NATURALISTIC DECISION MAKING AND UNCERTAINTY

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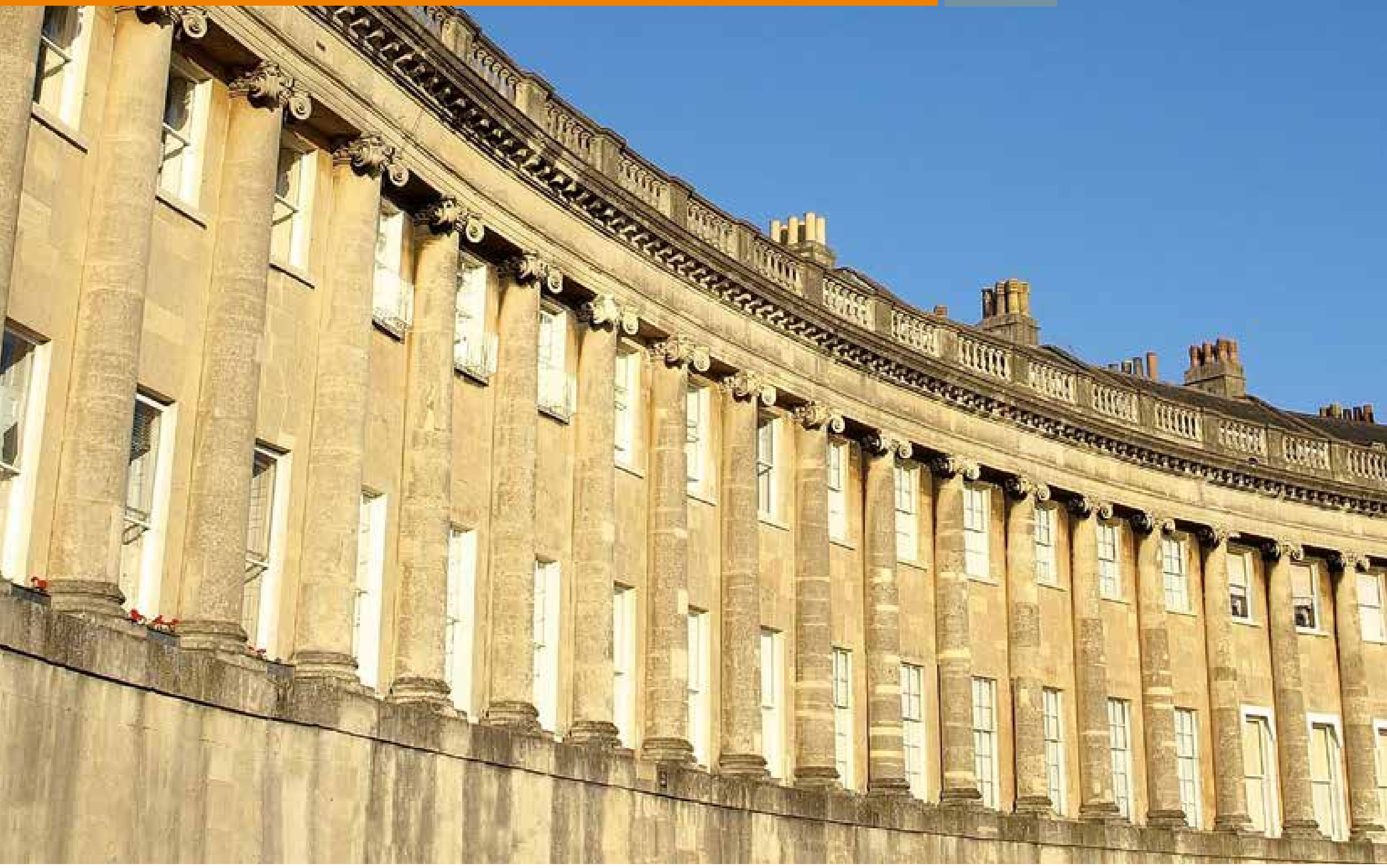

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Naturalistic decision-making perspective on uncertainty reduction by civil engineers about the location of underground utilities

