an effective WDA tool needs to:

1. Support the elicitation, capture, analysis, modification, verification, and reporting of the information at all levels of goal, function, process and system hierarchies and also enable further extensions of the analysis to be added through each of the iterations and phases of a new NPP project.
2. Support manipulation of information in formats suitable for effective visual representation, for example, tabular, graphical, outline or textual.
3. Produce professional-quality reports.
4. Support peer-review of results.

At present, no commercial tools dedicated to CWA or WDA development are available. To overcome this shortcoming, the textual and graphical treatment of WDA information in two complementary methods are described below.

5.4.1 Graphical Representations

- **The graphical AH or FAF format:**

  The traditional graphical representation of the WDA is based on the original work of Rasmussen (1986, p. 119), which was further elaborated by Vicente (1999), Jenkins et al. (2009) and others. This method uses four or five horizontal bars to represent the abstraction levels that are populated with text blocks and interconnecting lines. The highest levels describe the system's reason for being, its functional purpose, and its general functions. The lower levels describe the physical objects and the processes that they support. This graphical treatment is a very practical way to provide an overview of the system at a glance.

  The examples below, developed in Microsoft Visio, illustrate the traditional treatment of the WDA. The first diagram illustrates the blank format of the five-level diagram:

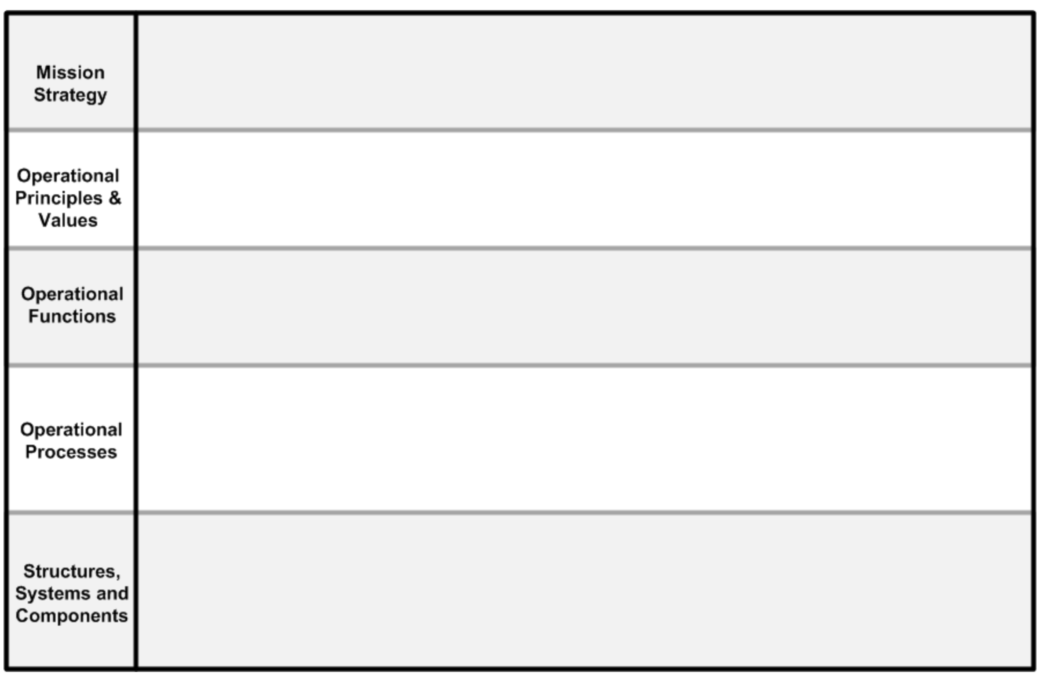


Figure 11. Generic functional abstraction framework diagram format.

The representation of so-called topological relations (that is, graphically linking related systems or processes within a level to indicate important dependencies, sequences or other relationships) may be a very useful and important addition to the graphical FAF, but a full discussion of this method is beyond the scope of this document and the reader is rather referred to Naikar (2013, p. 101).

