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# Work domain modeling to support winter road maintenance operations

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WORK DOMAIN MODELING TO SUPPORT WINTER ROAD MAINTENANCE OPERATIONS

by

Ju Qiu

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Civil and Environmental Engineering
in the Graduate College of
The University of Iowa

August 2008

Thesis Supervisor: Professor Wilfrid A. Nixon

# ABSTRACT

This thesis presents an application of Work Domain Analysis (WDA) to the domain of Winter Road Maintenance Operation (WRM). WDA is the first phase of Cognitive Work Analysis (CWA), a methodology for analyzing complex socio-technical systems. WDA can help to structure system information in a manner that is meaningful for decision making and computer-based information system design. The Abstraction Decomposition Space (ADS) is an important tool used during the Work Domain Analysis. In this thesis an ADS model for Winter Road Maintenance (WRM) work system is created. This model gives a innovate structural description of WRM work system that can help WRM operators gain a more detailed understanding about the components in WRM work domain and their interrelationships. This model structures the WRM work domain in a manner that can help to identify information requirements for effective and efficient WRM operation decision making. In this thesis, from the ADS model, 65 information requirements are extracted. This thesis makes a theoretical contribution to extending application of Work Domain Analysis and proves WDA is a worthwhile and valuable technique to improve WRM information collection and decision making, which will result in more effective and efficient WRM operation.

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CERTIFICATE OF APPROVAL

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PH.D. THESIS

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This is to certify that the Ph.D. thesis of

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has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
degree in Civil and Environmental Engineering at the August 2008 graduation.

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# CHAPTER I

# BACKGROUND INFORMATION

## 1.1. General Introduction

During winter, snow and ice on roads may create hazardous road conditions, and thus significantly impact the surface transportation system. The primary goals of Winter Road Maintenance (WRM) are to maximize mobility of the traveling public, and minimize crashes due to winter traveling conditions. State and local agencies spend more than $2.5 billion on snow and ice control operations each year (FHWA, 2003), not including indirect costs due to accidents, lost productivity and delay, and environmental costs.

Winter weather has a direct impact on local and national economies. Nowadays, in the United States, many goods and services are based on just-in-time delivery, a practice employed by 45 percent of industry (AASHTO, 1999), so the delay or disruption in mobility caused by adverse winter weather conditions brings considerable negative economic impact. Clearly, the societal and economic impacts of adverse weather in winter on the highway system are considerable.

Timely decisions on snow and ice control can prevent roads from being closed and reduce the number of accidents. Accurate decisions prevent unnecessary deployment of vehicles and material—a crucial advantage in areas where each deployment represents a sizeable portion of the local road maintenance budget (OFCM, 2002). Each decision is based on information, and the value of a WRM decision rests both on the accuracy and timeliness of the information, and on its relevance (Nixon, 2002). Thus, an effective and efficient provision of winter service mainly depends on good information that supports WRM decision making, and on how well that information impacts the decision making process (Nixon, 2002).

## 1.2. Information Categories

The information needed for decision making in WRM is interdisciplinary. It falls into five categories: weather information, road surface conditions, transportation conditions, resource information, and others. Most of the information is dynamic (i.e. changes with time) during a winter event, and both current and forecast information are needed for effective decision making. The information from each category may be influenced by, and influence, information in other categories. For example, during a winter storm when the traffic volume reduces, the road surface condition is likely to deteriorate. (Hanbali & Kuemmel, 1993).

Winter weather impacts nearly all highway maintenance activities, so of the five categories, weather information has always been an important and recognized input to WRM decision making. However, the weather forecast is not always reliable, so weather information is uncertain and the level of uncertainty can not at present be fully quantified. Therefore, during WRM operation, maintenance supervisors and operators have to make decisions based upon uncertain information. The need for accurate, timely and reliable weather information to aid tactical and strategic planning for safe and judicious operations with limited and costly resources is clearly evident (Stewart, 2004).

### 1.3. Information Overload

Traditionally, the procedure of snow and ice control practice is to initiate operations after the snow or ice begins to form on the roads, through a combination of plowing, deicing, and sanding. Sometimes, when severe winter weather makes travel unsafe and dramatically increases crash rates, some roads will be closed directly. For traditional reactive approaches, the need for weather information is simple, basic and straightforward. The road supervisors just need to know when to start and when to stop the operation.

With increasing concern about environmental issues and higher public expectation with regard to road conditions, the processes used in WRM in the United States have undergone substantial changes over the past ten years. The methods of snow and ice control have moved from reactive methods to proactive methods (e.g., anti-icing) that begin operations before or very early in storm events to prevent the bonding of ice or snow pack to the pavement. There is growing evidence that, relative to traditional snow and ice control methods, anti-icing provides a very rapid recovery or achievement of a satisfactory pavement condition during and after the storm events, and it improves safety. Stowe (2001) outlines the benefits associated with applying anti-icing chemical to the roadway surface by a proposed automatic anti-icing system for a problematic section of a Washington State interstate. Based on the analysis, the benefit/cost ratio is over two, the net benefit is over $1 million, and snow and ice related collisions would be reduced by 80 percent. Boselly (2001) also reports that states can reduce their snow and ice control budget by 10 to 20 percent in a study that evaluated the use of anti-icing procedures by state highway agencies in nine states.

However, this innovative approach requires the use of considerable judgment in making decisions, requires that available information sources be utilized methodically, and requires that operations be anticipatory or prompt in nature (Ketcham, *et al*., 1996). Compared with the weather information needed by traditional methods (e.g. deicing and plowing), the anti-icing process requires better weather information, especially with regard to the onset, type, intensity and duration of winter storms, so the weather information for the anti-icing approach is more predictive and dynamic than the information for traditional approaches. Thus, more accurate and timelier data sources are needed for this innovative method.

Meanwhile, there has been increasing use of advanced weather forecast systems, remote sensing, computer, telecommunications, and engineering technologies in WRM since the mid 1980s, so more information resources have been available to winter maintenance supervisors. These have included National Weather Service (NWS) reports, weather radars and sensors along the roads and bridges. However, few of these sources issued road-specific forecasts and there has been a lack of linkage between the information available and the decisions made by winter maintenance supervisors (Pisano & Nelson, 2000). Specifically:

- Not all the weather information is provided in a useful way. For example, NWS provides weather forecast for various weather users, from agriculture to marine and aviation interests, so the weather information that NWS provides is not specific enough for winter road maintenance supervisors to use to make winter road maintenance decisions. Further, NWS forecasts do not provide information on road surface temperatures. Knowledge of these temperatures is critical in WRM decision making.

- Not all the weather information is provided in a friendly way. Some of the weather information is provided without integration. The information is presented without a clear understanding of what information should be used under given conditions, which has the effect of reducing decision makers' performance instead of enhancing it.

Boselly (1992) indicates that more quantity of information is not necessarily good for road supervisors, and more emphasis might be placed on the quality of information from the perspective of the WRM supervisors and operators, so more locally-specific, timely weather forecasts are required. Currently, the problem is no longer a shortage of weather information in WRM, but how to filter, integrate and present the information to the road supervisors in a form that they can understand and make good use of the information to make sound decisions.

Furthermore, in WRM, decisions are not based on weather information alone. In addition to collecting and interpreting weather information, road supervisors must consider other information at the same time, such as traffic condition, available materials, labor and equipment, and so on, and most of the information is also dynamic.

WRM information sources range from human observation and experience to multiple and often contradictory weather forecasts. All the challenges brought by information collection and integration, plus regulations about chemical applications, environmental impacts, tight budget and high public expectation, lead to information overload for WRM supervisors (Pisano & Nelson, 2000).

The systematic use of all available information sources is essential for effective decision making (Pisano & Nelson, 2000). Therefore, efforts to develop data fusion technologies for aiding WRM decision making will have significant potential for helping winter road supervisors cope with the data explosion problem. This should, in turn, increase their situation awareness together with their decision speed and accuracy.

### 1.4. National Research Efforts

In the late 1980s, a technology termed Road Weather Information Systems (RWIS) was imported into the United States from Europe and then developed and implemented in many states. At present, deployed RWIS components may include roadside sensor stations, a communication network, data access tools for maintenance personnel, tailored weather forecasting services, advanced weather modeling, pavement temperature modeling and prediction, and an internet website for maintenance decision making and traveler information. Other features are being added by the industry, in response to expressed needs. The system allows WRM supervisors to retrieve up-to-the-minute data (e.g., pavement temperatures and salt concentrations) on pavement, at bridges and at other trouble spots. WRM supervisors can monitor the weather and see a projected freeze-up time for the roads. Therefore, the WRM supervisors can make timely and efficient winter maintenance decisions and the WRM operators can be mobilized to plow and apply materials when and where they are needed. The deployment of RWIS assists the use of cost-effective, proactive snow and ice control practices (e.g., anti-icing) that improve safety and the level of service provided to road users.

Some Value Added Meteorological Services (VAMS), which are vendor-provided forecast services, are already available to supply tailored weather forecast for the specific needs of individual agencies, locations, and their practices and procedures. VAMS typically provide a 24-hr forecast of tailored weather information in a graphical format, such as anticipated road conditions, type and amount of snow or ice accumulations expected over time, and other weather conditions critical to the WRM decision makers (AASHTO, 1999).

All the weather information systems improve the data gathering process and provide decision maker with more accurate, timely data for managing snow and ice removal. However, weather information is only part of information required for making effective and efficient WRM decisions. Due to the information overload that WRM supervisors are facing, now, more than ever, advanced decision support systems and collaborative or integrative work aids and displays are needed to help WRM supervisors manage the increasing amounts of information to make more accurate and efficient decisions.

In 1998, the office of the federal Coordinator for Meteorological Services and Supporting Research (OFCM), together with United State Federal Highway Administration (U.S. FHWA), undertook a study of existing and potential needs for weather information for surface transportation. From the symposiums, the questionnaire responses, and agency interviews, a wide range of weather information related to operational decisions about surface transportation systems was identified and analyzed (OFCM, 2002). In 2000, the United State Federal Highway Administration (U.S. FHWA) Road Maintenance Management Program sponsored a series of workshops for State Department of Transportation (DOT) personnel and members of the meteorological community. From those workshops, a list of decisions that may be made during fighting a winter storm, were developed (Pisano & Nelson, 2000).

Utilizing information obtained from these outreach activities, in 2001 the FHWA, in conjunction with five national research centers, began to develop a conceptual prototype Maintenance Decision Support System (MDSS) tailored for WRM decision makers (Kroeger & Burkheimer, 2003). MDSS promises to enhance weather information integration, and thus reduce the cognitive demands on operators in understanding the weather information and maintaining situation awareness. The overarching goal of these efforts was to provide WRM decision makers with information with enough specificity to directly support their decision making process so that more efficient operations result.

The MDSS functional prototype (MDSS FP) software (version 1.0) was developed between October 2001 and September 2002. Since then, significant changes have been made to the MDSS software as a result of valuable results from four field demonstrations conducted during the winters from 2003 to 2007. In the future, more field demonstrations will be held, and enhancements made to the system based on the demonstration will be included as part of future software release. Until now, MDSS FP version 4.0 has been available to the public and version 5.0 will be made available soon. The prototype of MDSS has proved that MDSS is able to provide highly targeted weather information and decision support models that codify the best of past practices, and MDSS can help maintenance supervisors make more informed decisions by using the results of cost-benefit analyses. The MDSS is still under development and the most recent update of MDSS development can be obtained from their website.

In addition to MDSS, some other similar Decision Support Systems also have been developed. Boselly (2004) presents a tool for maintenance operations decision-making, called the Automated Real-time Road Weather System (ARROWS). This system takes a numerically generated forecast from an ensemble of eight national and international global models, and presents the forecast information in a format for easy use and understanding by WRM road supervisors. This system also generates location specific warnings based on the weather forecast to assist road supervisors. ARROWS has been field tested twice during the 2003-2004 and 2004-2005 winters. The results of these two demonstration indicated that ARROWS helped the users perform their work more effectively and efficiently, and this system also has been changed and upgraded based on feedback from field users.

### 1.5. International Research Efforts

Many other countries in the world are also struggling with snow and ice on the road in winter like the US. Over the last decade, Japan and several European countries also have made significant efforts to improve the efficiency and effectiveness of winter road operations, particularly in the areas of public communication and information system integration. In these countries, advanced road condition measuring equipment and data have been used by the transportation officials to improve the management of winter road operations and to advise public road users of the hazardous winter road conditions. For instance, some enhanced sensors were developed and deployed on winter maintenance equipment to measure the road surface conditions, some winter maintenance decision support systems like MDSS were developed, and improved information systems have been used to inform public road users of winter road conditions and educating them on the potential dangers of driving during hazard winter weather.

In order to evaluate those significant advances abroad for potential application in the United States, in 1994, an International Winter Maintenance Technology Scanning Tour was organized under the auspices of the Federal Highway Administration's International Outreach Program and the AASHTO- sponsored National Cooperative Highway Research Program to examine snow and ice control operations in Japan and Europe. Important differences in different aspects of WRM between the US and these foreign countries were found, such as removal equipment, materials, weather monitoring and so on. By evaluating and implementing the advanced practices developed abroad, better, safer and more environmentally sound roads will be provided to the American public road users.

## 1.6. Conclusion

Timely and accurate decision-making is the key to the success of Winter Road Maintenance Operation and all decisions depend on good information. In this section, the category and characteristics of information needed for WRM decision making were introduced. The importance of weather information and the challenge caused by the unreliability of weather information were discussed.

In order to provide better and safer winter road condition to the public road users, various national and international efforts have been made. Many advanced technology and technique have been introduced to the WRM field, such as anti-icing, advanced sensors and decision support system. Through cooperative technical exchange program, many advanced management practices and research have been adapted to US federal, state and local highway programs.

# CHAPTER II

# PROBLEM STATEMENT

## 2.1. Problems

From the introduction, it can be found that many studies have been conducted on information collection and integration and computer-based decision support system development in WRM domain. The results from the studies are very valuable, but some problems related to the information system design still can be identified.

First, few studies have *systematically assessed* the information requirements within the WRM domain, such as the weather information needs for road supervisors in support of operations that reduce delays and increase the safety of operations, how to optimize the flow of information, and how to optimize the communication of information between operators, supervisors and the public road users.

Second, like the information systems currently in use, *no human information interaction study* with the WRM domain has been conducted for the computer-based decision support systems for WRM (e.g., MDSS) to determine whether this system is displaying the appropriate information in an appropriate manner for the WRM decision makers. According to the literature review, in the development of any WRM decision support systems, there is no detailed plan for integrating multiple source of information onto user displays. Studies indicate that an information system design based on an understanding of human information interaction of their intended users would be most effective (Fidel & Pejtersen, 2004), and an effective display could increase the road supervisors' strategic planning role.

Third, the information system design based on *personal descriptions* would inherit mistakes or deficiencies of the mental models of those surveyed. For most of the decision support systems of WRM, the information requirements are based on the information collected from many WRM personnel by various symposiums. This kind of descriptive approach of information system design has following limitations:

- This information is just a collection of observed behaviors. People's information behavior is informed by the mental models they have on the information world around them, and some of these models may be incomplete or wrong. It is very important that these mental models match the true state of affairs of the WRM domain.
- Moreover, WRM personnel tend to operate intuitively rather than analytically, so they cannot always describe in precise detail their rules for initiating action when snow threatens (Stewart *et al.*, 2004).
- Further, not all people have the same mental model for the same situation but a system designer cannot know which models are complete and correct (Fidel & Pejtersen, 2004). Indeed it is possible that the actions proposed by the system developed by this descriptive way would be inappropriate or even wrong.

Fourth, information systems designed in this way have no ability to cope with *unanticipated events.* As discussed, studies conducted for information system design for WRM have been based on describing the phenomenon under investigation, rather than *analyzing* the information requirements, so the system designers only know that a road supervisor would employ a specific strategy under a certain condition, or what kind of conditions can motivate the road supervisors to select a strategy (Fidel & Pejtersen, 2004). However, this method can not include all the situations in the WRM domain, so if any unanticipated event happens, the information system would not necessarily be able to assist people's decision making. A good information system should have the ability to predict behavior under various changing circumstances, so describing the current practice in a work domain is not enough for information system design (Fidel & Pejtersen, 2004).

Finally, the mode of design and evaluation of the decision support system is neither efficient nor effective. The technique used for the system design in WRM is to create prototypes of a new design, evaluate these prototypes by having WRM personnel use them to perform representative tasks (field testing), and then use the evaluation findings to iterate the system design. This technique is a valuable tool for information system evaluation and design improvement, but it has limitations: Due to various reasons, the number and range of tasks that personnel were asked to perform during the field testing is not complete, so for each field testing, only part of the system design deficiencies can be found, and for most of them it will take several iterations to find them. It is very possible that some of the deficiencies will never be found in this manner. In the first two MDSS field demonstrations, for example, neither winter produced a sufficient number or variety of storm events to thoroughly test the system, so not all the aspects of information system could be tested by this way.

All the problems mentioned above derive from the method adopted for modeling work demands in WRM domain—Task Analysis (TA). Work demands are cognitive and environmental constraints that govern people's activities in a work domain. TA's potential for information system design guidance is based only on event-dependent descriptions of current work practice, in the form of tasks and actions, information cues, patterns and relationships workers perceive, the knowledge they use and strategies for processing information in performing these tasks. TA techniques only describe what currently happens in the work domain without offering any real analytic capability to support design (Preece, 1994).

### 2.2. The Characteristics of the Method Needed

Based upon the above discussion, a new technique for modeling work demands for WRM is needed to eliminate the modeling limitations of TA methods. The new technique should have the following characteristics:

First, this approach must be *holistic*. The WRM is a multi-dimension work environment (Smithson, 2004) and it includes *planning* and *evaluation* (e.g., budgeting, training, and performance measurement), winter season and event preparedness (e.g., procurement of equipment, salt, aggregate, staff/contractor call-in), and event response (e.g., routing and treatment decisions), so a holistic approach is needed to analyze several dimensions of WRM simultaneously. Moreover, this approach should be able to allow a richer description of the decision making environment and also allows a description of the set of relationships between intent, generic decision tasks, generic activities and available resources (Chin *et al*., 1999).

