Demonstrating CWA Strategies Analysis: A Case Study of Municipal Winter Maintenance

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Widespread acceptance of Cognitive Work Analysis (CWA) as a framework for design of complex socio-technical systems is dependent on how well the theoretical foundations can be applied to real-world systems. Although literature on CWA has many application examples, the first phase, Work Domain Analysis, is over-represented. Later phases such as Strategies Analysis, the third phase of CWA, can provide comparable insight to designers. Understanding how activities can be performed can be instrumental in designing work support tools that are robust to changing priorities and conditions. In this paper, a Strategies Analysis is applied to the City of Toronto Municipal Winter Maintenance Program to illustrate how an analysis can be conducted. Both a traditional Strategies Analysis in decision-making terms and a novel Strategies Analysis in work domain terms are presented.

The theoretical bases for Cognitive Work Analysis (CWA) have been published and discussed in the literature (e.g., Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). While academia acknowledges these foundations of CWA, widespread acceptance of the framework is hindered by perceptions that it can be cumbersome and unclear in practical applications. Methodological support for practical applications have been developed, but largely focus on either Work Domain Analysis, the first phase of CWA (Naikar, Hopcraft, & Moylan, 2005), or applications of CWA such as Ecological Interface Design (Burns & Hajdukiewicz, 2004; Vicente, 2002). Publications demonstrating the application of the remaining phases of CWA are scarce (Bisantz & Burns, 2008). Part of this scarcity is due to the lack of well-defined methodologies and tools for later phases of analysis. Developing practical resources for all CWA phases is key to enabling the framework's full potential. In this paper we will contribute to the methodology for Strategies Analysis.

STRATEGIES ANALYSIS

Strategies Analysis (StrA) is the third phase of CWA. It builds on the results of the previous two CWA phases: Work Domain Analysis (WDA) and Control Task Analysis (ConTA). WDA documents the constraints and purposes of a system that define *where* and *why* activities are performed, ConTA determines *what* activities need to be done, and StrA investigates *how* these activities can be performed within the context of the task and work domain (Vicente, 1999). Strategies have been more formally defined as a "*category* of cognitive task procedures that transforms an initial state of knowledge into a final state of knowledge" (Vicente, 1999, p. 9). A given cognitive task can almost always be performed using different cognitive processes and mental models of the system (Rasmussen & Jensen, 1974).

Designers of work support tools can benefit from StrA by incorporating a range of existing strategies into their products (Burns, Momtahan, & Enomoto, 2006), or enabling potentially effective but cognitively effortful strategies through computer support (Rasmussen et al., 1994). However, applications of StrA have not been extensively discussed in the literature. Case studies are limited to individual problem-solving, such as electronics troubleshooting (Rasmussen & Jensen, 1974) and medical decision support for cardiac nurses (Burns et al., 2006); and systems at the extremes of the causal-intentional continuum (Rasmussen et al., 1994), such as a process control microworld (Vicente, 1999) or library information retrieval (Rasmussen et al., 1994). Systems containing a mix of causal and intentional constraints can present challenges to analysts and further case study demonstrations may be beneficial (Naikar et al., 2005).

This paper introduces such a Strategies Analysis of the Municipal Winter Maintenance Program of the City of Toronto (Canada) as a novel case study.

CASE STUDY: WINTER MAINTENANCE

The City of Toronto receives an average of 130 cm of snow annually on 5,100 km of roads and 8,200 km of sidewalks (Welsh, 2002). Snow, sleet and hail are serious hazards and are implicated in over 12,000 traffic collision fatalities per year in Canada (Transport Canada, 2001). To keep road transportation effective and safe, Toronto spends over $60 million annually on its Municipal Winter Maintenance Program (MWMP). This organization coordinates 1,900 workers and over 1,500 pieces of equipment, 24 hours a day, to remove snow and ice from city roads and sidewalks.

In addition to preserving safety and mobility, the MWMP must also remain within budget, meet its legal requirements, and minimize its environmental impact by reducing the 140,000 tonnes of salt distributed yearly. To this end, the City of Toronto developed a Salt Management Plan (Welsh, 2002), which introduced communications upgrades, as well as new ways of measuring weather, road, and equipment conditions, and distributing salt. Given the MWMP's exposure to external disturbances (e.g. traffic and weather conditions), complexity of managing numerous equipment and human resources, and magnitude of the impact on public safety, the MWMP was a suitable candidate for CWA.