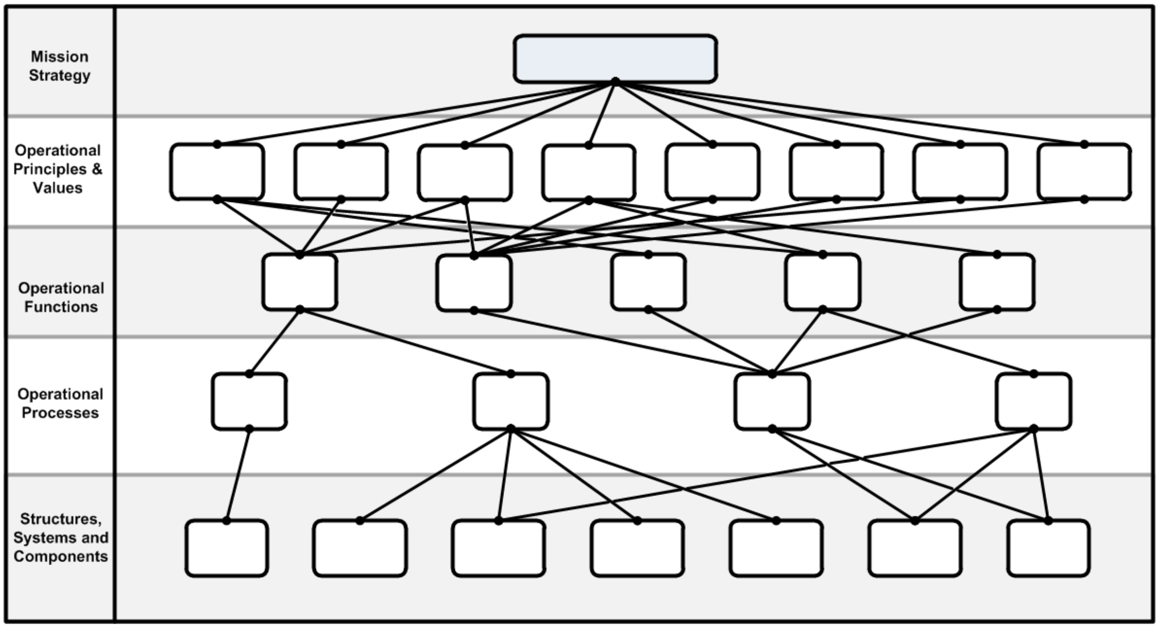


Figure 12. Generic functional abstraction framework diagram.

The bottom level of the hierarchy shows each of the physical objects within the domain. In most models this is comprised of all of the equipment and all of the actors within the domain, and more specifically, all the SSC required to support the objectives of a specific operational condition. The two levels above this describe the technical processes that each of the objects can perform and the functions that they support. The examples illustrate the possible many-to-many, one-to-many, and many-to-one relationships between SSC, processes and functions. For example, every process will require at least one SSC, but a particular function may be supported by a number of SSC.

The generalized functions in the middle of the hierarchy are the functions required to perform the purposes of the system. Each of these levels can be linked by means-ends relationships using the why-what-how relationship. This type of analysis results in a FAF such as shown in Figure 13.

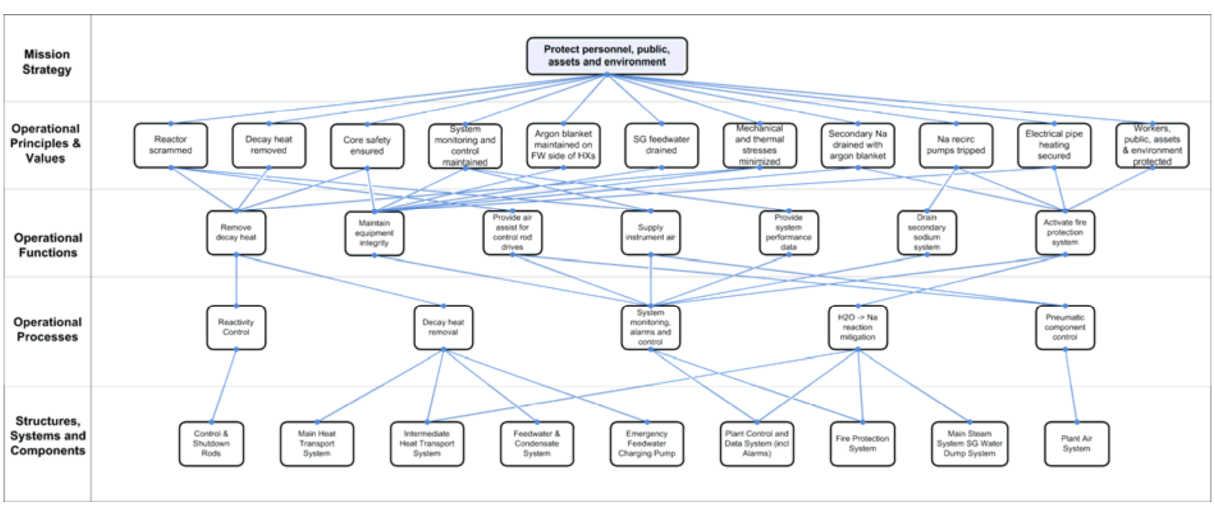


Figure 13. Functional abstraction framework for a sodium leak scenario.

- **FAF Hierarchical Map Format**

  Another format that has been tested and found promising is the hierarchical map format. This format uses the unique features of the Mindjet MindManager® software, a system that excels in the representation of hierarchical information. This method allows structuring of the levels of the FAF as a hierarchical tree or a horizontal map with an unlimited number of branches at any level. A very powerful feature of this software is the ability to expand and collapse any branch of the hierarchy. This allows the construction of very large hierarchies and with the ability to expand and collapse parts of the map, it becomes much easier to see the big picture and also focus on lower levels of detail.

  The example below illustrates a part of the FAF that was developed for a generic SFR described in the January 2015 report (Hugo & Oxstrand, 2015). It shows the top three levels of the FAF partly expanded, and the bottom two levels collapsed. It also shows that, unlike the conventional AH format, each of the levels can contain as many sublevels as necessary to fully describe the domain.