Second, the new analysis approach should be *event-independent,* and focus on the behavior-shaping constraints that the work domain imposes on actors, rather than on the observed behavior of actors (Fidel & Pejtersen, 2004). Most of the interest in current information systems of WRM relates to event-response, and the design of the information systems bases on guidelines that often identify very specific temperature (related to road salt effectiveness) and precipitation accumulation (various thresholds for plowing) criteria for action (Smithson, 2004).

Third, this new approach also should consider the design implications of *limitations* of the operator's performance in accessing and decoding information. In WRM, both the communication between different operators at various levels and the capabilities of individual workers are very critical for the success of WRM activities. Therefore, studies of human information interaction that uncovers what users need, what is possible for them to do, and what is not possible, would be most useful for systems design (Fidel & Pejtersen, 2004).

Finally, the new approach should have the ability to help operators deal with *unanticipated situations*. The WRM domain is a complex and dynamic environment full of uncertainty so it consists of emergent and unanticipated events (e.g., a severe snow storm or traffic accident) with critical consequence (e.g., jeopardizing public safety).

The framework of Cognitive Work Analysis (CWA) has proven fruitful for analysis and design of complex sociotechnical systems (Vicente, 1999). The CWA puts emphasis on the process by which designers and researchers uncover information necessary for the design and evaluation of computer-based support systems (Ahlstrom, 2004). In the following part of this thesis, CWA will be briefly introduced and the feasibility study of applying CWA for the WRM work system design will be analyzed.

# CHAPTER III

# COGNITVIE WORK ANALYSIS

## 3.1. Introduction of Cognitive Work Analysis

Cognitive Work Analysis (CWA) is a multidisciplinary framework, developed by Rasmussen, and colleagues (Rasmussen, 1986; Rasmussen & et. al, 1994; Vicente, 1999) and it arose from work first done in the nuclear power plant domain (Vicente, 1999). Until now, it has been frequently and successfully used for the analysis, design, and evaluation of the *interface design* for complex work domains (e.g. Reising & Sanderson, 1998; Burns, 2000; Rasmussen, 1998)

Researchers also have explored the use of CWA for a variety of problems other than interface design, for examples, the design of new large-scale systems (Bisantz *et al*., 2003), evaluations of design proposals (Naikar & Sanderson, 2001), team design (Naikar *et al*., 2003), the development of performance measures (Crone, *et al*., 2003), and some other domains. All these applications demonstrate that CWA has been extended to applications beyond interface design, and they also demonstrate the practical relevance and feasibility of CWA for other domains except nuclear power. However, it has so far received little attention by the WRM domain.

The framework of Cognitive Work Analysis (CWA) (Vicente, 1999) has proven to be a powerful tool for the evaluation and design of information systems for the context under investigation. It is especially effective in investigating the Complex Sociotechnical Systems (CSS) and exact information needs about this kind of systems. There are many characteristics that characterize complex sociotechnical systems, including large problem spaces, social, heterogeneous perspectives, distributed, dynamic, hazard, coupling, automation, uncertainty, mediated interaction and disturbances (Vicente, 1999). Some details about each characteristic are given in Table1.

However, not all complex sociotechnical systems rate highly and equally on all of these characteristics. Differences exist among various application domains, such as a

Table 1 The Characteristics of Complex Sociotechnical Systems

| Characteristics | Explanation |
|---|---|
| Large Problem Spaces | CSS are composed of many different elements and forces |
| Social | CSS are composed of many people who must work together |
| Heterogeneous Perspectives | CSS are composed of people from different backgrounds |
| Distributed | People working in CCS may be located in different places |
| Dynamic | CSS are usually dynamic |
| Hazard | There could be a high degree of potential hazard in operating CSS |
| Coupling | CSS are usually composed of many highly coupled subsystem |
| Automation | CSS are usually highly computerized |
| Uncertainty | There tends to be uncertainty in the data available to workers |
| Mediated Interaction | Sometimes, some properties of a CSS cannot be observed by human perceptual systems unaided |
| Disturbances | Sometimes, workers in a CSS are responsible for dealing with unanticipated events |

nuclear power plant vs. a hospital. Some characteristics are relevant to some systems but not to some others. Therefore, all complex sociotechnical systems have at least some of the characteristics mentioned above, and they also have their own unique characteristics of complexity to some extent.

CWA begins with and gives primary importance to the *constraints* that the environment (work domain) imposes on workers' actions rather than trying to predict workers' actions themselves (Vicente, 1999). This viewpoint is based on an *ecological* perspective to human factors because it gives precedence to the constraints that the work ecology imposes on goal-directed behavior (Fidel & Pejtersen, 2004). In CWA, constraints are enablers of action because without them action cannot take place (Fidel & Pejtersen, 2004), and they are factors that can shape workers' behaviors but cannot be changed by workers' actions. For an example, gravity is the constraint that makes an apple fall down to the earth not fly away to space and the influence of gravity cannot be changed by the apple. Identifying these constraints is important because they specify the information required for both routine operations and unanticipated situations. There are five different constraint layers in a CWA, each one corresponding to a different type of behavior-shaping constraints.

1. *Work Domain Analysis:* to analyze the constraints that the work domain imposes on workers' actions, using the Abstraction-Decomposition Space (ADS).
2. *Control Task Analysis:* to analyze what needs to be done in the work domain to achieve system goals, using Decision Ladders (DL).
3. *Strategies Analysis:* to analyze strategies to perform control tasks, using flowcharting map.
4. *Social-Organizational Analysis:* to analyze role allocation and relationship among operators, using the analysis outcomes obtained from previous three phases.

5. *Worker Competencies Analysis:* to analyze the human capabilities necessary for effective performance, using Skill-, Rule-, and Knowledge-based behavior taxonomy as a modeling tool.

Figure 1 is a common representation of the five phases of analysis that make up the CWA approach to design; See e.g. (Cummings and Guerlain, 2003).

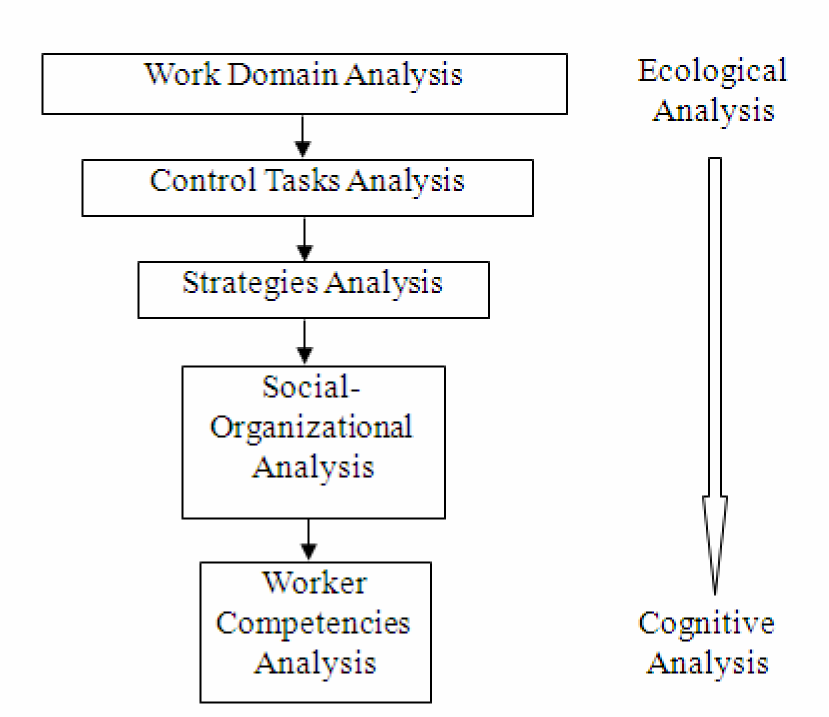


Figure 1 Five Phases of Cognitive Work Analysis

### 3.2. Characteristics of CWA

CWA is a *holistic* approach that can analyze several dimensions of a context simultaneously and it provides modeling tools which facilitate an in-depth investigation for each dimension of a context. These five dimensions include personal, social and organizational constraints and all the constraints play a role simultaneously and interdependently. Therefore, a CWA of a particular context is a multi-disciplinary investigation with the purpose of understanding the interaction between people and information in the work context. (Fidel & Pejtersen, 2004).

The analysis of goals and behavior-shaping constraints make CWA a *formative* model, which describes requirements that must be satisfied so that a system could behave in a new, desired way (Vicente, 1999). CWA is not a descriptive model that describes how things are, or a normative model that explains how things should be. It is also not a model or record of generalized or specific instances of expert problem solving or decision making (Burns, Bisantz & Roth, 2004). Here is a common example used to describe how CWA, a formative model, are different than normative and descriptive models: If you want to tell a person how to get to B from A, you have three ways: First, give him a step by step direction (a normative way); second, tell him how most people get there (a descriptive way); third, give him a map (a formative way). In this example, map would be a perfect way, especially when some unanticipated events happen, because it illustrates all the possible ways to get to B from A. If a road in the step by step direction closed for some reason, people can use the map to figure out how to take other routes to get their destination, and in this situation, the normative way and the descriptive way will fail to direct people to the destination (Fidel & Pejtersen, 2004). As a formative model, CWA can point out all the possibility of information behavior in a particular context, and then help workers cope with the unpredictable situations in a socio-technology environment. Therefore, an information system based on CWA has the ability to predict behavior under various changing circumstances.

The above example shows that the idea behind CWA is that if people can perceive the structure of a domain, in above case, the rivers, buildings, hills, roads and the objects within that domain and show the functions that each object affords (its affordances), and the limitations on their use (constraints), people can then perceive the situation in relation to their goals and devise a course of action to help themselves through that domain towards their intended goal.

The CWA is a *work-centered* approach not a user-centered approach, because the focus of CWA is on analyzing the constraints that the work domain imposes on the workers' actions, not the workers themselves, User-centered approaches focus on the study of people's behavior. However, the characteristic and life experience of every individual are diverse, and may affect individual information behavior. Therefore, it is impossible to consider all the possible behavior and their possible combination in a single study, or apply them all to the design of an information system design. The work-centered approach focuses on the analysis on the work domain and the requirements that it presents to the workers who operate within the work domain. The information system designed by this approach may adapt to the operators' work in the realm of stable, behavior-shaping constraints. This, then, makes it possible for the operator to adapt when situational and unpredictable factors arise (Fidel & Pejtersen, 2004).

## 3.3. Preliminary Feasibility Study

The CWA framework has been specifically developed to meet the challenges of Complex Sociotechnical Systems(CSS), and it arose from work first done in the nuclear power plant domain (Vicente, 1999), but it has so far received little attention by the WRM community. While there are many reasons to believe that there is a good fit between the demands imposed by WRM domain and the characteristics of CWA, it is important to provide a basis for evaluating this degree of fit. In this part, the fit will be evaluated from the following aspects:

- The demands imposed by WRM domain versus the characteristics of CWA
- The characteristics of the WRM domain versus the characteristics of the complex sociotechnical work system

### 3.3.1. The Demands Imposed by WRM Domain VS the Characteristics of CWA

Based upon the discussions in previous sections, Table 2 lists the problems that exist in the current WRM information system design and evaluation, what WRM needs to solve the problems, and the characteristics of CWA corresponding to WRM's needs. The table shows that CWA can answer all WRM's needs, so it is reasonable to consider CWA for WRM information system design.

### 3.3.2. The Characteristics of the WRM Domain VS the Characteristics of the Complex Sociotechnical Work System

The WRM domain is a complex and dynamic environment with highly coordinated work patterns among operators, and it possesses many characteristics that usually characterize a complex sociotechnical work system (Rasmussen *et al*., 1994; Vicente, 1999), such as uncertainty, dynamism, team work, stress, risk, variable and unpredictable demands, large and growing amounts of data to process, imperfect data (weather information), and human interaction mediated via computers. Further, the complexity of the WRM work system will undoubtedly continue to grow with the increasing application of advanced technologies.

Decision making in WRM has several similarities to the domain of nuclear power plant control for which WDA was developed (Table 3). First, like nuclear power plant control, many of the decisions made in the WRM domain are potentially critical and decision errors could be life threatening to public road users. Second, as in nuclear power, there are underlying physical constraints that the WRM supervisors must operate within for effective operation, such as the capability of equipment (e.g. snowplow), the availability of resources (e.g. salt), snow route characteristics, pavement characteristic and so on. Third, in both nuclear power plant control and the WRM domain, it is possible for operators or supervisors to encounter unanticipated situations that will require flexible knowledge-based reasoning to manage effectively. For these reasons, it was decided to try to apply CWA to the WRM domain to check its feasibility for the WRM domain, and to see whether the application could result in design or evaluation guidance for decision support systems (e.g. MDSS). There are also aspects of WRM that differ from nuclear power plant control that made the application of WDA to WRM challenging. For example, the WRM work system (a loosely bounded system) cannot be modeled with a very defined system boundary like nuclear power plant (tightly bounded system). In this thesis, we will study the winter activities of one highway agency, but we cannot simply define the geographical area of that highway agency as the boundary of this work system, for the activities within that area still need information or service from outside that area, like weather information or some equipment provided by agencies from adjacent areas. For another example, with tight budgets, the high expectation of the public for keeping roads clear of snow and ice, and the increasing concern of environmental issue, WRM operations have to undertake several missions, like road safety, traffic mobility and communication with the public road users, whereas a power plant ultimately has a very clear purpose – the generation of electrical energy.

Due to these differences between these two work domains and the challenges caused by the differences, this study will make a significant contribution to the existing work on CWA by providing an extensive analysis of a loosely bounded system. This extension will enlarge the applicability of CWA.

CWA spans the constraints imposed by the work domain or work context to the constraints imposed by the cognitive requirements of workers, so a complete CWA can be time consuming and complex to perform. It is evident from the literature review that the theoretical concepts and methodology for the other four phases of CWA are generally less well developed and understood than the first phase of CWA – Work Domain Analysis (WDA). Thus, in this thesis, the study focuses on WDA – the analysis of the boundaries or constraints that are imposed by the work context. Some of the principal features of the first phase of WDA will be examined in more details below.

### 3.4. Introduction of Work Domain Analysis

The first phase, Work Domain Analysis (WDA), is the fundamental phase of the Cognitive Work Analysis (CWA). WDA is a framework to generate information requirements for design, both in terms of data that need to be collected and in terms of

Table 2 Comparison of Problems, Method Needed and Characteristic of CWA

| Problems | Method Needed | Characteristics of CWA |
|---|---|---|
| Few studies have systematically assessed the information requirements within the WRM domain | A holistic approach is needed to analyze several dimensions of WRM simultaneously | A holistic approach that can analyze several dimensions of a context simultaneously and it provides modeling tools by which an in-depth investigation for each dimension of a context can be made. |
| The system design is based on personal descriptions | An event-independent approach | The focus of CWA is on analyzing the constraints that the work domain imposes on the operators' actions, not the operators themselves, so the CWA is a work-centered approach not a user-centered approach. |
| It has no ability to cope with unanticipated events. | The system based on this approach should have the ability to help operators deal with unanticipated situations | The analysis of goals and behavior-shaping constraints makes CWA a formative model, which describes requirements that must be satisfied so that CWA can point out all the possibility of information behavior in a particular context |
| The mode of design and evaluation of the decision support system is neither efficient nor effective. | A more powerful tool for the design and evaluation of the decision support system | The framework of Cognitive Work Analysis (CWA) (Vicente, 1999) has proven to be a powerful tool for the evaluation and design of information systems for context under investigation. |
| No human information interaction study with the WRM domain has been conducted for the computer-based decision support systems for WRM | This approach also should consider the design implications of limitations of the operator's performance in accessing and decoding information. | A CWA of a particular context is a multi-disciplinary investigation with the purpose of understanding the interaction between people and information in the work context. |

Table 3 Comparison of Power Plant Control Work Domain and WRM Work Domain

| System Characteristics | Power Plant Control | Winter Road Maintenance |
|---|---|---|
| System Purposes | Single, well defined over all context | Multiple, well defined in local context |
| System Boundary | Almost closed | Not closed |
| Physical Constraints | Important | Important |
| Effect of Intentional Constraints | Minimal | Could restrict decision making |
| Event Severity | Could be high | Could be high |
| Routine Operations | By procedural | By procedural |
| Unanticipated Situations | Possible | Possible |
| Dynamics | Slow | Slow or fast |
| Degree of Uncertainty | Low | Could be high |

information that needs to be derived through processing of this data. In this way, WDA is a useful tool to gather information requirements and inform display design (Burns *et al*., 2004).

WDA was first developed by Rasmussen and Lind (1981) to help nuclear power plant operators cope during plant disturbances. Since then, WDA has been explored for a variety of work domains, for examples, aviation (Naikar, 1999); biomedical applications (Hajdukiewicz *et. al*, 1998), naval command control (Chin *et al.*, 1999), and petrochemical process control (Jamieson & Vicente, 1998). Most of these studies report particular applications of WDA or the results of empirical evaluations that compare a WDA based approach to interface design to more traditional approaches (e.g. task analysis) to interface design (e.g. Burns, 2000; Naikar *et al.*, 2003; Naikar *et al.*, 1999; ). These papers demonstrate that WDA is applicable for a variety of work systems and that WDA can lead to better design products than other approaches, like task analysis. These studies also evaluate the feasibility and usefulness of WDA on large-scale industrial projects.