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ABSTRACT
Modern engineers must perform their work carefully to avoid damaging buried underground utilities. Before starting ground works the exact location of pipes and cables must be confirmed. Current detection equipment still cannot provide complete certainty and requires extensive training in order to obtain the correct data. Digging test trenches remains an important practical tool to interpret subsurface conditions, but deciding on the number and location of test trenches is problematic. Decisions seem to be taken randomly and are based mostly on intuitive judgments. We conducted interviews and workshops in order to uncover the strategies used to select test trench location. Our results show that choices are influenced significantly by decision-makers' experience. We describe our findings using Rasmussen's Skills-Rules-Knowledge model. We propose that any future decision support system should combine elements from both analytical and naturalistic models.

KEYWORDS
Decision-Making; Civil Engineering; Test Trenches; Naturalistic Decision Models

INTRODUCTION

Excavation work demands that modern engineers take many precautions. They must schedule their works in such a way that existing underground utilities will not be disturbed. This is a challenge, given that underground spaces have become increasingly busy. Many types of cables and pipes, underground infrastructures, precious fauna and flora, as well as archaeological findings, can make excavation work difficult. Underground utilities, particularly, and depending on their content, can cause many problems. Damages to high-risk pipes and cables (e.g. gas pipelines, the sewage system, industry pipelines and/or high-voltage electricity cables) can have profound impacts on the environment and the health of workers and people living and working in the area neighbouring the excavation area.

Ground Penetrating Radars (GPRs) and Augmented Reality (AR) technologies are used by engineers to improve the safety of excavation procedures. However, these technologies are costly and still do not provide complete certainty. Furthermore, even if maps and plans of underground utilities are available, the information contained by these sources might be incorrect. Therefore, test trenches are often dug to confirm the exact locations. These trenches are variously described as test holes (Canada), trial holes (UK and US), potholing (Australia) and proefsleuven (the Netherlands). They all have the same goal: to establish precisely what is underground before excavation starts.

There is always doubt as to where to locate test trenches. Utilities' maps, GPRs and AR support those decisions. Nevertheless, it is the responsible decision-makers (designers, contractors) who make the final choice. The process of selecting the test trench location appears to be random and mostly based on the personal judgment of an individual. This exerts considerable pressure on these decision-makers faced with meeting deadlines and faced with the nagging uncertainty about the actual location of subsurface utilities and the risk of excavation damage to the utilities. The problem is well known to practitioners. However, there is a dearth of information about locating test trenches in the scientific literature which is surprising given the importance of digging test trenches that is readily apparent from various national excavation damages programmes, such as "Reduction of Damage to Utilities and Careful Excavation" (ReDUCE) in the Netherlands, PAS 128:2014 standards in United Kingdom (UK) or "Call before you dig" in United States (US).

The analysis in this article examines the Dutch excavation context and where clarity of test trenches location strategy is one major goal of the Dutch Government. The Netherlands has a national digital mapping system (referred to as "klic"). This system was developed by the Cables and Pipes Information Agency (Cadastre) and provides the excavator with maps of utilities in the area of interest, together with necessary documentation. In spite of this, damage to underground utilities persists. According to the data provided by Cadastre, almost 33,000 cases of damage were recorded involving Dutch utilities in 2015 and the cost of their repairs mounted to €30 million per year (Kabel en leiding overleg KLO, 2016) . The Underground Networks Information Exchange Act (WION), together with klic, provides a solid foundation for making decisions. The WION describes the steps that excavators must follow before breaking the surface, and the klic system supports them with the relevant maps. Before excavation starts it is mandatory for a request to be sent to Cadastre. The agency will provide the excavator with necessary maps, together with important documentation (e.g. about precautions).
In Figure 18, the klic system is presented.