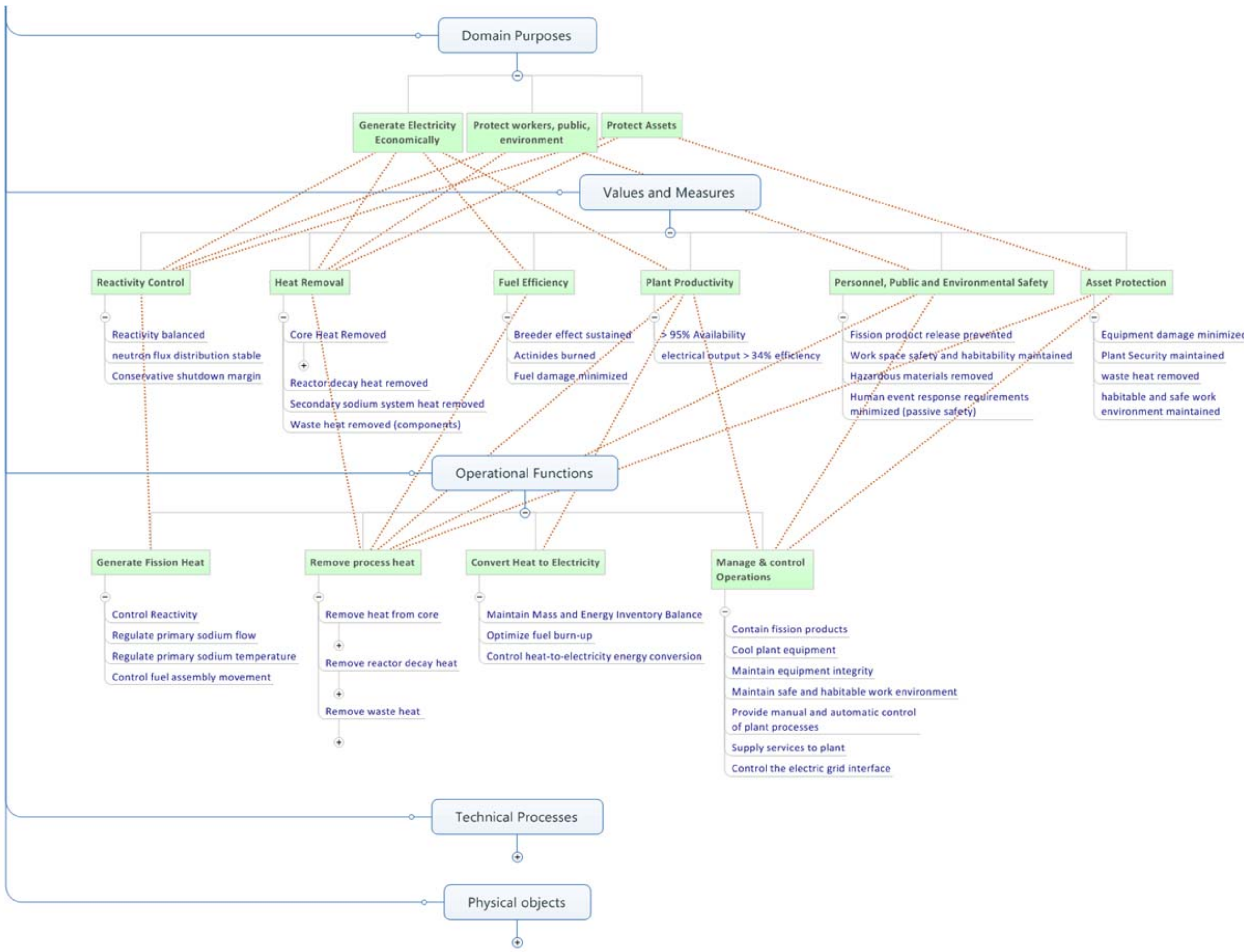


Figure 14. Hierarchical map example with means-ends links.

  One particular weakness that this format shares with the conventional graphical format is the obscuring effect of means-ends links. The example above (Figure 14 does not show all the possible means-ends links, but it is clear that even these few lines introduce a level of complexity that makes it more difficult to read the diagram.

  The next example (Figure 15) shows the same FAF without means-ends links. This diagram is easier to read, but it obviously loses much of its meaning. One way to overcome this difficulty is to translate the FAF into a textual version, as explained in Subsection 5.4.2.