By modeling the constraints related to the purposive and physical context of the work system (see Table 4) in which activities take place, WDA is able to provide workers with a correct model of the system so that the operators may develop the correct mental model and therefore control the system and handle problems with the system more effectively. The purposive context imposes constraints on workers by specifying the purposes of the system, the values and priorities that the work system

Therefore, as Table 4 shows, a typical work-domain model consists of five levels of work domain constraints (Rasmussen, 1986; Rasmussen & et. al, 1994; Vicente, 1999): functional purposes, abstract function (Value and priority measures), generalized function, physical function, and physical form.

### 3.5. Introduction of Abstraction Decomposition Space

In this thesis, the main tool used for WDA to modeling the purposive and physical constraints is Abstraction-Decomposition Space (ADS) (Figure 2). It is

Table 4 Five Levels of Work Domain Constraints

| | | | |
|---|---|---|---|
| Work System | Purposive Context | Functional Purposes | Why the system exists |
| | | Value and Priority Measures | Overall system values and priorities for both goal accomplishment and system integrity |
| | | Generalized Function | Purpose-related functions that are executed and coordinated to achieve system purposes |
| | Physical Context | Physical Function | The functional capabilities and limitations of physical objects in the work system that enable the generalized function |
| | | Physical Form | The Physical objects that afford the physical function and their associated configuration such as size, shape, color, and location |

| | Whole System | Subsystems | Components |
|---|---|---|---|
| Functional Purposes | | | |
| Values and Priority Measures | | | |
| Generalized Function | | | |
| Physical Function | | | |
| Physical Form | | | |

Figure 2 The Standard Two-Dimensional Format of an Abstraction-Decomposition Space

structured by supplementing the five level Abstraction Hierarchy (AH) by an orthogonal, part-whole decomposition showing systems, subsystems, and components. The AH is shown along the vertical axis of the ADS whereas the decomposition dimension is shown along the horizontal axis of the ADS. The AH is also referred to as means-ends dimension or abstraction dimension, and the decomposition dimension is also referred to as part-whole dimension.

### 3.5.1. Abstraction Hierarchy

The description of each level of Abstraction Hierarchy (AH) has been listed in Table 4. From the table, it can be outlined that the higher levels in the AH are represented at a less detailed and more abstract level than lower levels are. The links between each of the five abstraction levels are “means-end” links and indicate how the higher level element is achieved, or conversely, why the lower level element is available. These relationships can be characterized in terms of a “how-what-why” triad illustrated graphically in Figure 3 (Rasmussen, 1986; Rasmussen & *et. al*, 1994; Vicente, 1999). The level at which workers observe the work domain at any one point in time defines the “what” level, the level above specifies “why” and the level below specifies “how”. For the illustration sample in Figure 3, generalized function A specifies “what” is under consideration. Relationships from generalized function A to the level below, physical function B and C, indicate the means or “how” generalized function A can be implemented. Relationships from generalized function A to the level above, values and priority measures D, specifies the ends or “why” generalized function A is present in the work domain. As shown on the right of Figure 3, this “how-what-why” triad can be applied by starting at any level of abstraction in the ADS.

This means-end relationship gives AH unique and important characteristics. First, AH is purpose oriented and it identifies the structural work domain constraints on achieving purposes, so an AH representation supports *goal-directed problem solving* (Vicente, 1999). Second, AH preserves the complexity of the work system, because each level provides a different description of the system as a whole, rather than breaking it into isolated parts. Third, it provides a good mechanism to *cope with the complexity* because each upper level provides the context for the lower one and each lower level provides the means to achieve the upper one. In contrast to the task analysis approach, the hierarchy describes the constraints that the work domain imposes on the actions of any actor, not the actions themselves so all the constraints are event-independent. Thus, the constraints are relevant across a broad range of scenarios or situations, including unanticipated events (Vicente, 1999; Fidel & Pejtersen, 2004).

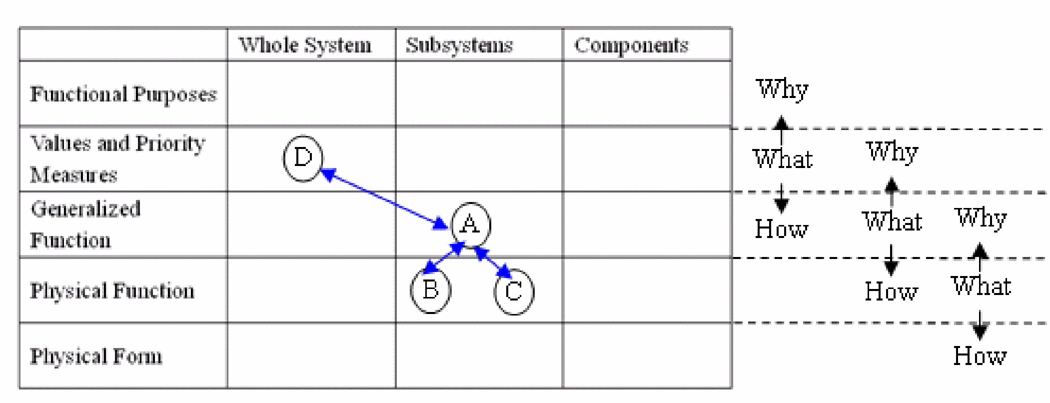


Figure 3 Means-End Relationship Between Different Levels of AH

### 3.5.2. Decomposition Hierarchy

The part and whole dimension represents the work system at different levels of detail. It decomposes the system into sub-systems and physical components. The relationships between the different levels of decomposition are part-whole relations. Lower levels of decomposition are parts of the higher levels of decomposition; conversely, higher levels of decomposition are composed of the lower levels of decomposition. Each level of decomposition represents a different level of resolution for viewing a work domain. This decomposition is very useful because it shows how the components in the system are organized to perform various functions and process.

### 3.5.3. Coupling of Abstraction Hierarchy and Decomposition Hierarchy

The abstraction dimension of the ADS represents the different conceptual lenses with which workers can view a work domain, whereas decomposition dimension represents the level of resolution of the conceptual lenses. Each cell in the ADS offers a complete but different representation of the same work domain (Vicente, 1999). The top left cell offers a purposive model of the whole system (coarse, purposive model) whereas the bottom right cell offers a physical model of individual components in the system (fine-grained, physical model).

Studies have shown that workers spontaneously shift their span of attention, depending on their task demands. When people are reasoning about a work system at higher levels of abstraction (e.g. functional purposes) they tend to use coarser levels of description (e.g. whole system). Conversely, when people are reasoning about a work system at lower levels of abstraction (e.g. physical objects) they tend to use finer levels of description (e.g. components). Thus, people tend to reason or adopt models along the diagonal of the ADS, the shaded part of Figure 2. Hence, although the two dimensions of the ADS are conceptually orthogonal, they are actually coupled in practice. Thus, in a work domain analysis, in most cases, only the shaded cells are populated (Rasmussen, 1986; Rasmussen & *et. al*, 1994; Vicente, 1999).

# CHAPTER IV
# WORK DOMAIN MODELING TO SUPPORT WINTER ROAD MAINTENANCE

In this thesis, the Winter Road Maintenance (WRM) domain will be analyzed with Work domain Analysis (WDA) (1) to investigate its feasibility for WRM domain, (2) to see whether this approach could generate some new information requirements for the design or evaluation for computer-based support tools for the WRM domain, and (3) to test the application of WDA to a new domain to enlarge the applicability of WDA framework.

Before constructing Abstraction-Decomposition Space (ADS) model, there are some import preliminary works. First, the system of analysis must be clearly determined, outlining what is considered to be the work domain in the given situation. And then the purposes for which the domain exists and whether or not the domain is also constrained by values or social organizational factors must determined.

In this thesis, the WDA will be conducted following the steps that were put forward by Naikar and her colleagues (2005).

Step 1: Establish the Purpose of the WDA

Step 2: Identify the Project Constraints

Step 3: Determine the Boundaries of the WDA

Step 4: Identify the Nature of Constraints

Step 5: Identify the Potential Sources of Information

Step 6: Construct ADS

Step 7: Validate the ADS

These steps will be considered further in this chapter.

## 4.1. Establish the Purpose of the WDA

The purpose of the WDA determines how the work domain will be modeled. The decisions that will be made in the subsequent steps, such as the decisions about the work system boundaries, will depend largely on the purpose of the analysis. The purpose of analysis will help to establish the boundaries for the WDA and decide which constraints to include in the analysis and how they can be modeled by using the framework. (Naikar *et al.*, 2005)

The purpose of the WDA in this thesis is to systematically analyze how the WRM system works, and then identify the information and their relationship that is required to guide road supervisors' decision making for WRM operations. The obtained information requirements will be used to evaluate the display design of current computer-based decision support system (e.g., MDSS), and then to inform the display design improvement.

### 4.2. Identify the Project Constraints

Project constraints are typically related to the schedule and budget (Naikar *et al.*, 2005). The project constraints of this study include:

- Staff budget constraint: there are insufficient analysts to perform this WDA and insufficient domain experts to consult.
- Schedule constraint: no field observation will be available due to the tight schedule

To deal with these constraints, the scope of the WDA for WRM will be reduced. There are three iterations when conducting WDA but in this study, only the first iteration will be conducted and the study work system will be limited to the geographical area controlled by a WRM garage instead of the area by larger WRM agencies responsible for more than one garage, and then the cooperation and communication between different garages will not be studied. Thus, the study will become less complicated but the benefits that will be obtained for WDA may be reduced.

## 4.3. Determine the Boundaries of the WDA

### 4.3.1. Perspective and Boundaries

Determining the boundaries of the WDA is to define the work system that will be the focus of the study. The boundaries of the WDA separate the work system from its environment (or its context). There is no such boundary that can absolutely isolate the work system from its context, and the changes or effects to some elements outside the work system will propagate to the elements inside the work system and vice versa (Rasmussen *et al.*, 1994). The boundary of a WDA is therefore essentially artificial divisions that are necessary for keeping the WDA within a useful scope (Naikar *et al.*, 2005).

Winter Road Maintenance has been performed in a manner where separate WRM agencies handle snow and ice activities within a defined geographical area. The complexity of the command system for snow and ice control operations is generally related to the size and responsibility of the WRM agency (Minsk, 1998). Figure 4 shows the organizational structure of a large agency and Figure 5 shows the organization structure of a small agency. There is considerable variety between those extremes. Currently, in order to solve the problem of inconsistent level of service across maintenance area boundaries and to effectively and efficiently manage winter maintenance resources over a large region, in the North Central Region of the Washington State Department of Transportation (WSDOT), consideration is being given to new structures like Figure 6, wherein one agency takes charge of a large region directly.

Figure 4, Figure 5 and Figure 6 show there are various workers at different levels in WDA domain, like road agency CEO, regional manager, garage supervisors, and truck drivers. Different workers with different duties have different perspectives for the same work system. A critical step before determining the boundaries of the WDA is to define the perspective of the domain. Considering the purpose of this WDA, in this thesis, the work system will be defined from the perspective of the workers who have the decision making responsibility for each storm, such as garage supervisors (Figure 4), highway superintendent (Figure 5), or regional storm managers (Figure 6). In the three figures, the boxes identifying the workers with ultimate authority of decision making for each storm have been shaded. Their common job is to provide the safest road surface possible through the efficient use of all available resources, and through decision making under constantly changing circumstances caused by the winter snow events.

Considering the perspective of the work system (the person with ultimate decision authority to decision making for each winter event) and the project constraints, the work system will be defined as the environment of a geographical area that one WRM garage is responsible for.

Garages are the basic functional units of WRM. Each garage is responsible for portions of roads. In the State of Iowa, the Department of Transportation has 110 garages with 879 snowplows. These garages are responsible for removal of snow and ice on 24,215 lane miles of Iowa's roadways, specifically, those roads that "belong" to the State Department of Transportation. City roads are in general the responsibility of city personnel, while County roads are managed by the County administration.

For the agencies with structures shown as Figure 6, we can consider the regional storm manager as a garage supervisor responsible for a large area, so in this case the large area would be our study work system. While it is untrue that a garage can work independently without being affected by the environment of adjacent areas, for modeling purposes it can be treated as such, and useful models of the work system will be constructed in this way. Thus, in this study, the cooperation and communication between different garages will not be considered, which will lessen the complexity of this WDA. However, it is quite clear that in reality communication between different garages (or equivalent levels of operation) can be critical to the efficient and effective execution of winter maintenance operations.

In the WDA of this WRM work system, diverse factors in this work system will be considered which include characteristics of the geographic area, weather situations, traffic conditions, pavement, natural environment, local economy, political system, road users, WRM operators, and WRM response resources (including functional capabilities and limitations of resources).

Supervisors in different WRM garages have a lot in common in their role of being the leader of the battle against snow and ice on roads by coordinating available resources, but their job is also very unique, because every road jurisdiction has a different transportation infrastructure to service. Each garage has a different mix of human resources and equipment available to fight snow and ice during winters, the roads conditions (e.g. Level of Service) and traffic conditions differ from one jurisdiction to another, and the weather conditions are different for different garages. The strategies designed to meet specific local challenges and the public expectations are also different from one garage to another. Therefore, the size, complexity and the responsibilities are various from one garage to another. For example, some garages are responsible for longer, but less traveled rural routes through farm fields while other garages are responsible for busy urban or commuter routes. While the operational objectives of these two kinds of garages is the same, providing appropriate LOS for road and thereby improving traffic mobility and safety, these two kinds of garages could use different operational strategies to achieve their common objectives.

The aim of Work Domain Analysis (WDA) in this thesis is to capture all the constraints that affect the decision making for Winter Road Maintenance (WRM) operations, so in this thesis the WDA of WRM deals with general characteristics and principles of winter road maintenance that can be applied in various garages. Thus, herein, the studied garage will not be a specific one, and accordingly the boundaries of the work system will be clearly artificial. The results based on a specific garage would not be applicable to any other garages. Therefore, the studied garage is a hypothetical one that is responsible for the WRM of a geographic area. This definition of boundary used here makes it clear that only the WRM activities *within* a garage are studied and the cooperation between different garages is not considered.

In order to insure that the analysis results are applicable for various kinds of

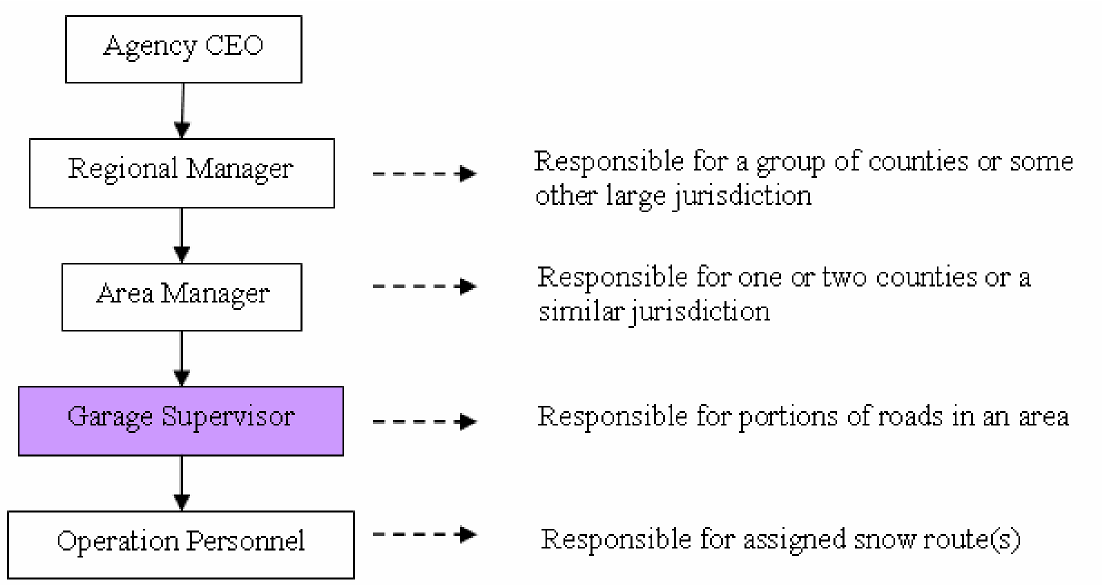


Figure 4 Organizational Structure of a large WRM Agency

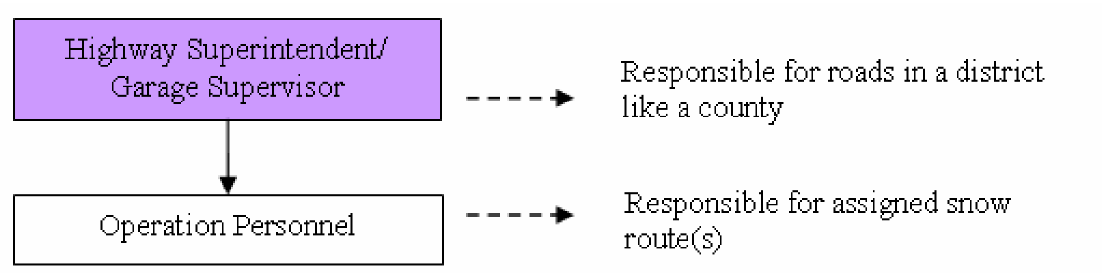


Figure 5 Organizational Structure of a Small WRM Agency

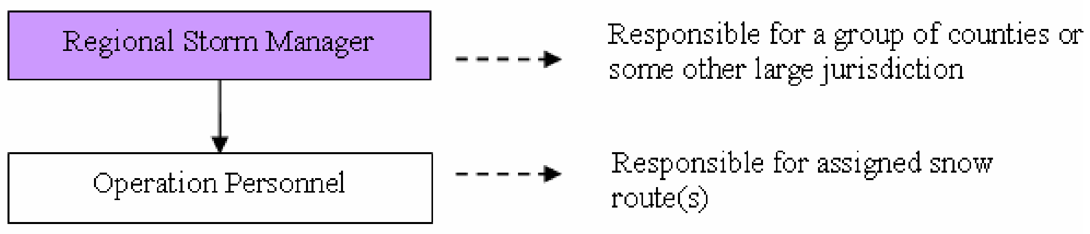


Figure 6 Organization Structure of an Agency Responsible for a Large Region

garages, some assumptions are made for this study work system as follows:

- All kinds of winter weather events could happen in this area during every single winter, including snow, freezing rain and sleet.
- This area includes roads with different Levels of Service (LOS).
- All kinds of mix of human resources and equipment are possible.