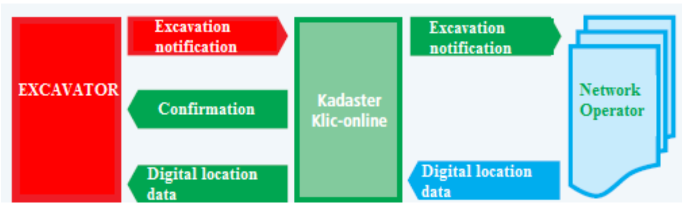


Figure 18. The klic system in the Netherlands (Groot, 2008)

New European regulations, such as Infrastructure for Spatial Information in the European Community (INSPIRE), as well as feedback from klic users, allow Cadastre to receive feedback to improve the system. As a result, the klic-win system was developed that is slowly being implemented to provide users with location data in vector format to create data sets with added value, such as 3D visualizations (Kadaster, 2016).
The authors intend to develop a Decision Support System (DSS)[4] for selecting test trenches to help decision-makers minimize risk and uncertainty during excavation and, as a result, reduce the number of cases where excavation damages underground utilities.

To achieve this goal, it is necessary to optimize the current decision-making strategy. This, in turn, requires careful analysis of current strategies, logic and decision-makers' behaviour. To that end, interviews and workshops were conducted. The purpose of those meetings was to check how people make decisions when factors such as risk, uncertainty and time play an important role. The research showed that on many occasions mental simulations conducted by decision-makers leading to their subsequent choices, were aligned with the degree of their expert level (i.e. expert vs novice). In this article, we investigate how decision-makers use their experience to decide on where to locate test trenches and whether it is possible to use Naturalistic Decision Models (NDM) as a decision support tool for Civil Engineering.

The structure of this article starts by outlining the background information of Naturalistic Decision Making models. Then, the methodology used to collect the data is described. Subsequently, the results of analysis are presented. The paper finishes with conclusions.

BACKGROUND ON NATURALISTIC DECISION MAKING (NDM) MODELS

To make a decision entails using information to choose between options from amongst the available possibilities (Ishibushi & Nii, 2000). On many occasions, researchers develop Decision Support Systems (DSS) from an analysis of several decision models as we did also (Racz, Van Buiten, & Dorée, 2016). However, we observed that this approach directed us more towards the development of the system itself and de-emphasised a focus on its users. The system would then represent an idealized example of reality by excluding actual users from the decision process (Blanchard & Fabrycky, 2011). NDM researchers consider the DSS development process differently (Klein, 2008). First, current strategies are analysed to examine how people behave during extreme situations where there is time pressure, uncertainty, unexpected conditions and/or risk (Klein & Klinger, 1991), rather than just simply checking whether people were effective or not. Civil engineering projects seem natural candidates for such an approach. Engineers and workers always perform their job under time pressure. The rush commonly results in mistakes with potentially dangerous consequences. In addition, construction work puts considerable responsibility

4 University of Twente, Reggefiber and other partners created the ReDUCE program (Reduction of Damage to Utilities and Careful Excavation). This programme is realised to promote careful approaches in construction and maintenance of the underground infrastructure, by investing in the development of new methods and technologies that prevent excavation damages (Reggefiber & University of Twente, 2015). The analysis are part of a PDEng (Professional Doctorate in Engineering) project entitled "Improved strategies, logic and decision support for selecting test trench location".

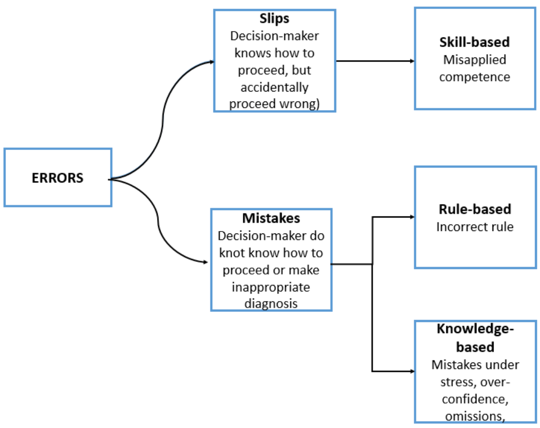
onto the persons involved when the work must also be done within environment and health and safety regulations. Typically, problems do naturally arise during civil engineering projects. If these problems were correctly identified, an adequate response can be formulated.