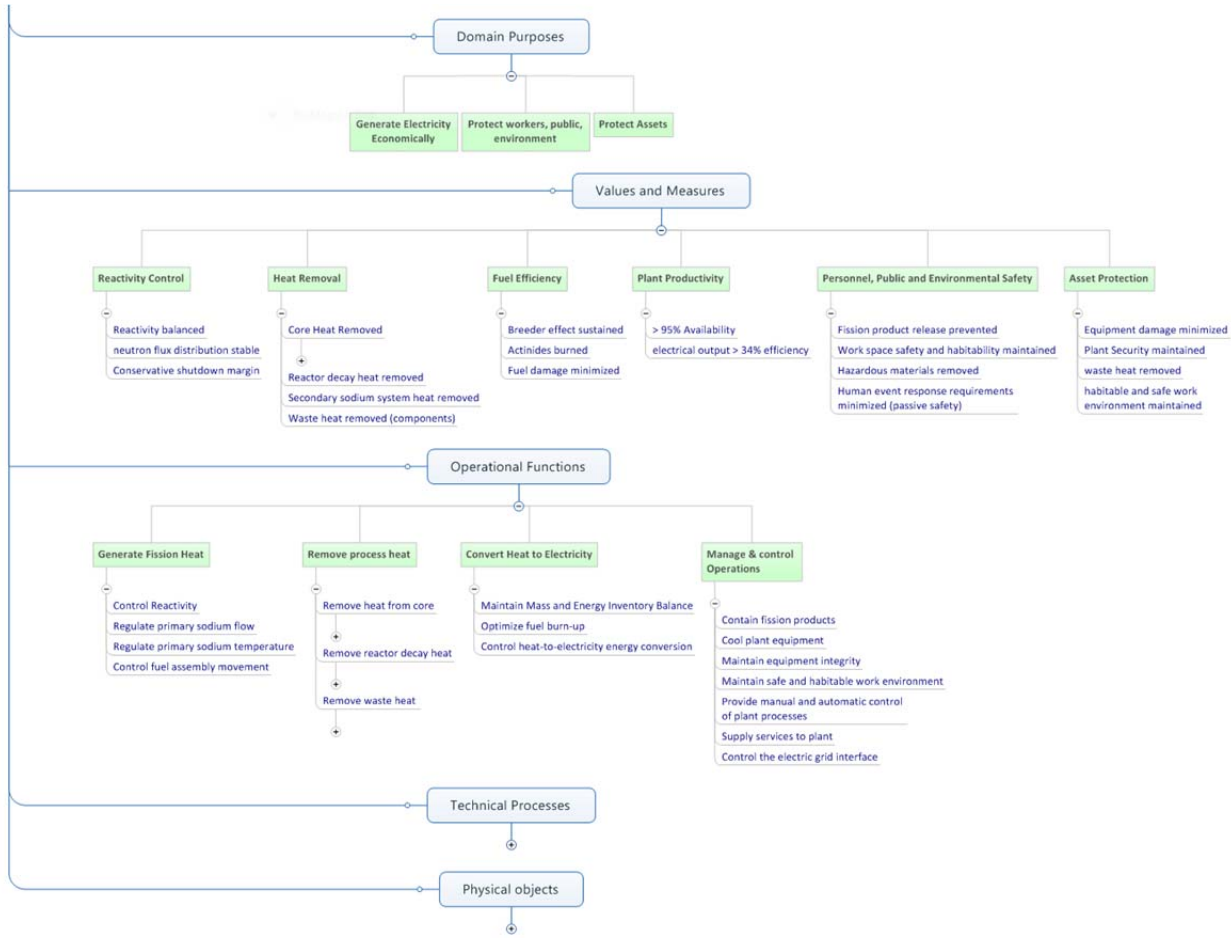


Figure 15. Hierarchical map example without means-ends links.

In developing this format, it was found a much more rapid way of creating the FAF initially, mainly due to the ability to expand and collapse the hierarchy. Another important advantage of this format is that the software allows the information to be displayed in various layouts, including an outline format as illustrated below (Figure 16), as well as exporting of the content to a normal document or a spreadsheet.

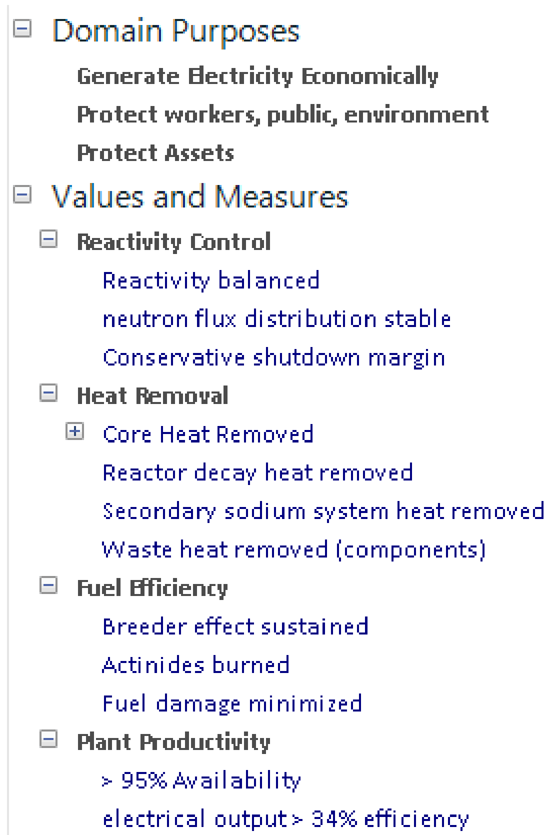


Figure 16. Part of the functional abstraction framework in outline format.

It is clear, however, that the inefficient treatment of means-ends links is an important deficiency in both versions and it thus concluded that graphical formats may be suitable for rapid development at first, but for detailed analysis a textual format may be the only practical solution.

- **CAA and CAT format**

  CAA and its representation in the CAT represent an important departure from the original CAT phase described by Vicente (1999). As described in the Terminology section (Sections 37 and 38) above, the focus in the CAA is on contextual activities (or events) instead of *tasks*. Although a table format is typically used to identify the intersections between plant functions and operational conditions, it is often useful to add graphical elements to the table to indicate the different relationships between functions and operational conditions.

  An Excel spreadsheet was found to be the most practical method to analyze and represent the CAA. The first example (Figure 17) below illustrates the general treatment of the CAT (adapted from Lintern, 2012, and Naikar, 2013, pp. 237, 269).