These assumptions make the model that will be developed a prototype model that can be used by any WRM garages independent of the different weather and traffic conditions a particular garage may experience.

### 4.3.2. Description of WRM work system

The activities in a WRM domain include WRM operation during winter seasons, the pre-winter preparation, and the post-winter performance evaluation.

#### 4.3.2.1. Decision Making and Operations during the Winter Season

In this study, the ultimate goal of analyzing WRM work domain is for the design and evaluation of information system that can *support WRM decision making* in real time for rapid response to dynamic winter conditions. Therefore, it is important for this study to fully understand the characteristics of the WRM decision making context and decision making process.

##### 4.3.2.1.1. Characters of Decision Making Context

WRM domain is characterized by high tempo activities and dynamically changing situations, time constraints, high stakes, inter-dependent decisions, and ambiguous information, which makes it a naturalistic decision making (NDM) environment (Orasanu & Connolly, 1993).

The contexts of NDM typically involve limited time, dynamically changing conditions (e.g., weather and road surface conditions), goal conflicts (e.g., mobility vs. safety), and information sources of varying reliability (e.g., weather forecast sources).

Decision makers may operate in team and organizational contexts, and have available tools or other information resources available to aid their decision making (Orasanu & Connolly, 1993).

The NDM process typically involves recognizing that a problem exists (e.g., a coming snowstorm) and assessing the situation to define the nature of the problem and relevant factors (e.g., the onset and severity of the snowstorm). A candidate solution (e.g., anti-icing or road closure) is recommended, evaluated and applied if it meets a criterion of adequacy (Klein, 1997). There is not usually an exhaustive evaluation of all options because decision makers' experiences also play an important role here. There are high stakes involved and a wrong decision can have severe consequences and possibly loss of life.

Figure 7 shows how the WRM system works when a winter event happens. It involves phases from gathering and interpreting road and weather information, deciding on a site-specific treatment, implementing the treatment, and monitoring and evaluating the operation. Due to the continually changing characteristics of winter weather events and road surface conditions, this decision making process is not a one-time action but an ongoing action. Appropriate and perhaps different methods will be used before, during and after the storm event (Minsk, 1998). From Figure 7, we can see when fighting adverse winter events:

- The WRM supervisors will implement a series of specific operational strategies to meet the objectives of WRM
- Various categories of information have to be considered
- The real-time data communication and update play a significant role on the success of the WRM
- The follow-up measurement of every treatment decides the next treatment decision

There are four phases for this work process, and next these four phases will be described step by step.

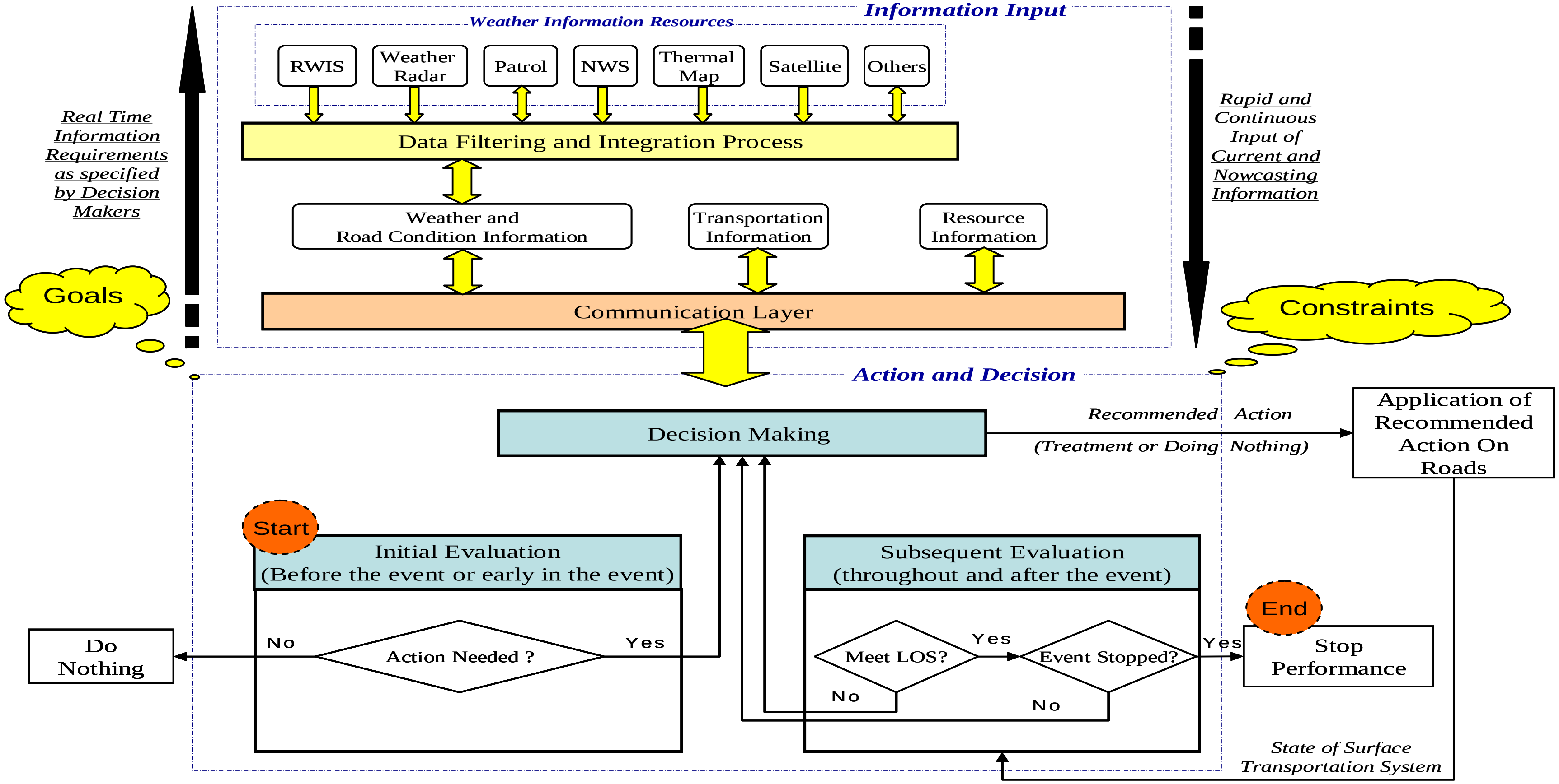


Figure 7 The Decision Making and Operation Process during a Winter Weather Event

4.3.2.1.2. WRM Decision Making Process

*4.3.2.1.2.1. Activities before the Event*

When the garage supervisor receives the first notice that a winter event (e.g. a snowstorm or black ice/frost) is coming and may affect the maintenance area, they should start assembling information about the nature and characteristics of the anticipated event. The information includes weather forecast, weather radar data, satellite data, local road condition and Road Weather Information System (RWIS) data, pavement temperature forecasts, and any RWIS data from areas outside the immediate maintenance jurisdiction that might have already have been affected by the approaching storm. Then, all the information assembled will be reviewed to estimate when and where the event will begin, its extent and severity. (Ketcham *et al.*, 1996)

After the information review, the decision on whether or not to initiate a treatment, when to start it and what type of treatment to apply will be made. The decision is based on when precipitation is expected to start, what form it will be, the probable air and pavement temperatures, the anticipated trend of the temperatures, the expected sky condition, the wind speed and direction, and the intended timing of the treatment. Most of the information is forecast information, so the accuracy of the information is a critical factor for initial the treatment decisions (Ketcham *et al.*, 1996).

In addition to weather information, the WRM decision makers also should be provided with other information such as pavement conditions, traffic information, equipment resources and their availability, personnel resources, and materials resources (as discussed above). All these factors influence choice or timing of the initial operational treatment.

A typical initial operation is an anti-icing treatment with the application of a chemical freezing-point depressant (either as a liquid or a pre-wet solid) to the pavement before enough snow has accumulated to keep the chemical for reaching the pavement. (Ketcham *et al.*, 1996)

*4.3.2.1.2.2. Activities during the Event*

It is very important that pavement and weather conditions, weather forecast updates, and RWIS data be closely monitored after the initial operation has taken place, and this monitoring process should continue to be conducted during the whole winter event and after the event. Special attention should be paid to pavement temperature and trend, and to changes in precipitation type and intensity. In addition to depending on technologies like RWIS, visual observation is also an important tool for monitoring and making operational decisions. Additionally, the use of on-vehicle pavement temperature sensors has proven to be a popular, and reportedly very effective, tool for monitoring road condition in real-time. During the operational period, information on road conditions, progress of operations, and projected road conditions are reported by operators and patrolling supervisors. Some experienced trained maintenance personnel are able to judge the severity of conditions and to make or recommend corrective action. (Ketcham *et al*., 1996)

During the winter event, the evaluation of treatment effectiveness is very important because its results decide whether a subsequential treatment is needed. For the evaluation, many information resources are needed. In addition to the visual observations of precipitation/weather and pavement conditions from patrols, the indication or the measurement of chemical concentration on the pavement and the measurement of frictional resistance to sliding are also necessary for treatment effectiveness evaluation. All subsequent recommended snow and ice treatments are made based on atmospheric and pavement conditions at the time of treatment and on how these conditions are expected to change over the time period prior to the next anticipated treatment. As the storm and storm fighting efforts continue, there are usually cycles of plowing followed by the spreading of materials.

*4.3.2.1.2.3. Activities after the Event*

Even after the event has stopped, the monitoring process and the evaluation of treatment should be continued until the after-event LOS of the roads is achieved. For example, in some cases, although the event itself has stopped, the melted snow and ice may refreeze and cause a slippery road surface if the pavement/air temperature is low. The post-storm activities are almost as important as the primary operations of plowing and spreading. They can significantly minimize hazards to the traveling public (AASHTO, 1999). Such activities include melt water control, clean up of special roadway features, handling and disposal of snow/ice/abrasive, and so on.

*4.3.2.1.2.4. Evaluation after the Event*

There is a very important phase that is not represented in Figure 7—post-event evaluation. Post-event evaluation is almost as important as the pre-event planning and decision making during the event. After a snow and ice operation shown in Figure 7 is completely finished, a post-storm evaluation of the whole operation should be conducted. This evaluation would be very beneficial because lessons can be learned from both the successes and the failures of any winter maintenance operation. Improvements in operations and equipment can be identified and implemented through a post-storm assessment of the practices and treatments used. In addition the assessment can identify needs for subsequent storms.

The provision of a good WRM operation during the winter season also depends on the proper pre-winter planning and preparation for winter operations, and post-winter performance evaluation.

4.3.2.2. Pre-winter Preparation

In the WRM work system, planning and preparing for winter operations, if done properly, will make the WRM operation more efficient and effective. Much work should be done before the onset of winter weather. The following are some examples of the work: (Minsk, 1998)

- Check material and equipment inventories
- Make sure that communications channels are functioning, and traffic rules and regulations are in place, ready to be invoked on ice- or snow-affected streets
- Train and indoctrinate personnel

- Analyze dry runs of various operations and make last minute adjustments
- Make sure all items of equipment have been serviced and fitted with the necessary attachments, and multipurpose equipment has been refitted for winter duty
- Verify that contracts have been signed with suppliers of materials and equipment

#### 4.3.2.3. Post-winter Performance Evaluation

Seasonal Performance evaluation can assist management in judging the impact of resource levels, training, public relations efforts, litigation, and other management issues. It is a valuable management tool used to assure continuous improvement and justify resource investment. There are a number of tools and techniques that can assist in developing a performance evaluation program, such as accident analysis, management debriefings, and recording keeping.

Therefore, when conducting WDA for WRM work system, in order to capture the constraints of the whole system as completely as possible, all the aspects, from pre-winter preparation, winter operation (including activities before the event, activities during the event, activities after the event, and evaluation after the Event), to post-winter performance evaluation should be considered in the WDA for WRM.

### 4.4. Identify the Nature of Constraints

This step is to identify where the work system falls on the causal-intentional continuum. Defining the location of the work system along this continuum provides clues to the nature of the constraints that should be modeled in the WDA (Naikar, 2005). Rasmussen (1994) describes five categories of work systems in terms of the role that human intention plays in the systems, as shown in Table 5 ranging from highly causal to highly intentional, which can be used as a basis for considering where on the causal-intentional continuum a work system falls.

According to the characteristics of WRM work system, WRM work system falls under the middle category – *systems governed by actors' intentions* that are characterized by work situations where users may act autonomously but within social constraints. This category of work systems are also referred to as *less-tightly coupled work systems* (Rasmussen *et al.*, 1994). In WRM work system, the garage supervisor has control over a collection of resources, such as weather information, material, personnel, and equipment resources, but does not have direct control over the entire work domain, That is, incidents or accidents that are out of the control of garage supervisors can occur within the WRM work system, such as adverse weather events or a traffic accident caused by a slippery road condition. Garage supervisors have resources available to mitigate the impact of incidents or accidents, but do not have control over the elements that caused the incidents or accidents, such as the winter weather. This lack of complete control is an inevitable characteristic of *less-tightly coupled work systems*. This category of systems has following characteristics (Naikar, 2005):

- *Production* in these work systems is based on the organization, work practices, and accepted rules of conduct of the staff, and on the resources supplied.
- *Intentionality* in these work system is defined by policies, plans, legislation, and other forms of regulation in the organization, social laws and conventions, and individual workers' intentions and motives. The workers and the system can therefore be seen as sharing control.
- Although work systems in this category have physical constraints associated with man-made objects and tool (such as equipment and material used for snow and ice removal), it is usually *not possible to predict* the outcomes on the basis of physical constraints alone.
- *Causality* is represented through the decisions and activities of the workers, and the workers' execution of those decisions, instead of mathematical relationships as in nuclear power plant that falls under the left most work systems in Table 5. Individual workers' motivations and intention often influence outcomes as they seek to respond to events within their areas of the system. Therefore, the outcomes are largely determined by intentional constraints.

## 4.5. Identify the Potential Sources of Information

This step is to identify the potential sources of information for constructing the ADS (Abstraction-Decomposition Space). There are three major source of information.

The first source of information for constructing the ADS is documents relating to the work system (Naikar, 2005). In this study, the documents relating to WRM include operation manuals, operational guide books, DOTs' or counties' annual operation report, project reports, textbooks, commercial brochures, academic papers, policy documents, training manuals, operational records, operational procedures, accident reports and some other materials available.

The second source of information for constructing the ADS is the work setting itself (Naikar, 2005). Multiple field observations should be carried out to develop a general understanding of the work system first, and a more detailed understanding of particular aspects of the work system later (Naikar, 2005). Due to the project constraints of this research, there is not enough time and budget to carry out field observations. The type of winter weather events that will occur in a winter is unpredictable, so in order to obtained the understanding of WRM at general and particular levels, it will take several years to observe all operations for different kinds of weather events. In this study, the training video tapes of field operation and WRM garages' operation logs will be used to replace field observations.

The third source of information for constructing the ADS is domain experts. Much valuable information can be elicited by interviewing the experts or involving them in walkthroughs, talkthroughs, or table-top analyses (Naikar, 2005).

## 4.6. Construct ADS

As part of the aim to examine the feasibility of the technique for the WRM domain, work domain models will be developed here for a WRM garage.

Table 6 is a basic work domain analysis for Winter Road Maintenance with a standard format of Abstraction-Decomposition Space tool. The WRM work system is a complex one with elements in different aspects so if all the elements were included in

Table 5 The Five Categories of Work Systems Ranging from Highly Causal to Highly Intentional (Rasmussen *et al.*, 1994)

| Categories of work systems | Automated systems governed by laws of nature | Mechanized systems governed by rules of conduct | Systems governed by actors' intentions | Systems governed by actors' personal objectives | Systems for the autonomous, casual user |
|---|---|---|---|---|---|
| Examples | Industrial process plants e.g., nuclear power plants, chemical production plants. | Manufacturing systems based on mechanized work. | Hospitals, offices, and manufacturing systems based on manual work. | Public service systems e.g., research institutes, universities. | Information systems for the general public e.g., websites. |
| Production | Functionality is based on physical processes that are constrained by technical equipment. | Functionality is based on mechanized processes that are constrained by technical equipment. | Functionality is based on the organization, work practices, and accepted rules of conduct of the staff, and on the resources supplied. | Functionality is based on individual actors' personal objectives and work practices and on the resources supplied. | Functionality is based on users' personal objectives and work practices and on the tools supplied. |
| Intentionality | Intentionality is embedded in automatic control systems and in formal operating procedures and represents the designers' operational objectives. The task of the staff is to ensure that the functioning of the automatic control system is consistent with the designers' operational objectives. The personal goals and preferences of the staff are of little significance. | Centrally planned and scheduled manufacturing systems: intentionality is embedded in rules of conduct. Flexible and discretionary manufacturing systems: intentionality is defined by high level management objectives and by staff who make daily operational decisions to fulfill those objectives. | Intentionality originates from the interpretation of environmental conditions and constraints by high-level management which then becomes implemented in more detailed policies and practices by staff at intermediate levels. Staff at intermediate levels still have many degrees of freedom that are resolved in light of situational factors and subjective criteria. | Intentionality is defined by individual actors within the space determined by institutional constraints such as high-level institutional objectives and resources. | Intentionality is defined by individual users and their goals, values, and preferences at the time of use within the constraints of the tools supplied. |
| Sources of regularity | Causal constraints based on the laws of nature. | Causal constraints based on the laws of nature, which govern the operation of the technical equipment, and intentional constraints based either on preplanned schedules and formal or informal rules of conduct, which govern the staff's decisions, or on management objectives. | Intentional constraints based on organizational policies, plans, legislation, and other forms of regulation; social laws and conventions; and actors' intentions or motives. | Intentional constraints based on high-level institutional objectives; social laws and conventions; and actors' personal objectives. | Intentional constraints based on individual users' goals, values, and preferences. |

this table, this table would be a huge one and it will be beyond scope of this paper so the contents in each cell are very general.