In order to conduct the Strategies Analysis, the WDA and ConTA for the MWMP were first developed to a rough draft stage. These initial models and knowledge were used to structure the StrA, and the resultant findings were integrated into subsequent revisions of all analysis phases (Thompson, Hilliard, & Ngo, 2008). Although the WDA and ConTA analyses are not within the scope of this paper, they are referenced where necessary to provide context to the StrA.

When conducting a StrA, analysts should try to uncover common reasoning patterns or "recurrent routines" (Rasmussen & Jensen, 1974), meaning that a systematic investigation of multiple sources is recommended (Rasmussen, 1986). Several methods can be used to conduct a strategies analysis. If the control task is performed by one worker, is relatively rapid, and is non-verbal, then a 'speak-aloud' method in the natural work environment may be useful to elicit internal cognitive processes (Rasmussen & Jensen, 1974). Questionnaires and structured interviews are also effective in eliciting strategies after-the-fact (Burns et al., 2006).

StrA can be conducted in either a descriptive or formative manner (Vicente, 1999), a choice that depends in part on whether evolutionary or revolutionary design interventions are desired. Our MWMP client's interest in exploring novel integration of information technology and developing new work practices suggested that a formative analysis would be appropriate. We attempted to consider a range of valid strategies independently of the MWMP's current organizational structure or the current competencies of its workers, sensors or automation. This formative approach considered strategies at a broader, institutional level, with the intent that the actual cognition required by a strategy could be distributed between managers, dispatchers, vehicle operators, or automated decision aids.

CASE STUDY FINDINGS

We will demonstrate StrA using one of the identified control tasks for the MWMP work domain: the De-Icing control task. De-Icing is an activity to distribute an appropriate quantity of salt (or other material), in order to melt roadway snow and ice, while balancing natural physical processes, legal responsibilities, and equipment capabilities. A ConTA of De-Icing can be found in our full report (Thompson et al. 2008).

We first present our StrA conducted in decision-making terms (Vicente, 1999), and next introduce a novel approach to StrA, using work domain terms.

Strategies Analysis in Decision-Making Terms

In our ConTA, we modeled de-icing using a Decision Ladder information processing approach (Rasmussen et al., 1994). In this model, MWMP workers 1) are alerted to the need to remove roadway ice and snow, 2) estimate quantities of snow and salt on the roadway, 3) determine the minimum amount of salt that needs to be applied to the roads to ensure that they are safe and passable, 4) formulate a plan of action to coordinate the distribution of salt, and finally 5) communicate this plan to vehicle operators.

Within the De-icing ConTA, we chose to focus the StrA on the strategies available to conduct the second to last information processing step, *Formulate Procedure* (see Figure 1). Our reference material suggested that MWMP dispatchers typically formulate procedures by assigning entire truck fleets to distribute salt on pre-planned routes through the city. These routes are planned during summer months with the intent of minimizing driving distance, covering all roadways, and allowing salting trucks to quickly re-load at city depots at the end of a route. These routine routes require little decision-making from truck operators and only simple communications between dispatchers and operators. However, when we inquired about non-routine situations, we determined that dispatchers sometimes customize routes to address 'trouble spots', and truck drivers often improvise detours when faced with disturbances such as an automobile collision blocking traffic. These findings led us to hypothesize four categories of strategies for formulating a de-icing procedure: selecting pre-planned routes, selecting a custom subset of pre-planned routes, generating routes from pre-planned templates, or generating freeform customized routes.

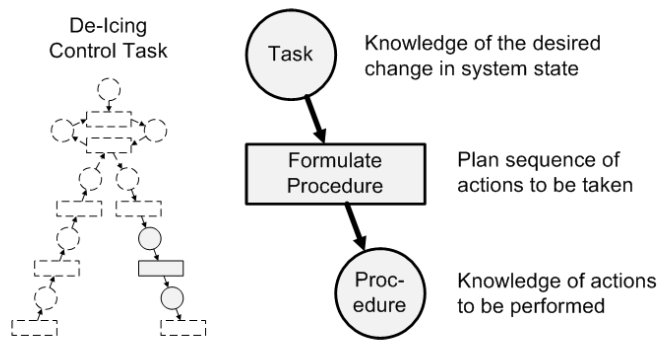

Figure 1 - Control Task showing the information processing step chosen for Strategies Analysis.