Functions \ Situations	Condition 1	Condition 2	Condition 3	Condition 4
Function 1	✓	✓	⃠	⃠
Function 2	✓	✓	⃠	⃠
Function 3	✓	?	?	?
Function 4	✓	✓	⃠	⃠
Function 5	✓	✓	✓	✓
Function 6	✓	✓	✓	✓
Function 7	✓	✓	?	?

Symbol Explanation:

✓ The function can and typically does occur in this condition

? The function could occur in this condition, but typically does not

⃠ The function is not possible, not necessary, or prohibited in this condition

Figure 17. Generic format of the contextual activity template.

The following examples (Figure 18 and Figure 19) illustrate the use of the CAT for various operational conditions. The examples illustrate how annotations may be added to clarify specific conditions and constraints.

Functions \ Situations	Normal Startup from Refueling	Normal Startup from Hot Standby	Normal Shutdown to Refueling	Normal Shutdown to Hot Standby	Normal transition from low to full power	Normal Temp Fluctuations at power	Testing	Comments
Remove Heat from Core	✓	✓	✓	✓	✓	✓	✓	
Control Reactivity	✓	✓	✓	✓	✓	✓	✓	Reactivity may be controlled during testing, but not changed.
Transport Heat from Primary to Secondary Sodium Systems	✓	✓	✓	✓	✓	✓	✓	This will depend on redundancy provisions
Maintain Equipment Integrity	✓	✓	✓	✓	✓	✓	✓	
Optimize Fuel Burnup	⃠	⃠	⃠	⃠	?	✓	?	Optimal fuel burnup only possible at operating temperatures.
Cool Plant Equipment	✓	✓	✓	✓	✓	✓	✓	
Control Fuel Temperature and Integrity	✓	✓	✓	✓	✓	✓	✓	
Convert Mechanical Energy to Electricity	⃠	✓	⃠	⃠	✓	✓	?	
Manage Electric Grid Interface for electricity export	✓	✓	✓	⃠	✓	✓	?	
Manage & Control the Operating Environment	✓	✓	✓	✓	✓	✓	✓	
Provide standby electrical power	⃠	⃠	⃠	⃠	⃠	⃠	?	
Generate Steam	✓	✓	⃠	✓	✓	✓	?	Dumping steam to the condenser
Manage & Control the Operating Environment	✓	✓	✓	✓	✓	✓	✓	
Provide Personnel Comfort and Safety	✓	✓	✓	✓	✓	✓	✓	
Ensure Safe and Habitable Operating Environment	✓	✓	✓	✓	✓	✓	✓	
Protect Assets	✓	✓	✓	✓	✓	✓	✓	

Figure 18. Contextual activity template for normal transitions.

Functions \ Situations	Reactor does not scram	Station Blackout	EDG failed to start	Portable EDG not available	Piping systems failed (leak)	Component damage	Personnel injury	MCR habitability compromised	Passive decay heat removal system failed
Remove Heat from Core	✓	✓	✓	✓	?	?	?	?	Limited
Maintain criticality	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘
Maintain reactor subcritical	✓	✓	✓	✓	✓	✓	✓	✓	✓
Control Reactor Startup and/or Shutdown	✓	✓	✓	✓	✓	✓	✓	✓	✓
Contain Fission Products	✓	✓	✓	✓	✓	✓	✓	✓	✓
Remove Decay Heat	✓	✓	✓	✓	?	?	?	?	Limited
Transport Heat from Primary to Secondary Sodium Systems	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘
Maintain Equipment Integrity	✓	Depending on time to start EDG	Deploy portable EDG	?	Depending on severity of damage	Depending on severity of damage	✓	Depending on severity of damage	✓
Cool Plant Equipment	✓	Depending on time to start EDG	✓	✓	Depending on severity of damage	Depending on severity of damage	✓	✓	Limited
Optimize Fuel Burnup	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘
Control Fuel Temperature and Integrity	✓	✓	✓	✓	✓	✓	✓	✓	✓
Convert Mechanical Energy to Electricity	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘
Protect turbine generator rotational parts	✓	Depending on time to start EDG	Depending on time to start EDG	Depending on time to start EDG	✓	✓	✓	✓	✓
Provide standby electrical power	✓	Deploy portable EDG	Deploy portable EDG	⊘	✓	✓	✓	Depending on severity of damage	✓
Maintain Control Functions	Manual scram	Depending on time to start EDG	Short duration only	⊘	Depending on severity of damage	Depending on severity of damage	✓	Short duration only	✓
Generate Steam	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘	⊘
Provide Personnel Comfort and Safety	✓	Limited	Limited	Limited	✓	✓	✓	Limited	✓
Ensure Safe and Habitable Operating Environment	✓	Limited	Limited	Limited	✓	✓	✓	Limited	✓
Protect Assets	✓	Depending on time to start EDG	✓	Limited	Depending on severity of damage	Depending on severity of damage	✓	✓	Limited

Figure 19.Contextual activity template for safe-shutdown earthquake.

- **StrAn Format**

  The StrAn is essentially an information flow chart and is best represented graphically. The first diagram (Figure 12) illustrates the generic treatment of the strategy (i.e., the flow of information and activities) for any specific condition. The strategy starts with an initial condition on the left, from which one or more alternative strategies may be followed to achieve the end state or condition, on the right.