In Table 6, in the horizontal direction, the WRM work environment is divided into three levels of decomposition. The first level is the whole WRM system. At the second level of decomposition hierarchy, subsystem, the whole WRM system is divided into three subsystems--pre-season preparation, in-season operation and post-season performance evaluation. The in-season operation is further divided into three sections -- before the storm, during the storm and after the storm. At the third level of decomposition, the WRM work system is described by the components like snow plow, sensor, truck, computer, worker and so on. In the vertical direction, the WRM work environment is divided into five levels of abstraction with the lower levels providing the means for achieving the higher level purposes.

Table 6 is a Work Domain Analysis of Winter Road Maintenance operation with a standard format with both levels of abstraction and levels of decomposition, but this format is not convenient to connect the elements at different abstraction levels to show the means-end connection between elements. Therefore, Table 6 is transferred to the format shown as Figure 8. This format is frequently used by other WDA application studies to report their WDA results. Figure 8 shows a schematic representation of the model for WRM domain. In order to save space, the content in each box has been shortened. Due to the limited space, every object-related process is substituted by a number and its specific content is list below.

1. Planning and organizing resources
2. Ordering and storing Product
3. Ordering and preparing equipment
4. Organizing snow disposal;
5. Identifying and reviewing salt vulnerable areas
6. Preparing communication strategies
7. Recording
8. Information gathering

9. Formulating actions
10. Implementing actions
11. Cleaning
12. Coordinating actions
13. Training
14. Monitoring
15. Informing public

In this chapter, a Work Domain Analysis (WDA) on Winter Road Maintenance (WRM) has been conducted following the steps put forward by Naikar *et al*. First, the purpose of this WDA has been established, which determines how the model will be developed. Next, the project constraints were identified. Due to these project constraints, the scope of this analysis is necessarily limited. At the third step, the boundaries of the WDA were determined and a detailed description of WRM work system within the boundaries has been given. In the next step, the nature of constraints of the WRM work system was identified. This identification defines where the WRM work system falls on the causal-intentional continuum, which in turn indicates the nature of the constraints that should be modeled in the WDA. Step five identifies the resources of information that will be used to develop the model. Based on all the above steps, the WDA is conducted by using ADS as modeling tool. It has first been given in the standard format of ADS and then in order to make connections between elements at different levels easier, it has been transferred to the format of Figure 8.

While the links shown in Figure 8 are entirely consistent with both the literature and the practice of WRM, they are not the only possible links that could be considered. Part of the further work, based on this study, would be an optimization-based investigation of all possible linkages. Such an investigation is beyond the scope of the current study.

There are many elements at each abstraction level. In chapter five, the meaning of each abstraction level and detailed descriptions of elements at each level will be given.

Table 6 The Abstraction-Decomposition Space (ADS) Model of Winter Road Maintenance (WRM) Work System

| | Whole System | Subsystems | | | | | Components |
|---|---|---|---|---|---|---|---|
| | | Pre-Season Preparation | In-Season Operation | | | Post-Season Evaluation | |
| | | | Before the storm | During the Storm | After the Storm | | |
| Functional Purpose | Mobility and Safety | | | | | | |
| Value & Priority Measures | LOS; budget; environmental concern; public satisfaction | | | | | | |
| Purpose-Related Functions | Preparation/planning; Operation; Communication; Evaluation | | | | | | |

Table 6 – Continued

| | Whole System | Subsystems | | | | | Components |
|---|---|---|---|---|---|---|---|
| | | Pre-Season Preparation | In-Season Operation | | | Post-Season Evaluation | |
| | | | Before the Storm | During the Storm | After the Storm | | |
| Object-Related Processes | | Planning and Organizing Resources; Ordering and Storing Product; Ordering and Preparing Equipment; Organizing Snow Disposal; Preparing Communication Strategies; Identifying and Reviewing Salt Vulnerable Areas; Training the Personnel. | Gathering Information; Formulating the Action Plan; Monitoring Variables That Affect Road Conditions; Implementing Proactive Operation; Keeping the Public Informed; Recording | Coordinating Chemical and Mechanical Removal of Snow and Ice; Monitoring Variables That Affect Road Conditions; Keeping the Public Informed; Recording | Cleaning the Snow From the Streets; Operating the Snow Disposal Site; Evaluating the Result of Snow and Ice Removal Activities; Recording | Decommissioning the Snow Disposal Site; Cleaning Up the Maintenance Yard; Completing the Record-keeping and Reporting; Training the Personnel. | |
| Physical Objects | | | | | | | Personnel; Equipment; Resources; Sensors; Computers; Transportation infrastructure Geographic Feature; Snow Disposal Sites; Chemical Storage Site |

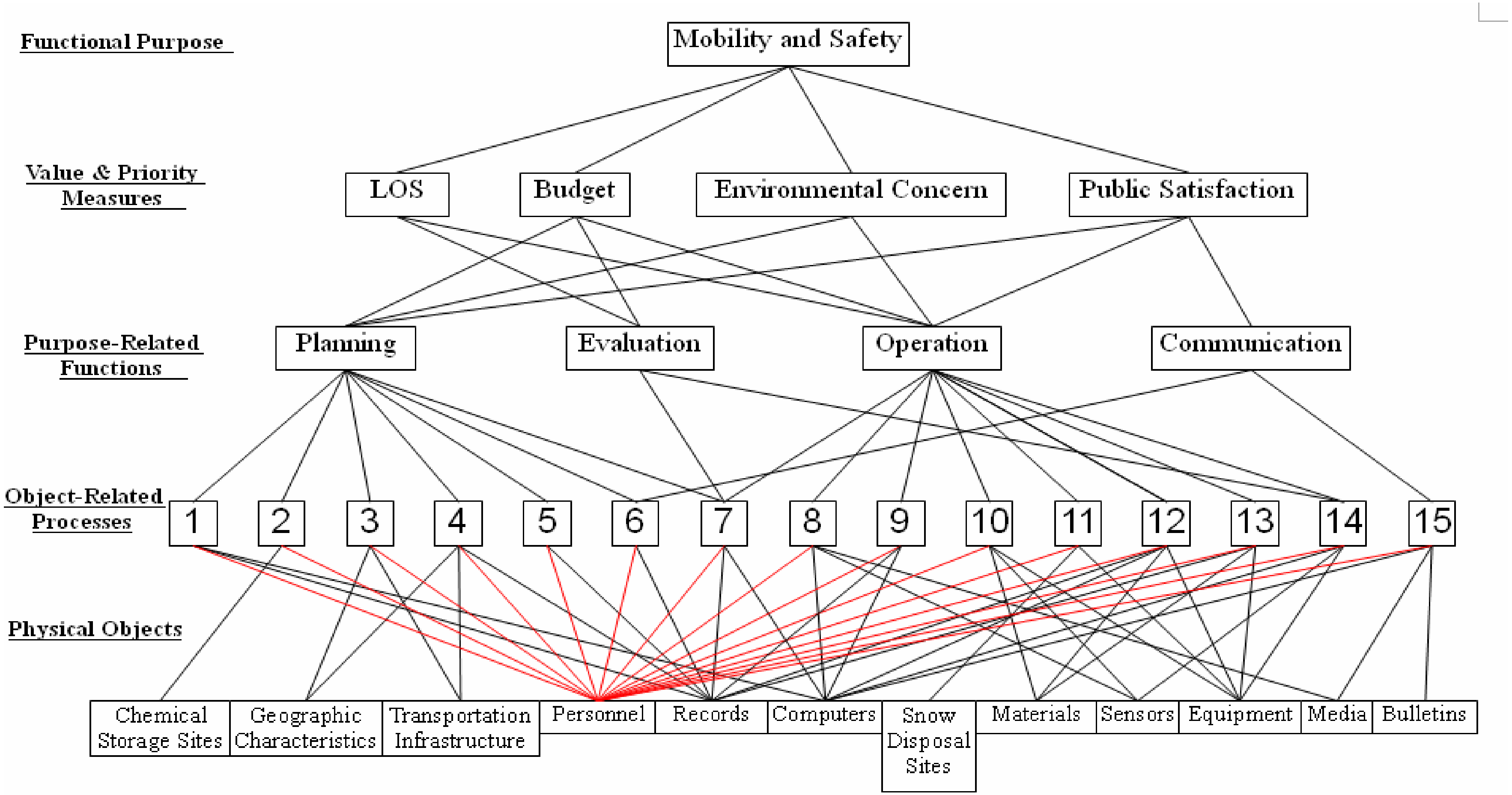


Figure 8 Abstraction Hierarchy of Winter Road Maintenance Work System

# CHAPTER V
# DESCRIPTION OF EACH LEVEL OF ABSTRATION HIERARCHY OF WINTER ROAD MAINTENANCE

As an intentional system, the WRM work environment is constrained by values, priorities, and rules and practices (e.g. assignment of equipments and staff according to the roads' Level of Service). There are also causal constraints in this model, such as the balance and function of resources. All these constraints co-exist in the same WRM work environment.

The WRM supervisors need information about different aspects of the WRM work environment and various levels of abstraction to dynamically make decisions on the allocation of resources and prioritization of emergencies. A discussion of each abstraction level within the work environment is given herein.

## 5.1. Functional Purpose

Functional Purposes (FP) are the purposes across the work domain and they are the purpose for which the system exists. The FP of the WRM work system is to provide safety and mobility for the traveling public effectively and efficiently in winter adverse weather.

During winter, snow and ice on roads may create hazardous road conditions, and thus significantly impact the surface transportation system. Many studies have proven that winter storms have great impact on traffic mobility and safety.

Hanbali and Kuemmel have investigated the relationship between winter storms and traffic volume reduction, using traffic volume and weather data from at least the first three months of 1991 at 11 locations in four states. Traffic volume reductions were calculated for different ranges of total snowfall, average daily traffic, roadway type, time of day, and day of the week. The calculation results show that the traffic volume reductions caused by winter storms ranged from 7 to 56 percent (Hanbali & Kuemmel, 1993). Nowadays, many goods and services are based on just-in-time delivery, so such a disruption in traffic mobility can brings considerable economic loss.

Some researchers have explored the relationship between adverse weather and safety. For example, it has been found that total injuries and fatalities increased by 25 percent and the rate of injuries and fatalities increased by 100 percent on snowy days (Perry & Symons, 1991).

Therefore, effective and efficient WRM efforts must be made to minimize the impact of winter weather on traffic, that is, to maximize mobility of the traveling public, and minimize crashes due to winter traveling conditions. As mentioned in the background information section of this thesis, state and local agencies spend more than $2.5 billion on snow and ice control operations each year (FHWA, 2003), not including indirect costs due to accidents, lost productivity and delay, and environmental costs.

After several decades of WRM practice, more and more advanced technologies and techniques have been introduced to the WRM field and WRM efforts have achieved, in many cases, desirable results. According to some university studies (Hanbali, 1994), during the first hours after initial application of salt application, the public receive $6.50 in benefits for every dollar spent on snow and ice removal. Other studies demonstrate how snow and ice removal significantly reduce fuel consumption, lost wages for employees arriving late to work and losses of shipment of goods, plus traffic accidents, injuries, fatalities and property damages are reduced dramatically after deicing roadways. For example, Hanbali found a significant decrease in crash rates as a result of deicing maintenance activity (1994).

### 5.2. Purpose-related Functions

Purpose-related Functions are the general functions that must be carried out in the work domain in order to achieve the functional purpose. For a WRM domain, these purpose-related functions would be preparation/planning, operation, communication, evaluation.

The goal of WRM Operations is to develop and implement the appropriate winter maintenance strategy based on best practices.

The principal objective of WRM communications is to ensure that the citizens of the city or region understand the service levels provided.

Preparation and planning can make WRM efforts more efficient and effective. The better the preparation and planning is, the more time will be saved during fighting snow and ice in the winter.

Evaluation is conducted both after each event and after each winter. Lessons can be learned from both the success and failures of any winter maintenance operation. It is a valuable management tool used to assure continuous improvement and justify resource investment.

### 5.3. Value and Priority Measures

The level between the Functional Purposes and the Purpose-related Functions is the level of Value & Priority Measures. These measures indicate how well the Purpose-related Functions are achieving or serving the Functional Purpose.

Most of the early applications of the ADS related to the process control system, such as thermodynamic systems, so this level was often presented in terms of mass and energy balance. However, when applying ADS to Winter Road Maintenance domain, an intentional work system instead of a causal system, it will make no sense to describe the system solely in terms of mass and energy, because the WRM kind of system is governed mainly by workers' intention and social laws rather than physics (Hjdukiewicz *et al.*, 1998).

Winter Road Maintenance is a complex system consisting of a variety of elements. The degrees of importance of the elements vary with the size of the operational jurisdiction it covers and the complexity of its road network. However, Level of Service (LOS), budget, environmental concern and public satisfaction are important for all road agencies.

Winter Road Maintenance activities are very costly to road authorities and users and potentially to the environment, so budgetary constraints increasingly become a center of focus, while at the same time customers seem to demand more service. Yet more service, especially related to the use and storage of chemicals, can potentially impact the environment in additional ways. (FHWA 1996) Therefore, WRM supervisors have to try to use their limited available budget effectively to achieve desirable LOS during winter while minimizing the impacts on environment and maximizing public satisfaction. For the ADS of WRM work system, the level of Value & Priority Measures is all about balancing these four competing priorities.

### 5.3.1. Level of Service (LOS)

WRM is a Level of Service (LOS) driven activity. Snow and ice Control programs establish LOS that satisfy (in the ideal) the customers and is attainable within available budget and resources.

In traffic engineering, the LOS is an estimate of congestion and performance of the transportation system. Letters are designated from A (best) through F (worst) based on national methodology and standards. The following table is the level of service rating signalized and unsignalized intersections. This table is from Highway Capacity Manual (TRB 2000). There are different LOS ratings in terms of different aspects of traffic system.

**Level of Service Ratings for Signalized and Unsignalized Intersections**

| LOS Rating | Average Delay for Signalized Intersections (seconds/vehicle) | Average Delay for Unsignalized Intersections (seconds/vehicle) |
|---|---|---|
| A | 0 – 10 | 0 – 10 |
| B | > 10 – 20 | > 10 – 15 |
| C | > 20 – 35 | > 15 – 25 |
| D | > 35 – 55 | > 25 – 35 |
| E | > 55 – 80 | > 35 – 50 |
| F | > 80 | > 50 |

Figure 9 An Example of LOS Rating of Traffic Engineering

LOS in the context of WRM refers to a set of operational guidelines and procedures that establish maintenance activities associated with the prevention and removal of snow and ice from roadways, such as the timing, type, and frequency of snow and ice treatments. (Guide, TSM). LOS generally establishes a prescribed end-of-storm condition, intermediate stages acceptable while obtaining that condition, or the frequency of snow and ice control maintenance operations.

Usually, the LOS of Winter Road Maintenance is determined by traffic volume, the road classification, and importance of the corridor for access, such as emergency route, truck route, economic corridor, school bus routes, transit routes, high accident/problem locations, commercial/business locations, health facilities, fire house locations and school.

The level of snow and ice control service is defined in different ways by road agencies. Some agencies use description of road condition. For example, the Washington State Department of Transportation (WSDOT) defines LOS by describing the expected condition after treatments completed as Figure 10. This table can be found on the website of WSDOT.

Some agencies prefer to specify only the coverage time periods for snow and ice operation. For example, the LOS definition of the Colorado Department of Transportation (CDOT) is twenty-four-hour coverage for roads with more than 2,000 vehicles on average daily and fourteen-hour coverage for roads with less than 2,000 per day.

There are a variety of ways to determine the attainment or non-attainment of LOS. The most popular one is a visual approach. It is based on visual observations of pavement conditions by either operators or supervisors. Examples of visual characterization of road surface are “centerline bare,” or “loose snow covered.” In addition to the visual approach, indices have also been developed to measure LOS during or/and after the winter event. Report cards of customer satisfaction surveys, friction measurements and some other methods have also been used to decide the attainment of LOS.

| Expected Season LOS | Expected Road Condition after Treatment Completed | |
|---|---|---|
| A to B | Snow or ice buildup encountered rarely. Bare pavement attained as soon as possible. Travel delays rarely experienced. |  |
| B To C | Snow or ice build up encountered at times but infrequent. Travel at times may experience some isolated delays with roads having patches of black ice, slush, or packed snow. |  |
| C to D | Snow or ice buildup encountered regularly. Travel likely to experience some delays with roads having black ice or packed snow with only the wheel track bare. |  |
| D to F | Compact snow buildup encountered regularly. Traveler will experience delays and slow travel. |  |
| N/A | Closed periodically or for the duration of the winter season. | |

Figure 10 The LOS Definition of WSDOT

### 5.3.2. Budget

With today's tightening budgets and increased road maintenance needs, there is an increasing concern of how to meet WRM LOS objectives with limited dollars. Due to limited material and manpower resources that result from this shortage of money, it is not practical for road agencies that all roads meet their highest LOS at once, so agencies must prioritize their efforts. Generally, in severe storms or when resources are not enough to service all roads, snow and ice operation may concentrate on roads with higher LOS. However, in some emergent cases, field supervisors can assign trucks to the road with problems regardless of road's LOS. For example, a lower LOS road might be in danger of becoming impassable due to traffic accidents or the shortage of trucks or drivers, while a higher LOS road is providing adequate service. The truck assigned to the higher LOS road can be temporarily assigned to the lower LOS road to relieve the problem.