To provide a basis for differentiating these decision-making strategies, we identified constraints and performance criteria that would be expected to influence which strategy would be most desirable, shown in Table 1. In addition, each mental strategy was analyzed with respect to the tradeoffs in functional purposes identified in the WDA: minimizing environmental impact, maximizing safety, minimizing costs, minimizing impact on city transportation, and meeting legal requirements.

We estimated the performance of each strategy on these criteria, illustrated with a five point scale in Table 1. Dark circles represent the best relative expected performance or impact and white circles the worst. Where added uncertainty might exist, we indicate a range (i.e. multiple circles). It should be noted that we do not expect workers to select strategies simply by the "highest score" – however a strategy that rates well across all categories would be expected to be employed frequently. As the relative importance of each performance criterion changes depending on the system context and the cognitive capabilities of the actors assigned to the task, different strategies may be made more desirable.

The analysis yielded several interesting observations. The four strategies we identified have a marked difference in their demands on the decision maker and their likely effect on functional purposes. We discuss each of the strategies in turn.

Table 1: Summary of Strategies Analysis in decision-making terms, and the work domain constraints that limit their effectiveness. Greater dark fill indicates greater typical criteria satisfaction.

Strategy		**Select a pre-planned set of routes**	**Select a custom subset of pre-planned routes**	**Generate routes from pre-planned templates**	**Generate freeform custom routes**
Work Domain or Task constraints		The number of routes requires more readied equipment and staff than are available	The route is not possible due to changes in the work domain (e.g. roadway construction)	Pre-planned templates have not been prepared	The state of the work domain is not known in sufficient detail
Criteria	Knowledge of system state	●	◕	◕	○
	Complexity of cognition	●	◕	◕	○
	Sophistication of heuristics	●	◑	◕	○
	Complexity of output	●	●	◕	○ to ◑
Functional Purposes	Environment	○	◔	◑	◔ to ●
	Safety	◕	◕	◕ to ●	○ to ●
	Budgetary	◑	◕	◑ to ●	○ to ●
	City Transport	◕	◕ to ●	◑ to ●	○ to ●
	Legal	◕	◕ to ●	◑ to ●	○ to ●

Select a pre-planned set of routes. This strategy has the lowest demand on all cognitive resources as it requires little consultation of the state of the work domain. Pre-planned routes can be designed to meet legal, transportation impact and safety requirements, albeit at the expense of budget and environmental impact due to conservative salt over-use. However, this strategy cannot be used if more drivers and trucks are required than are available.

Select custom subset of pre-planned routes. In this strategy, planners choose a sub-set of pre-planned routes to deploy. This requires more knowledge of the appropriate change in system state, and therefore more knowledge of system and goal states. Overall, the salt use will be more effective, though the structure of pre-planned routes may still lead to over- or under-salting on a street-by street basis.

Generate routes with pre-planned procedure templates. This strategy requires cognitive resources and knowledge of the work domain to generate custom salt spreading routes and salt spreading rates based on procedure templates. The output state of knowledge is more complex than a pre-planned route, which will require increased actor competency in interpreting the procedure. The increased dependence on these cognitive factors introduces risk into functional purpose tradeoffs, as truck drivers may be unable to navigate the complex and novel routes developed by planners. However, if successful, this strategy can perform well on almost all functional purposes.

Generate freeform custom routes. This strategy consists of a completely dynamic generation of route and salt spreading rate 'on the fly'. It requires extensive and detailed work domain knowledge and complex cognitive activity to integrate system state observations and update procedures continuously. If successfully executed, this strategy has the potential to optimize salt application to every location in the city. If poorly executed, confusion and disorganization could result in catastrophically worse performance. Not surprisingly, in current practice this strategy is used only occasionally and on an ad-hoc basis, due to the effort and risk involved.