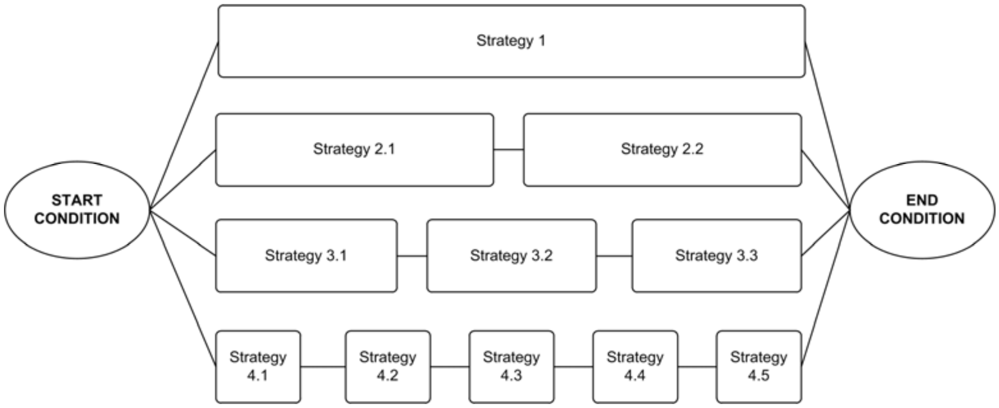


Figure 20. Generic strategies analysis format.

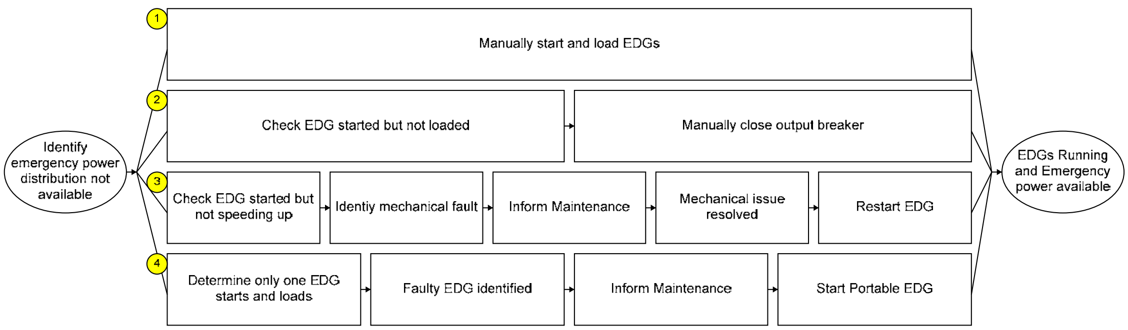


Figure 21. Strategies analysis for restoring emergency power supply.

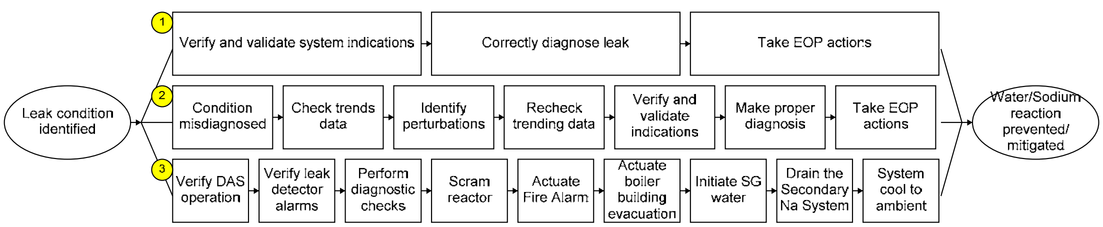


Figure 22. Strategies analysis for mitigating a water-to-sodium leak.

5.4.2 Textual Representation of the Functional Abstraction Framework

The traditional graphical representation of an AH shown in all CWA literature provides information about the goals, measures, general functions, processes and physical objects of the sociotechnical system under consideration. It also indicates the "why, what, how" dependencies and relationships between entities. For example, the means-ends links between "physical functions and effects" and "physical components" indicate that often more than one system is required for a process, and that several processes may require the same systems. This treatment is sufficient and useful for smaller analyses, but it will quickly become clear that the traditional graphical presentation of the FAF is not feasible when applied to large complex sociotechnical systems due to the visual complexity and difficulty in following the links. When the FAF for a large and complex design is represented graphically, it becomes very difficult to read and follow the links. To ensure that the FAF becomes a useful analysis tool it is often more practical to use a tabular treatment that uses a look-up method rather than graphical lines, as shown in this example Figure 23) that uses an Excel spreadsheet:

1. Domain Purposes	Means/Ends Links
1.1 Generate Electricity Economically	2.1, 2.2, 2.3, 2.4
1.2 Protect workers, public, environment	2.2, 2.5, 2.6
1.3 Protect Assets	2.3, 2.6