### 5.3.3. Environmental Concern

In addition to LOS objectives and budget, the environmental concern should also be considered in design of any snow and ice control program. The traditional methods to remove snow and ice on the roads are applying solid salt as a primary chemical deicer and sand as an abrasive for better traction. (Tierney & Silver, 2000).

In past years, the application of chemical and sand has helped maintain effective traffic mobility and safety in adverse winter weather conditions, but a major concern in using chemicals and sand for winter road maintenance is environmental impact. Studies showed that soils, vegetation, water, highway facilities, and vehicles may be affected by the chemical used in winter road maintenance (WTIC, 1996). Sand, as well as other abrasives, may create air quality or dust concerns, clog drainage features along highways (e.g. catch basins, gutters, ditches, etc.), and may pit or crack windshields. Therefore, WRM supervisors and operators should maintain a special environmental awareness and sensitivity in the use of chemicals and abrasives and procedures for snow and ice control.

Thus, for the successful design of WRM program, road supervisors must adjust the relationship of various priorities to achieve a compromise between: desirable service level of roads, available budget and environmental concern (Jelisejevs, 2005).

#### 5.3.4. Public Satisfaction

The traveling public is the ultimate user of the surface transportation system. People rely on the system as commuters, tourists, and consumers. In addition, police, fire fighters, school transportation systems, and emergency medical service providers, along with many others rely on the transportation system to meet the vital needs of the public. Therefore, the traveling public is also the ultimate service object of WRM activities and the degree of traveling public satisfaction is one of important measures that can be used to decide how well the snow and ice removal program works. Currently, the WRM divisions of different state DOTs are constantly striving to improve customer service in winter for the driving public.

### 5.4. Object-related Processes

The Object-related Processes level describes the "physical" processes that the objects serve in order to achieve the purpose-related functions. For a simplified example, at the physical object level of a WRM system, there are computers. The objected-related process of a computer during operation (a purpose-related function) is to gather information, monitor variables and formulate action plans. However, during evaluation (a purpose-related function), this same computer can serve the physical process of recording data.

Good pre-season preparation is as important as in-season operations, and it is the key to effective winter road maintenance operations. The more can be done before the winter comes, the more time can be saved in the winters to focus on the immediate tasks at hand. Pre-season preparation begins with the end of the previous winter. Pre-season objected-related processes include planning and organizing resources; ordering, storing, and handling product; ordering and preparing equipment; organizing snow disposal; preparing communications strategies; identifying and reviewing vulnerable areas; keeping the public informed; and training WRM personnel.

In-season activities are divided into three sections: before the storm, during the storm, and after the storm.

- Before the storm, the objected-related processes include gathering information, formulating action plans, and monitoring variables that affect road conditions and implementing proactive operation.
- During a snowstorm, the activities that have been planned and prepared for in the off-season and before the storm are put into action. During the storm the focus is on coordinating chemical and mechanical removal of snow and ice, and monitoring variables that affect road conditions.
- After-the-storm activities are almost as important as the primary operations of plowing and spreading. After-the-storm the objected-related process include cleaning the snow from the streets, operating the snow disposal site, and evaluating the result of snow and ice removal activities.

The post-season object-related processes include decommissioning the snow disposal site, cleaning up the maintenance yard, completing the record-keeping and reporting and training the personnel.

### 5.5. Physical Objects

The last level of Abstraction Hierarchy is the Physical objects that afford the object-related processes and their associated configuration such as size, shape, color, and location. In Table 6, at this level, due to the limited space, only some general information is given, such as the name of components. In a full deployment of this system, more detail information, such as the type of truck, sort of plow, and location of chemicals, should be listed. For example, equipment is listed at this level, but more information of equipment should be detailed at this level. Table 7 lists the types of some equipment. At this level, there is a large variety of equipment and all the different equipment types serve specific purposes.

Table 7 Types of Some Equipment

| Equipment | Type |
|---|---|
| **Vehicle** | Trucks; Motor Graders; Loaders; Snow Blowers; Mobile Conveyors; Snow Melters |
| **Plows** | Front Mounted; Front Mounted One-Way; Front Mounted Reversible; Underbody All Way; Wing/Wing-Plow |
| **Plow blade** | Rubber; Plastic; Sliding Blade Segment; Steel With Tungsten Carbide Inserts; Shoes and Tripping Mechanism; Castors; Wear Edges |
| **Spreader** | Hopper; Tailgate; New Multipurpose; Zero Velocity; Reverse Dumping; Dual Dump; Electronic Controllers |

## 5.6. Conclusion

In this chapter, each abstract level of WRM has been described. In ADS, each level is a description of the whole working system, so this chapter gives description of the Winter Road Maintenance from five views—functional purpose, value and priority measures, purpose-related functions, object-related process , and physical objects. The tradition way of describing WRM working system is mainly about the description of processes and activities, like the description in section 4.3.2. The traditional description of WRM is fourth level description of the five levels of ADS model of WRM, the object-related process level.

In the tradition way of WRM working system description, the whole WRM process is divide into parts as shown in Figure 9. Table 8 is the fourth level description of ADS model that is excerpted from Table 6.

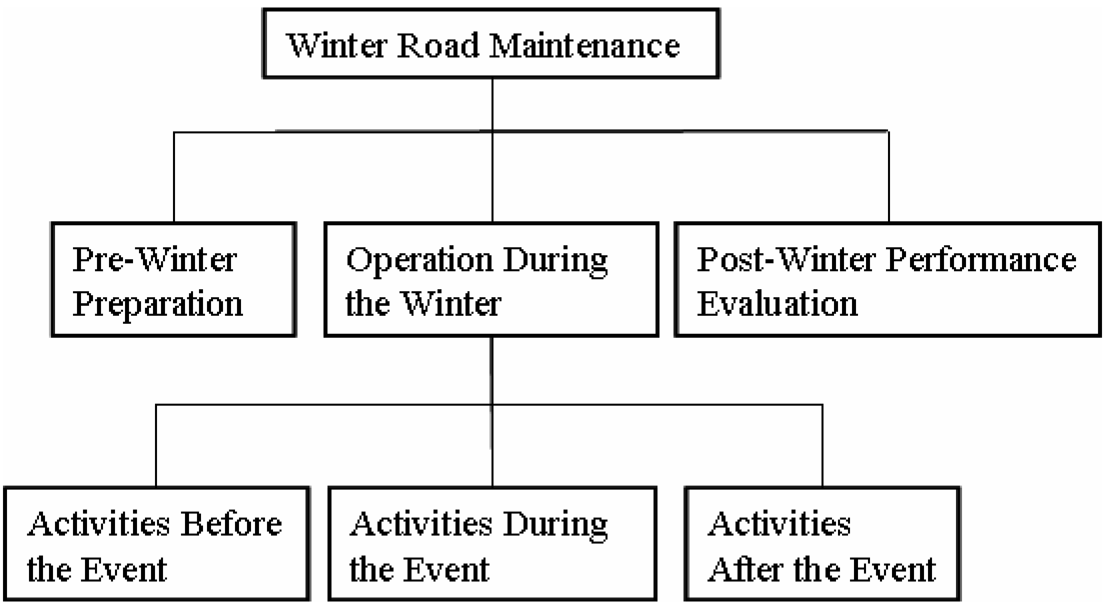


Figure 11 Structure of Traditional Description of Winter Road Maintenance System

From the comparison, it can be concluded that the description of the work system by the tradition way is only a part of the ADS presentation of the work system.

This new model gives the description in five abstract levels and the relationships between different components at different level are presented by the means-end links. The benefits of the structure links will be discussed in the next chapter.

Table 8 The Fourth Level Of the Abstraction-Decomposition Space (ADS) Model of Winter Road Maintenance (WRM) Work System

| | Whole System | Subsystems | | | | | Components |
|---|---|---|---|---|---|---|---|
| | | Pre-Season Preparation | In-Season Operation | | | Post-Season Evaluation | |
| | | | Before the Storm | During the Storm | After the Storm | | |
| Object-Related Processes | | Planning and Organizing Resources; Ordering and Storing Product; Ordering and Preparing Equipment; Organizing Snow Disposal; Preparing Communication Strategies; Identifying and Reviewing Salt Vulnerable Areas; Training the Personnel. | Gathering Information; Formulating the Action Plan; Monitoring Variables That Affect Road Conditions; Implementing Proactive Operation; Keeping the Public Informed; Recording | Coordinating Chemical and Mechanical Removal of Snow and Ice; Monitoring Variables That Affect Road Conditions; Keeping the Public Informed; Recording | Cleaning the Snow From the Streets; Operating the Snow Disposal Site; Evaluating the Result of Snow and Ice Removal Activities; Recording | Decommissioning the Snow Disposal Site; Cleaning Up the Maintenance Yard; Completing the Record-keeping and Reporting; Training the Personnel. | |

# CHAPTER VI

# LINKS BETWEEN LEVELS OF ABSTRACTION HIRACHY OF WINTER ROAD MAINTENANCE

## 6.1. The Invariability of the Links

The lines connecting the goals through to the objects in Figure 8 are the structural links of the system. These structural links are known as invariants - they do not change despite changes in the environment, and they are the relationships between objects, the processes, and system goals that exist regardless of how we view the process.

For example, in mountain areas, the WRM staffs have to deal with heavy snowfalls, but in the Midwest, like Iowa, the winter weather events are light snowstorms, periods of moderate or heavy snow, freezing rain storms and sleet storms. The WRM treatments and equipments used in these two types of areas must be different, but all the links in ADS model work the same way for both of these two areas in spite of the differences.

Figure 10 shows six links in this model. The characteristics of geography and transportation infrastructure are two factors that decide the types of equipments that will be ordered and prepared for WRM and the methods of snow disposal. The appropriate selection of equipment and snow disposal method can help agencies optimize their budget.

In Figure 10, the links between the bottom two levels reveal that the nature and range of tasks and the environment determine selection of appropriate equipment. For the mountain areas where heavy snowfalls occur frequently, snow and ice control operation is a very difficult and challenging task for road agencies, so agencies in the mountain areas should purchase equipment with snow and ice control operation as its main function over its service life , like some specialized wheeled or tracked vehicles designed specifically for the task of clearing snow or removing ice. For the Midwest areas where snow and ice only happen in winter, snow and ice control operation is the main task of road agencies only in winter, multiple-purpose equipment, like conventional dump trucks, should be purchase, so the equipment also can be used for other tasks during non-winter seasons. Appropriate preparation and ordering of equipment will help agencies optimize their equipment budget, which is what links between the upper two levels in Figure 10 has shown.

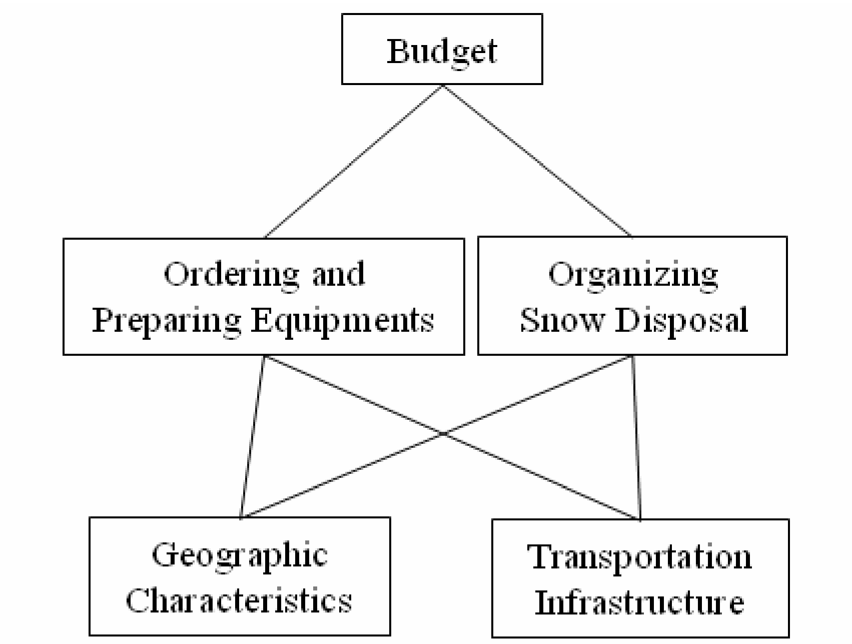


Figure 12 The Invariability of Links

In the United States, roads are owned and operated by state and local agencies, so the Winter Road Maintenance operation of different agencies may vary because of the climatic conditions, agency resources, roadway characteristics, geographic characteristics, and traffic pattern. However, this ADS model can be tailored to all road agencies with their own condition because of the invariability of the links.

### 6.2. The Diagnostic Purposes of the Links

The structural links can also be used for diagnostic purposes. In complex causal systems like electricity generation which have many interrelated sub-functions, the failure of one physical component can result in performance anomalies in several related processes which rely on that component. The effects of the failure are subsequently manifested in the performance of the higher constraints. Diagnosis of which component has failed becomes simpler because of the ability to trace the effect to the cause via the structural links or invariants.

These diagnostic purposes of these structural links also can be applied to an intentional system like WRM system. For instance, by following the links, one WRM supervisor can predict that if there are inaccuracies in one WRM activity, the effect on the whole WRM system will be delays or disruptions to other on-going activities. Alternatively, the source of delays in sending equipments and resources to the desired spot can be traced to either inefficiencies or problems in the communication, planning or evaluation functions and their related processes. These inefficiencies can then be addressed. Therefore, the ADS is useful in studying how failures or poor performance in functions or the physical components affects overall WRM system performance, and it also can help trace the reasons that cause operation failure.

In the next section of this chapter, discussion of the links will be given in order to further understand what the links mean and what information requirement they can reveal.

### 6.3. Information Requirements Identification

A work domain analysis is a precursor to the design and evaluation of decision support system. From the ADS model, many information requirements can be extracted. Each level of the model, or even each link, specifies a certain kind of information that should be provided in information displays for effective and efficient WRM operation.

All the information requirements obtained by this approach can be used to evaluate currently existing or proposed WRM computer-based decision support systems, like Maintenance Decision Support System (MDSS), and then recommendations for decision support system design will be given to make the systems better help WRM supervisors make sound WRM operation decisions. In this section, discussion of some of the links will be given in order to further understand what these links mean, how the components at different levels affect each other, and, more importantly, what information requirement they can reveal.

### 6.3.1. Links Related to Level of Service (LOS)

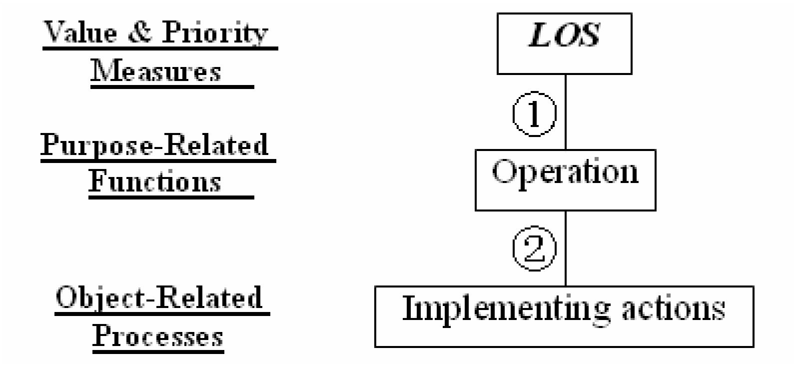


Figure 13 Links Related to Level of Service (LOS)

The level of service (LOS) standard is a defined objective for the winter road condition at a given time during and after the conclusion of the storm. To meet this objective, proactive operations are needed at the onset of the storm, followed by continuous operations that keep up with the weather. (Link 1)

LOS can determine priorities and theoretical routes for equipment to follow, and the LOS standard decides the resources assignment—put the right material in the right quantities at the right locations. In this way, WRM supervisors will be sure to assign the necessary amount of equipment to cover all road sections to achieve their desirable LOS during storm conditions. (Link 1)

Moreover, according to the definition of LOS, the desirable road condition should be achieved within a given time period during the storm or after the storm, so the operation effectiveness is determined more by the timing of material application than by the choice of material. For example, when applying liquid chemical, if applied too late in the storm, there is a risk that the chemical solution will become excessively diluted and lose its effectiveness. It is also the timing that defines whether the strategy of snow and ice removal is anti-icing or deicing. (Link 1)

These links show that operation is carried out to achieve LOS standard, the operation is realized by performing one or a series of WRM strategies (the choice of material and the timing of the application), and the LOS standard decides the operation strategies that will be used. (Link 2)

The information requirements elicited from the links discussed above are listed in Table 9.