These strategies are by no means exclusive, and actors are expected to switch between these strategies dynamically in response to system conditions. For example, an actor could select a subset of pre-planned routes to deploy. In the process of selecting pre-planned routes, knowledge of a constraint in the work domain, for example a blocked route due to road construction, could result in a need to switch to generating a custom route for a vehicle. Another actor executing the pre-planned route could switch to a custom freeform strategy in response to another disturbance, for example navigating around a vehicle collision, and resume the pre-planned route afterwards.

Since the template and freeform strategies have the most potential to reduce the MWMP's environmental impact, designers could consider ways to increase their effectiveness and adoption by workers. One approach could be developing work support tools that help workers to acquire relevant knowledge of the work domain, interpret it, and coordinate actions. ConTA and StrA can provide input for the development of concepts such as in-vehicle navigation systems or improved dispatcher route planning tools. Further analysis of MWMP worker competencies can help designers to mitigate risks such as driver distraction or miscommunications.

Table 2- Comparison of two strategies in work domain terms.

Criteria	Strategy	Spread rock salt directly on road	Spread rock salt pre-wetted with brine
Workload	Planner	Simple to schedule loading & equipment	Must plan to have sufficient brine storage & production
	Operator	Simple loading, calibration of truck	More equipment to operate & calibrate
Time	Preparation	Only one easily stored bulk chemical to load	Must also prepare & load liquid brine
	Field	Slow to dissolve: heat, moisture, and traffic required	Salt pre-dissolved, starts melting ice quickly
Functional Purposes	Environment	Rock salt scatters off road & seeps into groundwater	Liquid mix greatly reduces salt scattering
	Safety	Slow dissolving action, rock salt hinders traction	Melts snow quickly, can be distributed faster
	Budgetary	Rock salt equipment is cheap to maintain & operate	Requires operation of brine generation facilities
	City Transport	Works best on high traffic roads	Also melts snow & ice on low traffic roads
	Legal	May not satisfy more stringent environmental laws	Can meet new environmental laws

Strategies Analysis in Work Domain Terms

While conducting the StrA outlined above, we found that describing procedure formulation choices required extensive references to work domain elements such as purposes or equipment. This motivated the development of a novel approach to strategies analysis, in which we considered alternate means available to manipulate state variables within the de-icing control task. To identify relevant state variables, we consulted our WDA and highlighted the areas relevant to the de-icing control task, as in Figure 2. For example, when conducting de-icing, the state of any plowing equipment is irrelevant, but the temperature and quantity of snow on the roadways is relevant. Because the de-icing control task's most important physical process is salt dissolving, our Strategies Analysis in work domain terms focused on *how* salt dissolving could be achieved in the MWMP.

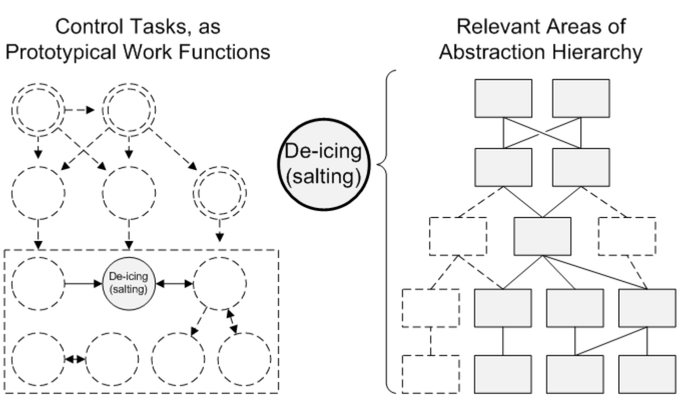

Figure 2 – Relation of the selected control task to the relevant areas of the work domain.

Our WDA documented that the MWMP's equipment had four capabilities to dissolve salt on roadways:

- Spreading rock salt directly on the road
- Spreading rock salt pre-wetted with water
- Spreading rock salt pre-wetted with brine
- Applying brine directly on road.

While the WDA documents these alternate means, and the ConTA uncovers constraints that limit the order in which they can be used, neither captures which means are likely to be most effective and appropriate for a given circumstance. We propose that the StrA in work domain terms is useful to answer this question, and to allow designers to consider the implications of social organization and worker competencies on attractiveness of strategies.