2. Values and Measures	Level 1		Level 2		Level 3	Means/Ends Links
2.1	*Reactivity Control*					To Level 1: 1.1, 1.2 To Level 3: 3.1
		2.1.1	Reactivity balanced			
		2.1.2	Neutron flux distribution stable			
		2.1.3	Conservative shutdown margin			
2.2	*Heat Removal*					To Level 1: 1.1, 1.2, 1.3 To Level 3: 3.2.1, 3.2.2, 3.2.3
		2.2.1	Core Heat Removed			
				2.2.1.1	Core safety and integrity ensured	
				2.2.1.2	Coolant circulated (forced and convective)	
		2.2.2	Reactor decay heat removed			
		2.2.3	Secondary sodium system heat removed			
		2.2.4	Waste heat removed (components)			
2.3	*Fuel Efficiency*					To Level 1: 1.1 To Level 3: 3.2
		2.3.1	Breeder effect sustained			
		2.3.2	Actinides burned			
		2.3.3	Fuel damage minimized			
2.4	*Plant Productivity*					To Level 1: 1.1 To Level 3: 3.2, 3.3., 3.4
		2.4.1	> 95% Availability			
		2.4.2	Electrical output > 34% efficiency			
2.5	*Personnel, Public and Environmental Safety*					To Level 1: 1.2, 1.3 To Level 3: 3.2, 3.4
		2.5.1	Fission product release prevented			
		2.5.2	Work space safety and habitability maintained			
		2.5.3	Hazardous materials removed			
		2.5.4	Human event response requirements minimized (passive safety)			
2.6	*Asset Protection*					To Level 1: 1.3 To Level 3: 3.2, 3.4
		2.6.1	Equipment damage minimized			
		2.6.2	Plant Security maintained			
		2.6.3	Waste heat removed			
		2.6.4	Habitable and safe work environment maintained			

Figure 23. Textual format of the functional abstraction framework (Example 1).

With this method, the means-ends links are presented as numerical references that indicate the links to specific items in the level above ("why") or the level below ("how"). This method may seem more elaborate than the graphical representation described in Subsection 5.4.1, but it is more accurate and also easier to modify.

This method also facilitates reading top-down as well as bottom up, for example, by focusing on an element in any level and then determining why that element is needed, and what is needed to ensure that it will serve that purpose. The example above is the top part of the FAF for a generic SFR that was included in the January 2015 report ((Hugo & Oxstrand, 2015). It shows the first two levels, Domain Purposes and "Values and Measures." To illustrate the top-down and bottom-up reading of the diagram, Item Number 2.3, "Fuel Efficiency" can be described as one of the results of the sustained breeder effect, actinides burned, and fuel damage mitigated. The first reference listed in the means-ends column is 1.1. Following this reference will answer the question of "why is this needed?" in this case to generate electricity economically. Following the reference from "Fuel Efficiency" to the level below provides the answer to "how can it be achieved?" in this case, by removal of process heat (reference 3.2).

In the same manner all references for the entire FAF can be examined. The next example (Figure 24) shows the (partially collapsed) bottom two levels of the same FAF. In this example, following the references for Item 5.5 (steam generator and turbo-generator) to the level above, shows the "why" in Items 4.5.1–4.5.4: the steam generator is one of the systems needed for energy conversion, including fission heat generation, steam generation, steam-to-mechanical energy conversion, and mechanical-to-electrical energy conversion.

4. Operational Processes	Level 1		Level 2		Level 3	
4.1	*Reactivity control*					To Level 3: 3.1, 3.4
4.2	*Fuel handling and optimization*					To Level 3: 3.1.3, 3.2.1
4.3	*Heat Transport*					To Level 3: 3.1, 3.2 To Level 5: 5.3., 5.4, 5.7
		4.3.1	Core Heat Removal			
		4.3.2	Reactor Decay Heat Removal			
		4.3.3	Component Heat Removal			
		4.3.4	Waste Heat Removal			
		4.3.5	Secondary system heat removal			
4.4	*Coolant circulation*					To Level 3: 3.2, 3.4.2
4.5	*Energy conversion*					To Level 3: 3.1, 3.3, 3.4 To Level 5: 5.5, 5.6.1, 5.6.4
		4.5.1	Fission Heat Generation			
		4.5.2	Steam Generation			
		4.5.3	Steam-to-mechanical energy conversion			
		4.5.4	Mechanical-to-electrical energy conversion			

5. Structures, Systems & Components	Level 1		Level 2		Level 3	
5.1	*Reactor Containment and Core*					To Level 4:
5.2	*In-reactor Fuel Handling System*					To Level 4:
5.3	*Primary Cooling System*					To Level 4:
5.4	*Secondary Cooling System*					To Level 4:
5.5	*Energy Conversion Systems*					To Level 4: 4.5, 4.7.3, 4.7.8
		5.5.1	Steam Systems			
				5.5.1.1	Steam Generator	
				5.5.1.2	Steam Dump System	
				5.5.1.3	Feedwater and Condensate System	
		5.5.2	Turbo-Generator			
				5.5.2.1	High-Pressure Turbine	
				5.5.2.2	Low-Pressure Turbine	
				5.5.2.3	Generator	
5.6	*Plant Service Systems*					To Level 4: 4.6
		5.6.1	Electrical and Automation Facilities			
				5.6.1.1	Plant Electrical Supply System	
				5.6.1.2	Building Electrical Supply System	
				5.6.1.3	Emergency/ Standby Generators & UPS	
		5.6.2	Inert Gas Distribution and Processing System			To Level 4: 4.7.9
				5.6.3.1	Argon Storage and Supply	
				5.6.3.2	Nitrogen Storage and Supply	
		5.6.3	Electrical Pipe Heating Systems			To Level 4: 4.7.10
		5.6.4	Plant Control and Data Facilities			
				5.6.4.1	Distributed Control System	
				5.6.4.2	Control Room & HSI	
				5.6.4.3	Remote Shutdown Facility	

Figure 24. Textual format of the functional abstraction framework (Example 2).