Table 9 Information Requirements I

| Link Number | Information Requirements |
|---|---|
| Link 1 | Definition of LOS |
| Link 2 | WRM strategies |

### 6.3.2. Links Related to Communication

Regularly scheduled communications updates will result in the clarification of service level expectation for the citizens and traveling public in the area that a WRM garage is responsible for. Good communications lead to better understanding on the part of the public and improved public relations. Developing and implementing communication strategies can support WRM efforts and improve the awareness of WRM service levels, and manage the public's expectations. Therefore, communication is one of the means to improve public satisfaction. (Link 1)

In preseason, a good preparation of communication strategies includes the careful considerations of the tools that will be used, the messages that will be conveyed and the timing of messages release. A good preparation of communication strategies can make the information delivery in winter easier and make the right and complete messages reach the target audiences at the right time. The communication strategies should be planned as carefully as the snowfighting operations. (Link 2)

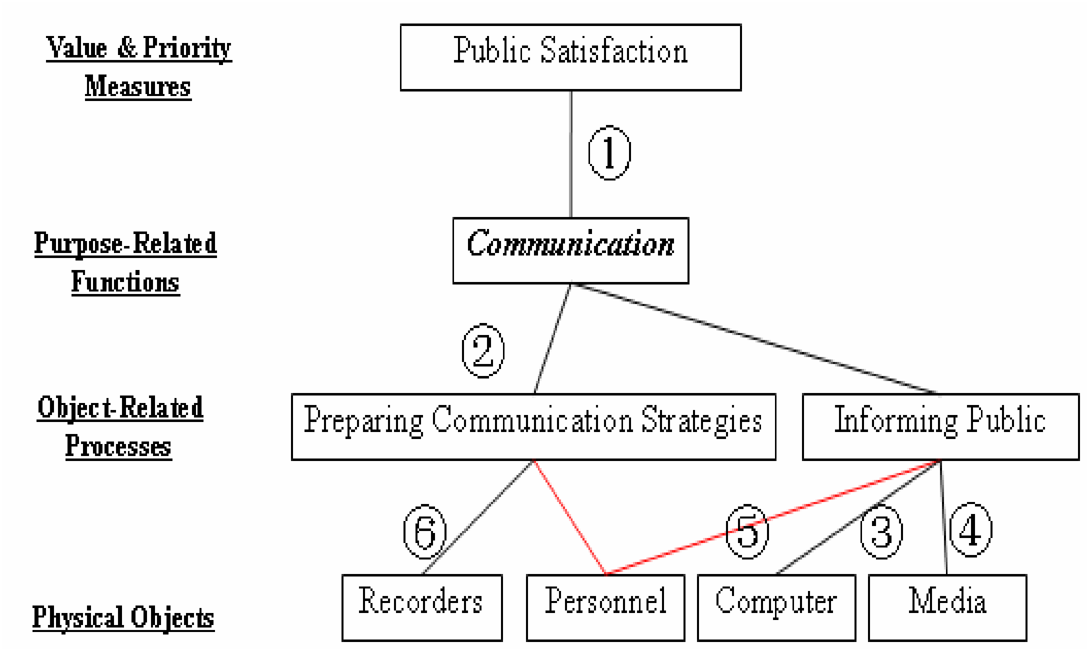


Figure 14 Links Related to Communication

When winter comes, weather bulletins, websites, media and other public announcements are used to inform the public and road users the information on winter road conditions, weather data, traffic data, and roadway operations and emphasize their responsibility to drive safely and appropriately for the condition they encounter or can expect.(Link 3,4,5)

The results of the communication activities are monitored, recorded and assessed, from which valuable lessons can be learned and some adjustments will be made if necessary. The records of communication strategies can be used in the future years for the preseason preparation of communication strategies. (Link 6)

The information requirements elicited from the links discussed above are listed in Table 10.

Table 10 Information Requirements II

| Link Number | Information Requirements |
|---|---|
| Link 3,4,5 | Type and location of communication tools |
| Link 6 | Records of communication activities |

### 6.3.3. Links Related to Recording I

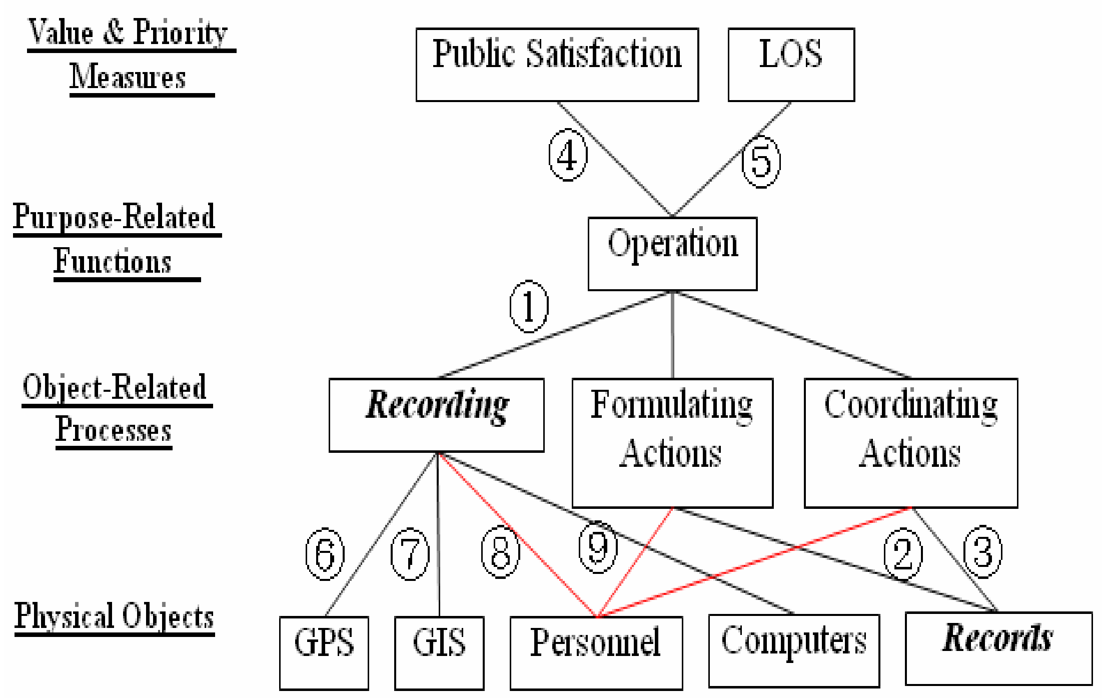


Figure 15 Links Related to Recording I

The success of the organization's operations depends entirely upon the information, current information and history information. Recording information during a snow and ice control operation can serve two purposes: to meet immediate operation needs and to provide a historical record for analysis for the improvement of future operation.(Link 1)

Keeping records during a winter event gives the WRM supervisors real time data on the status of snow and ice removal work, like snow accumulations, inventory of materials and planned operations. Then the WRM supervisors can use the data to resolve critical problems of task completion, personnel assignment, equipment and material needs. (Link 2, 3)

Keeping good historical records of snow and ice control actions taken in response to the weather events as they occur, along with information like material usage and changing road conditions can help WRM supervisors determine snow and ice removal strategies very quickly with some degree of certainty when winter events come. This will lead to effective and timely operation and then help achieve desirable LOS and then maximize the public satisfaction. (Link 1,4,5)

Traditionally, WRM personnel used paper forms to record data. Nowadays, with the emergence of advanced technologies, like fast networked computers, geographical information systems (GIS), and geographical positioning systems (GPS), recording has become faster, easier, and more accurate and complete. For example, the GPS can locate a WMR vehicle very quickly and accurately and GIS can show the LOS a street has achieved. (Link 6, 7, 8, 9)

The information requirements elicited from the links discussed above are listed in Table 11.

#### 6.3.4. Links Related to Recording II

Because of the unpredictability of winter weather, it is almost impossible to develop accurate budgets for WRM. Good historical record can help improve planning and then help save money, which is very important because currently budget has become the center of focus. (Link 1, 2)

Table 11 Information Requirements III

| Link Number | Information Requirements |
|---|---|
| Link 2,3 | • Amount and Type of Materials Used on Each Cycle or Run<br>• Road and Traffic Conditions Observed on Each Cycle or Run<br>• Weather Event Characteristics<br>• Treatments Used During the Weather Event<br>• Location of Treatments<br>• Time of the Treatments<br>• Description of Roads being treated<br>• Total Personnel in the Field<br>• Inventory of Equipment and Operational Status<br>• Inventory of Materials<br>• Number and Extent of Breakdowns<br>• Future Availability of Equipment |
| Link 1,4,5 | • Number, type and Characteristics of Operational Events Operation Effectiveness<br>• Weather Event Characteristics<br>• Time for Achieving Desired LOS (Or Time for the Completion of Operation) |
| Link 6,7,8,9 | • Type and location of recording tools |

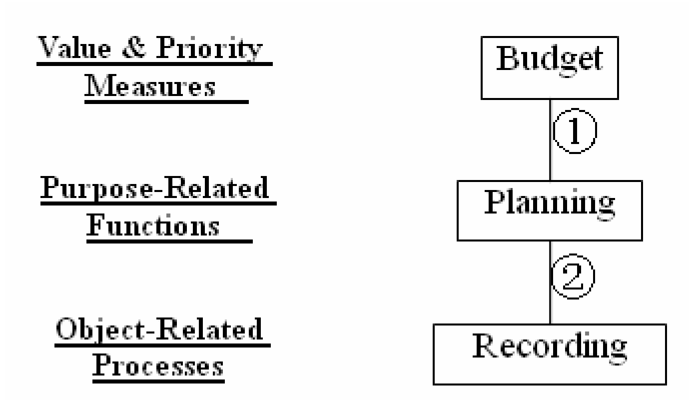


Figure 16 Links Related to Recording II

Using previous years' costs of actual personnel hours, equipment charges and materials use can provide the best basis for current year's budget. The farther back the historical records stretch, the more useful the information becomes. For example, the accurate history records of salt usage for 20 years can provide an accurate picture of how much salt has been used for each winter and give the WRM supervisors some degree of certainty to know how much they will need to get through an average winter. However, the records of salt usage for only 2 years could leave the WRM supervisors some guesswork to determine how much they will need. Currently, many DOTs are using historical records to forecast necessary material budgets.

The information requirements elicited from the links discussed above are listed in Table 12.

Table 12 Information Requirements IV

| Links Number | Information Requirement |
|---|---|
| Link 1,2 | • Cost Per Inch Per Lane-mile<br>• Cost of Personnel, Equipment, Materials and Supplies<br>• Cost of Administration |

6.3.5. Links Related to Evaluation

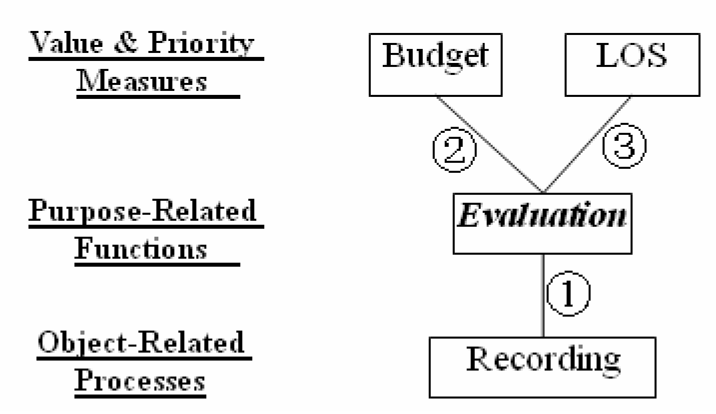


Figure 17 Links Related to Evaluation

There are two kinds of evaluations, post-event evaluation and post-season evaluation.

Post-season evaluation can assist management in judging the impact of resource level, training, public relations efforts, litigation, and other management issues. It is a valuable management tool used to assure continuous operation improvement and justify resource investment. It can help identify where changes are needed in equipment, material, and route configurations, and also help identify where changes in personnel procedures and training are needed to improve the effectiveness of the winter road maintenance. (Link 1, 2, 3)

Post-event analysis can provide statistics of one snow and ice removal operation, such as driver hours, truck miles, material applied). The statistics can help reduce the costs of future winter maintenance operations. This can also help identify areas that need improvement and changes that can be made in the treatment strategy. What can be learned from a storm when it's over is as important as what should be done before and during the event. (Link 1, 2, 3)

Recording keeping is one of the important tools and techniques that can assist in developing a performance evaluation program. (Link 1)

6.3.6. Links Related to Transportation Infrastructure Characteristics

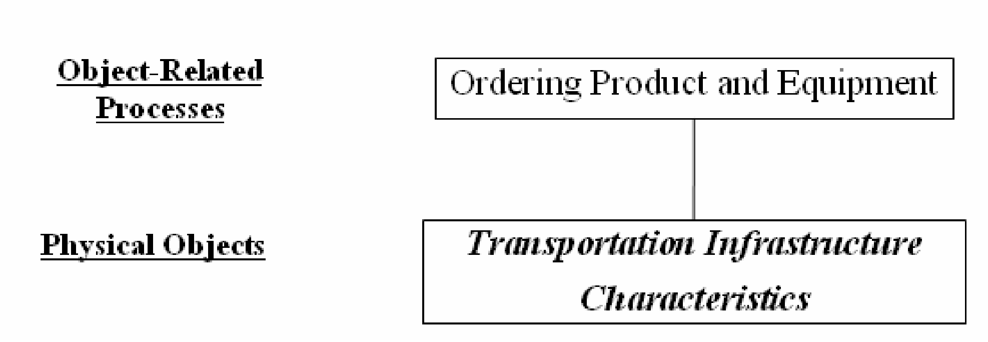


Figure 18 Links Related to Transportation Infrastructure Characteristics

The right choice of tools, technologies will help the WRM supervisors to meet LOS objectives most efficiently and cost-effectively, given the particular conditions and requirements. Transportation infrastructure is one of many factors that can affect the choice of tools and technologies. How the transportation infrastructure is built will be the most important determining factor in what equipment needed to buy. For example, if operating in an urban environment, the WRM workers may prefer the smaller, more maneuverable vehicles instead of the larger and more powerful trucks which are often used on rural roads or urban freeways.

Therefore, the characteristics of transportation infrastructure determine the ordering of tools and technologies

The information requirements elicited from the links discussed above are listed in Table 13.

6.3.7. Links Related to Personnel

Among the links between the last two levels, we can see “Personnel” is connected to every object-related process (the red lines). This means that people are involved in different aspects of WRM work system. People play a significant role on the success of WRM. The capability and limitation of persons affect every aspect of the

Table 13 Information Requirements V

| Links Number | Information Requirement |
|---|---|
| | • Road classification<br>• Road surface material<br>• Topography of roads<br>• Location and characteristics of special areas, like bridges and environmental sensitive spots |

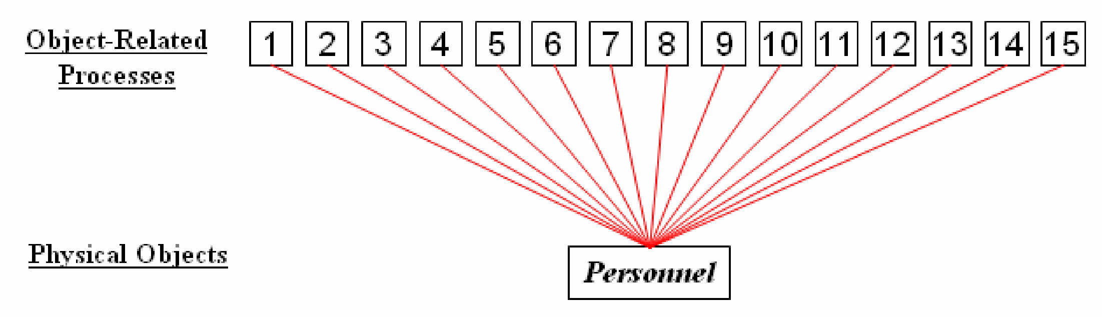


Figure 19 Links Related to Personnel

WRM work system. Thus, the success of WRM performance heavily depends on people's intention, ability and experiences, which is quiet different with the causal systems.

With the appearance of many technological innovations like RWIS, most of the information that is needed by WRM supervisors comes to the managers automatically and some advanced decision support systems like MDSS can even provide actions to deal with the snow and ice on the roadways under different weather conditions. However, no matter how sophisticated the technologies are, they cannot replace people's knowledge, skills and experience. All the information from RWIS systems is monitored by supervisors; all the decisions made by computer decision support system are reviewed by supervisors. People must have the capability to read and interpret the data provided by these innovative technologies.

The WRM of different US DOTs is using many new technologies, from sophisticated RWIS to prewetting and anti-icing techniques, but perhaps most important to the DOT WRM success are the dedicated staff who put the technologies into the practice.

The role of people in a successful WRM operation also indicates the importance of personnel training.

#### 6.3.8. Links Related To Training

Equipment is constantly improving, becoming more sophisticated, durable and easier to use, but the potential benefits can only be realized if maintenance staff are thoroughly trained and material use is closely monitored. Every staff has to be trained to understand their role, and why they are being asked to perform tasks that may be different from the way things were done in the past. Better training of maintenance staff can help to achieve savings in road salt use and then reduce the amount of money spent on material purchase and lessen the negative impact of salt on environment. (link 1,2)

In order to make the best of innovate technologies and techniques, such as anti-icing and RWIS, management, supervisory and operation personnel must be trained in the details. New more effective and more efficient WRM programs must be studied. A successful snow and ice control program will require more and better information for making decisions, will use different methods and materials, and require

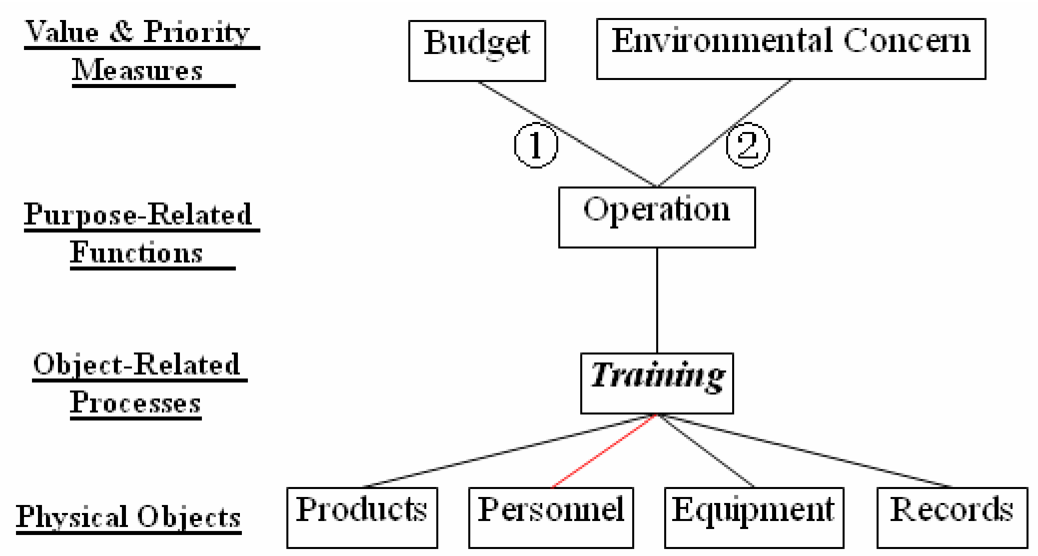


Figure 20 Links Related to Training

more emphasis on training. Training can be given by a consultant or by an agency staff using materials from various resources.