As before, we determined the expected performance of the strategies with respect to the functional purposes identified in the WDA. However, because this interpretation of strategies did not focus on information processing, our additional performance criteria were more pragmatic. We expected that the different strategies would vary in the workload required of planners and equipment operators, and in the time required to perform the control task, both in-house and in the field. We attempted to consider these criteria in work domain terms, such as equipment capabilities or natural laws. For example, while individual workers' task performance does contribute to the difference in preparation time between rock salt and brine trucks, we considered more invariant constraints such as the time required for the brine dissolving process.

Table 3- Summary of StrA in work domain terms. Greater dark fill indicates greater typical criteria satisfaction.

Criteria	Strategy	Rock Salt	Salt & Water	Salt & Brine	Brine
Workload	Planner	●	●	○	◔
	Operator	●	◑	○	◑
Time	Preparation	●	◕	○	◑
	Field	○	◑	●	●
Functional Purposes	Environment	○	◕	◕	●
	Safety	○	◑	◑	●
	Budgetary	●	◕	○	◑
	City Transport	○	◑	◕	●
	Legal	○	◑	◕	●

Each strategy was compared against the functional purpose tradeoffs and our performance criteria. A rating scale similar to that of Table 3 was used to compare the strategies across each dimension. The more positive the strategy with respect to each given dimension, the more shaded its circle. In addition to these symbols, where necessary, the cells were annotated with the rationale as to why a particular rating was assigned. Two such annotations are shown in Table 2.

The results of the analysis show that the strategy of 'spreading rock salt directly on road' generates the most positive ratings in terms of the performance criteria but conversely generates the most negative ratings with respect to the functional purpose tradeoffs. Spreading rock salt is logistically simple, but results in wasted salt and slow snow melting. The strategy of 'spreading rock salt pre-wetted with water' had little impact on performance criteria, and a generally positive impact on the functional purpose tradeoffs. Spreading rock salt pre-wetted with brine demanded more preparatory effort due to the additional brine production equipment, but allowed de-icing trucks to produce quick and effective results in the field with fewer environmental impacts. Finally, the strategy of 'spreading brine directly on road' also produced quick field results, with excellent satisfaction of functional purposes.

Comparing these strategies in Table 2 suggests that when planners and operators are pressed for time, they will likely prefer dry rock salt for its ease of handling and loading. If more preparation time and budget are available, and if quick snow-melting results are required, then preparing brine trucks may be more feasible. If environmental impact is to be minimized, work support tools should encourage the use of pre-wetting with either water or brine where possible.

In disturbance-prone systems that provide alternative means to accomplish changes in system state, we argue that StrA in work domain terms offers more support for analysts than a single 'optimal' strategy formulation. By systematically investigating a range of control options, this methodology can help design tools to support workers in making appropriate decisions that improve overall system performance.

DISCUSSION

The Strategies Analysis presented above is by no means complete. This is typical, as thoroughly analyzing every information-processing step of a control task or every means of changing system state is rarely practical. The choice of where to focus limited resources depends primarily on analysts' project goals and, to a lesser extent, on which system design interventions are available to them. Conversely, single-mindedly investigating only a single strategy leads to normative design interventions that may fail to support workers in dealing with unusual situations.

Analysts particularly interested in specific strategies in decision-making terms would next seek to formulate a set of required mental models and information processing activities. While some CWA examples have demonstrated a methodology for such an approach, such as Information Flow Maps (Rasmussen & Jensen, 1974), further work is needed. Analysts interested in more detailed StrA in work domain terms might find physical or statistical models of the system's processes a useful starting point to develop better indications of expected criteria satisfaction and tradeoffs. This could be used to assess the value of infrequently used affordances, and to provide a complement to operations research analysis when evaluating proposed technological interventions.

Common to both StrA methodologies presented here is the formative philosophy of identifying the multiple possible approaches to the planning and execution of tasks in complex sociotechnical systems. Observing normal work practices that satisfy established values and priorities may not be sufficient to reveal the possibilities enabled by new technology or required by a changing work environment. In the case of the MWMP, the additional communication and remote sensing capabilities introduced in recent years may in the future enable novel, and more environmentally sensitive, work practices.

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