5.5 Work Domain Analysis Examples

The January 2015 report on a WDA for a generic SFR (Hugo & Oxstrand, 2015) provides a full set of FAF, CAT and StrAn examples. Additional examples are available in the WDA for EBR-II (Hugo et al., 2014). The reader is also referred to examples in the literature mentioned in this report, specifically Burns et al., 2008; Jamieson et al., 2007; Jenkins et al. 2009; and Naikar, 2013.

6. OPERATIONAL CONCEPT DEFINITION

6.1 Purpose

As described before, the primary purpose of the WDA method during the early design stages of a new plant is to provide a reliable set of high-level concepts that would inform the development of operational concepts.

This report provides only a brief overview of the purpose and scope of the OCD and basic guidance on using the results of the WDA for the OCD. A comprehensive discussion of the OCD and its content, as well as a complete example will be provided in a forthcoming milestone report that will include validation of the various frameworks described in this current report.

6.2 Operational Concept Document Overview

An operational concept describes a sociotechnical system in terms of a user's point of view on what, who, when, where, why, and how a product is used throughout its life cycle:

1. *What* – Known components, elements, and top level capabilities that perform the necessary system functions.
2. *Who* – The product's interaction among various human elements within a system and external interfaces.
3. *When* – Description of activities, tasks, flows, precedence, and concurrent or sequence-related elements necessary to achieve mission objectives in various product modes and conditions)
4. *Where* – The product's geographical and physical locations in the user's facilities and interfacing systems.
5. *Why* – Provides the rationale to clarify the reader's understanding of specific events identified in operational concept scenarios.
6. *How* – Expectations about product usage, operation, and maintenance in a given environment. The emphasis is on concepts and not on system design or implementation.

Previous project reports (see Hugo et al., 2013, 2014) defined "Operational Concepts" or "Concepts of Operation" as a description of the characteristics of a new or existing system from the viewpoint of people who will use that system, while communicating the quantitative and qualitative characteristics of the system to all stakeholders.

To avoid confusion between the two terms, this WDA methodology adopts the term "operational concept" and the abbreviation "OpsCon". Following the INCOSE definition, the OCD is now defined for the purpose of this methodology as follows:

"The Operational Concept Document is a description, from the perspective of users and operators, of an organization's intent regarding the operation or series of operations of a specific system or a related set of specific new or modified systems. The OCD is designed to give an overall picture of the operations using the identified systems in the organization's operational environment." (INCOSE 2012)

In addition, the intended content of the OCD should follow the requirements stated in Revision 2 of NUREG-0711:

- The primary design and operating characteristics of the plant or system and the specific staffing goals and assumptions necessary to implement the OpsCon.
- The estimated number of personnel per shift who will have plant monitoring and operational control responsibilities, plus the basis for the estimate.

- The roles and responsibilities of each crew member and training and qualifications required for control personnel.
- An overview of how control personnel will interact with automated systems, plus a description of the basic automation and function allocation philosophy.

SFRs and all AdvNPPs will require descriptions of the plant, its SCC and their functions, and the unique operating scenarios that will influence the design of systems and procedures and the interaction of humans with systems and the environment. In spite of the typical lack of detailed design information early in the engineering process, it is very important that this phase of the analysis be as thorough as possible because the level of accuracy at this stage will determine the accuracy and validity of the remaining phases. Available information needs to be investigated and resolved in sufficient detail early in the project life cycle to enable designers to include the operational as well as human performance requirements in their designs, technical specifications, and procedures. Especially with FOAK designs, it is incumbent upon the designers to assemble these definitions, structures, functions and scenarios and make them available for the WDA. Without the WDA, it will be difficult to provide assurance that the evolving design will be usable by operators. WDA is the foundation upon which everything else is built and perhaps more important, it provides a large part of the necessary traceability for design decisions throughout the project life cycle. Past experience reported in the literature (Bisantz et al., 2003; Jenkins et al., 2010; Militello et al., 2010) has shown that engineering efforts that skip WDA and only perform FRA and system design are unlikely to deliver a viable system that supports optimal human performance.

7. CONCLUSIONS AND RECOMMENDATION

This document provides a practical methodology and broad principles that are intended to guide analysts and engineers in the development of a human factors basis for operational concepts for new NPPs. The methodology is described as far as possible in plain language to enable non-specialists to apply the specific methods and procedures needed to analyze or interpret multidimensional requirements and constraints within the scope of nuclear power plant operations.

The adapted WDA methodology presented in this document is the result of extensive experience developed over three years within the operational concept project. During this time the various techniques described in the literature were tested and modified to suit the unique requirements of projects dealing with new reactor technologies. The practical application of the method in the development of an example WDA for a generic SFR has provided sufficient confidence in the efficiency and reliability of the methods. The results are demonstrated in this and previous project reports.

Although every attempt was made to translate the theories from the literature into practical methods, it is nevertheless recommended that analysts supplement the implementation of the methods and formats described in this report with a thorough reading of the key literature referenced in this report.

8. REFERENCES

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