### 6.3.9. Links Related To Cleaning

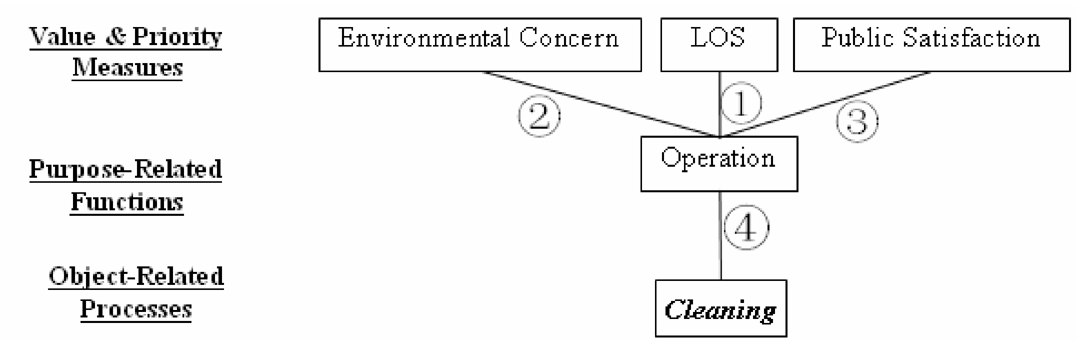


Figure 21 Links Related to Cleaning

Clean-up begins after the storm ends and after the levels of service by classification have been achieved. For the consideration of operation, under some circumstances, clean-up during overtime hours may be advisable. For example, a storm may have ended and all roads are providing the desired levels of service, but temperatures are dropping rapidly and are expected to remain low, or another storm is approaching. Removal operations should continue to remove as much snow and ice as possible prior to the freeze. (Link1, 4)

Recently, abrasives used in WRM operation have raised some environmental concerns in areas with air pollution. Air pollution from particles less than 10 microns in size (pm 10) has been documented from winter abrasive use. Except the air pollution, abrasives also can clog storm water inlets and sewers. Thus, for the consideration of environmental issue, quicker cleanup after the storm are also very required in some areas. (Link2, 4)

In order to keep abrasives unfrozen and usable, abrasives must be treated with salt. The Salt-treated abrasives can accelerate vehicle corrosion and then raise the public complaints. Therefore, for the consideration of public satisfaction improvement, cleanup as soon as possible after the end of a storm event is also very necessary. (Link3, 4)

### 6.3.10. Links Related To Operation

Currently, many DOTs are using a wide variety of snow and ice removal technologies, techniques and strategies to help keep roadways safe for travel.

Actions are the performance of WRM strategies by using various technologies and techniques. For WRM, strategies refer to the combinations of materials, equipments, and methods, including both chemical and physical that are used in snow and ice control operations to achieve a defined LOS. The following are strategies that are commonly used in WRM program:

- Anti-icing
- Deicing

- Mechanical removal of snow and ice together with friction enhancement
- Mechanical removal alone
- Traction enhancement
- Other (Road closure and snow fence)

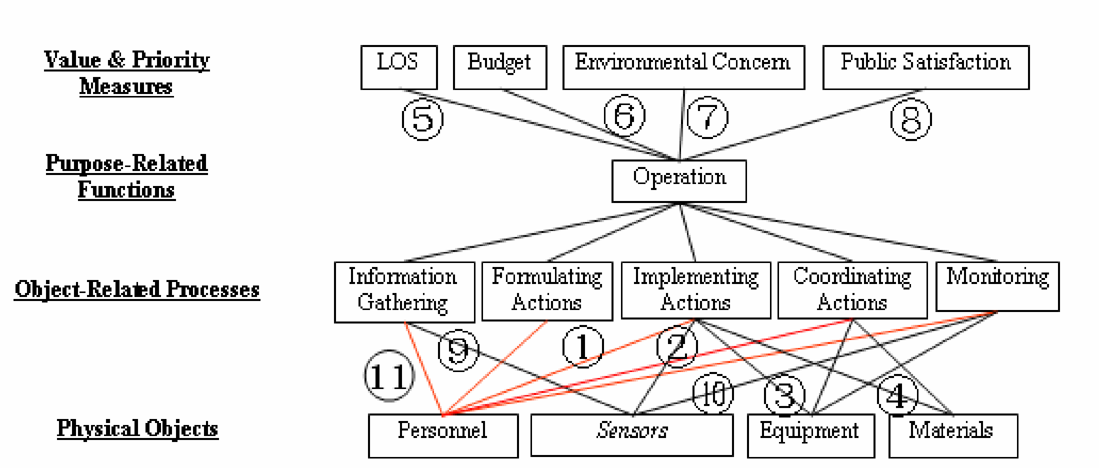


Figure 22 Links Related to Operation

Among all these strategies, anti-icing is a relatively new one that many DOTs are experimenting with. Anti-icing is a road maintenance strategy trying to keep the bond between ice and pavement surface from forming and anti-icing is spreading the brine on the roadways before or at the very beginning of the storm. By applying brine prior to a precipitation event, it adheres to the surface of the roadway and is ready to go to work when the snow or rain begins to fall. This speeds up the entire melting process and also makes roadways easier to plow. With anti-icing, less material are used and snow and ice are easily removed, saving taxpayers' money or providing a higher level of service to the traveling public. (Link5, 6, 7, 8)

Anti-icing is a systematic approach to Winter Road Maintenance. It requires the use of right tools, material, equipment, personnel and strategy (Link1, 2, 3, 4). Accurate weather forecast is crucial to anti-icing process, so advanced equipment that can predict the impending storm are required to make anti-icing effective.

As part of the extensive information gathering process, the maintenance division in many state DOTs are utilizing the state-of-the-art Roadway Weather Information System(RWIS) that can provide the DOT maintenance staff with precise and real-time weather information about actual roadways' conditions. Each RWIS station includes pavement sensors embedded in the road surface and atmospheric sensors mounted on the tower that can be seen along the roadways. Pavement sensors can measure the temperature of the pavement surface and its trend, determine whether the pavement is wet or dry, and measure the concentration of chemical left on the road. Atmospheric sensors can measure temperature, precipitation, and relative humidity. (Link9)

There are few storms when any single strategy is adequate. It is not unusual to start fighting a storm with anti-icing procedures, then switch to deicing and before the storm end go back to the liquid. Sensors can be used by maintenance managers to monitor the weather and pavement conditions during a storm. Thereby, subsequent decisions will be made throughout the storm based on the knowledge provided by RWIS, and crews can be mobilized to plow and apply materials when and where they are needed. (Link10)

Therefore, the sensor is crucial for a success WRM operation, especially anti-icing procedure, so advanced new sensors with more abilities should be developed and applied to WRM operation.

In addition to hi-tech information system, the advanced material technologies are also important means to achieve more effective application sand, salt and other chemicals. Many DOTs are investing in and testing new equipment technologies. (Link3)

The information requirements elicited from the links discussed above are listed in Table 14.

Table 14 Information Requirements VI

| Link Number | Information Requirement |
|---|---|
| Link1,2,3,4 | • Equipment Types, Amounts and Allocation<br>• Material Types, Amounts and Allocation<br>• Personnel Number and Their Availability<br>• Personnel Standby and Call-out Procedures<br>• Geographic Distribution of the Material Storage Locations |
| Link5,6,7,8 | • Strategies of Snow and Ice Removal<br>• Guidelines of Treatments |
| Link 9,11 | • Air Temperature<br>• Temperature trend during and after the storm<br>• Chemical Concentration(Brine)<br>• Wet or Dry<br>• Wind Direction and Speed<br>• Relative Humidity Ranges<br>• Precipitation Type, Rate and Intensity<br>• Precipitation start and end time<br>• Visibility<br>• Cloud Cover (Percent Clouds, Cloud Density)<br>• Climatologically Characteristic of the pavement<br>• Dew Point Temperatures<br>• Time of the Day or Season<br>• Road Surface Temperature<br>• Road surface temperature trend during and after weather event<br>• Road Surface Condition (Icy, Loose Snow, Packed Snow, Slush, Wet, Bare, Dry)<br>• Measured or Estimate Pavement Friction<br>• Ice-Pavement Bond<br>• Freezing Point of a Chemical Solution<br>• Chemical Concentration(Brine) |
| Link10 | • Application Material<br>• Application Rate<br>• Treatment Type (Anti-icing, De-icing, Plowing, Applying Abrasives, Doing Nothing)<br>• Treatment Cycle Time<br>• Location of Treatment<br>• Time of the Treatment<br>• Locations of working road crews and equipment and current status of operations<br>• Results of Each Treatment |

### 6.3.11. Summarization of Information Requirements

In the previous sections (from section6.3.1 to section6.3.10), some of the links in this ADS model are studies to give a illustration of how this model works to show the relationship between different components at different levels and elicit information requirements from links. After going over all the links in this model, 65design requirements are generated by this manner. All the information requirements are summarized and categorized as shown in Table 15.

## 6.4. Conclusion

This chapter mainly discusses the links in ADS model of Winter Road Maintenance from three aspects--invariability, diagnostic purposes and ability of information requirement identification. Their invariability makes the model can be tailored to different road agencies in various conditions. The ability of tracing of these links make them useful in studying how failures or poor performance in functions or the physical components affects overall WRM system performance and it also can help trace the reasons that cause operation failure. In the final sections of this chapter, some of the links are detailed discussed, illustrating how links reveal the way this model works to show the relationship between different elements at different levels and elicit information requirements from links. In the end of this chapter, all the information requirements are summarized and list in Table 15.

Table 15 Summarization of Information Requirements

| Category | Information Requirement |
| --- | --- |
| Weather | 1. Air Temperature<br>2. Temperature trend during and after the storm<br>3. Chemical Concentration(Brine)<br>4. Wet or Dry<br>5. Wind Direction and Speed<br>6. Relative Humidity Ranges<br>7. Precipitation Type, Rate and Intensity<br>8. Precipitation start and end time<br>9. Visibility<br>10. Cloud Cover (Percent Clouds, Cloud Density)<br>11. Climatological Characteristic of the pavement<br>12. Dew Point Temperatures<br>13. Time of the Day or Season |
| Road Surface Condition | 14. Road Surface Temperature<br>15. Road surface temperature trend during and after weather event<br>16. Road Surface Condition (Icy, Loose Snow, Packed Snow, Slush, Wet, Bare, Dry)<br>17. Measured or Estimate Pavement Friction<br>18. Ice-Pavement Bond<br>19. Freezing Point of a Chemical Solution<br>20. Chemical Concentration(Brine) |
| Road | 21. LOS<br>22. Road Classification<br>23. Road Surface Material<br>24. Topography of Roads<br>25. Locations and Characters of Special Areas, Like Bridge and Environment Sensitive spots |
| Traffic | 26. Traffic Volume and Speed Before and During the Treatment<br>27. Timing(Rush Hour or Congestion)<br>28. Significant Incidents<br>29. Road Closures |
| Resource | 30. Equipment Types, Amounts and Allocation<br>31. Material Types, Amounts and Allocation<br>32. Personnel Number and Their Availability<br>33. Personnel Standby and Call-out Procedures<br>34. Geographic Distribution of the Material Storage Locations |

Table 15 – Continued

| Category | Information Requirement |
|---|---|
| Operation | 35. Strategies of Snow and Ice Removal<br>36. Guidelines of Treatments<br>37. Application Material Type (Solid Chemical, Liquid Chemical, Rewetted Solid Chemical, Abrasives)<br>38. Application Rate<br>39. Treatment Type (Anti-icing, De-icing, Plowing, Applying Abrasives, Doing Nothing)<br>40. Treatment Cycle Time<br>41. Location of Treatment<br>42. Time of the Treatment<br>43. Locations of working road crews and equipment and current status of operations<br>44. Results of Each Treatment |
| Records (Storm Specific) | 45. Critical Accident Data<br>46. Critical Spots Conditions<br>47. Amount and Type of Materials Used on Each Cycle or Run<br>48. Road and Traffic Conditions Observed on Each Cycle or Run<br>49. Weather Event Characteristics<br>50. Treatments Used During the Weather Event<br>51. Location of Treatments<br>52. Time of the Treatments<br>53. Description of Roads being treated<br>54. Total Personnel in the Field<br>55. Inventory of Equipment and Operational Status<br>56. Inventory of Materials<br>57. Number and Extent of Breakdowns<br>58. Future Availability of Equipment |
| Records(Seasonal) | 59. Cost Per Inch Per Lane-mile<br>60. Cost of Personnel, Equipment, Materials and Supplies<br>61. Number of Operational Events and Their Characteristics<br>62. Operation Effectiveness<br>63. Weather Event Characteristics<br>64. Time for Achieving Desired LOS (Or Time for the Completion of Operation)<br>65. Cost of Administration |

# CHAPTER VII

# CONCLUSIONS

The purpose of this thesis has been to investigate the application of Abstraction Decomposition Space to the Winter Road Maintenance process. The following findings have been made:

## 7.1. Problem Statement and Proposed Method

At the beginning of this thesis, by discussing the current situation of Winter Road Maintenance (WRM) operation, some problems related to the WRM information collection and support system design are identified, and the characteristics of the method that is needed to solve the problems are discussed.

Then, Cognitive Work Analysis (CWA)—a multidisciplinary framework for the evaluation and design of information systems—is introduced. A basic evaluation of the degree of fit between the demands imposed by Winter Road Maintenance and the characteristic of Cognitive Work Analysis is provided, and the feasibility of applying CWA to WRM is considered and proven.

## 7.2. Contribution to the Application of Work Domain Analyses

There have been numerous examples of Work Domain Analyses (WDA), but most of them have been performed on physically coupled causal systems, like thermodynamic systems which are predominantly constrained by the laws of nature. There are relatively fewer examples of the application of this technique to systems that are generally structured by user intentions, rules and practices, like Winter Road Maintenance (WRM) system.

The application of WDA to WRM domain adds a new example to the application of this technique and it demonstrates how a WDA can be used for analyzing an intentional system. WDA is a relatively new technique so attempts to apply this approach will result in the development of the approach. The application of WDA to

WRM work domain in this thesis makes a theoretical contribution to extend the application of WDA framework.

## 7.3. Benefits to the Winter Road Maintenance

In this thesis, Abstraction Decomposition Space (ADS), the modeling tool of Work Domain Analysis (WDA), was used to develop a schematic representation of the Winter Road Maintenance (WRM) domain. By this model, two main benefits of this application to the WRM domain have been demonstrated.

### 7.3.1. A Structural Presentation of Winter Road Maintenance System

The model in this thesis provides an innovative way to describe how the Winter Road Maintenance (WRM) system works. The traditional method of describing the WRM work system mainly focuses on procedures used in performing tasks. However, this model identifies the functional structure of Winter Road Maintenance (WRM) work domain independently of activities, modeling the physical and functional constraints ranging from physical objects and their forms, through specific and general functions, to values and the purposes of the whole system.

This model also identifies the means-end links between the constraints at different levels. The links reveal a function at a higher level must satisfied by functions at lower levels. The links can help staff to gain a more detailed understanding of the interrelationships between people, technology and systems and therefore control the system and handle problems with the system more effectively.

This structural description of the Winter Road Maintenance (WRM) system had not hitherto been available.

### 7.3.2. Information Requirement Identification

Sixty five Information requirements (Table15)were derived based on this model. These information requirements can be used to qualitatively evaluate the effectiveness of a proposed or existing decision support system. This is supported by some evidence in the application of Abstraction Decomposition Space in other work domains.

## 7.4. Future Study

### 7.4.1. Validation of Abstraction Decomposition Space Model

This Work Domain Analysis (WDA) model in this thesis is just early stages of the WDA. The next step is to validate the Abstract Decomposition Space (ADS) model. The main goal of validating a work domain model is to confirm that the model is as complete as possible. Since the objective of developing ADS model is to have a rich description of the WRM work system, it is important that the model captures the constraints of the work system as completely as possible without regard to prioritization by frequency of use of the information. (Burns *et al*.., 2001).

According to literature, the validation approach used by Burns and her colleagues (2001)—mapping scenarios against the domain model developed has been proved effective for confirming the completeness of the model and accommodating the workers' reasoning patterns in a variety of situations.

The information used to validate the ADS should not be the same with the information used to develop this ADS (Naikar, 2005). The information used for validating the ADS should be in the form of particular examples or instances. To validate the ADS model for WRM, the information should be something like the following examples:

- The reports of particular incidents and accidents that describe what went wrong and how the garage supervisor or the truck driver attempted to deal with them, like a traffic accident happening on a plowing route during the snow and ice removal operation.
- Documents that describe case studies of workers' experiences in challenging or novel situations, like how to operate during the rush hours. The documents should include what challenges or problems they encountered and how they responded to them, like the decisions they made or actions they took.

### 7.4.2. A Complete and Detailed Cognitive Work Analysis

Work Domain Analysis (WDA) is the first phase of the five phases of Cognitive Work Analysis (CWA). Despite the other four phases of CWA are less developed and understood than WDA, there are still some studies about these phases, for examples, control task analysis has been used for team design (Naikar, 2003). Therefore, there may be considerable benefits to be gained from developing a complete Cognitive Work Analysis.

A complete and detailed CWA of WRM domain would be an extensive project requiring a significant investment in resources time and funding. However, compared with the potential benefits that the CWA would bring to WRM information system, the research of CWA on WRM would be worthwhile.

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