Researchers have distinguished six types of problems (Ishizaka & Nemery, 2013; Roy, 1981): (1) The choice problem (select best option or reduce the set of options), (2) The sorting problem (classification into categories), (3) The ranking problem (from the best to the worst), (4) The description problem (option and their consequences), (5) The elimination problem (related to sorting problem), and (6) The design problem (identification of the goal or creating a new actions). Civil engineers often face these problems while making decisions about work performance.

Even though modern technology helps to perform the work much more safely than in the past, there is always a risk involved. Some civil engineering works, such as excavation, are also very uncertain and require care. According to the literature (Lipshitz, Klein, Orasanu, & Salas, 2001), there are three forms of uncertainty: (1) inadequate understanding (insufficient situations awareness), (2) lack of information (incomplete or unreliable information) and (3) conflicted alternatives (difference between them is insufficient). Organisational units and people involved in the construction process have different experience and, even if they have the same data sources, their decisions may differ. Lipshitz (1993) identified nine NDM models. We would like to focus on three that we believe are applicable to the design project: (1) Rasmussen's model of cognitive control SRK, (2) Klein's Recognition Primed Decision model (RPD) and (3) Recognition/Metacognition model (R/M).

Rasmussen differentiated three kinds of behaviour (Rasmussen, 1983): (1) Skill-based, (2) Rule-based and (3) Knowledge-based. *Skill-based* behaviour arrives from experience. The decision is made based on past information stored in the subconscious. In case of r*ule-based* behaviour in decision-making, the unit will behave according to the rules set because these had generated good results in the past. This kind of behaviour is typical for decision-makers who do not have enough experience, but know the rules needed to accomplish a task. *Knowledge-based* behaviour is assigned to new situations when there is no set of rules available. The units must first identify the problem, generate the alternatives to solve it and, finally, choose the best solution.

Psychologists Gary Klein, Roberta Calderwood and Anne Clinton-Cirocco created the RPD model to describe how people make decisions. Decision-makers based their decisions on experience by connecting the current situation with the solutions performed in the past (pattern-matching). There are three variations of RPD models that differ according to their complexity (Klein & Klinger, 1991): (1) Simple Match RPS, (2) Developing a Course of Action RPD and (3) Complex RPD Strategy. The RPD model cannot be used in the case of knowledge-based behaviour, multi-criteria analysis cases and Search-for-Dominance Structure (SDS) strategy (Klein & Crandall, 1996). *Variation 1* describes a situation well known to decision-makers. Thus, they can easily simulate what the further scenarios are and notice the typical signs that indicate the use of particular solution. Conversely, in *variation 2,* the situation is not so easy to diagnose. Thus, decision-makers need to collect more data and/or assess the situation by looking into their past experience. Sometimes, decision-makers do not know which solution to select for the case (*variation 3*). However, in case of NDM methods, the choice of the best solution is not done by Multi-criteria Decision Analysis, but by generating a single action using mental simulation of possible scenarios. Nevertheless, even the most experienced decision-maker can make mistakes. The possibility of failure should always be considered. Human failures are distinguished by researchers (Embrey & Lane, 2005) from errors (which are related to the skill, rules and knowledge-based behaviour) and violations (which are exceptional or caused by routine). The types of errors are presented in Figure **19**.



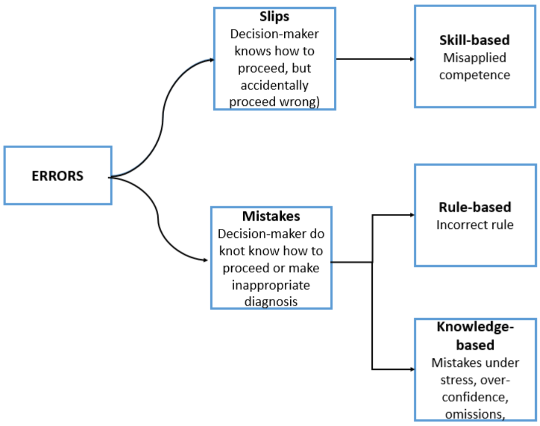


Figure 19.Types of errors (adopted from Embrey and Lane (2005))

The Recognition/Metacognition (R/M) model compares to the RPD focuses on the situations when decision-makers fail, while recognizing the case (Lipshitz et al., 2001). The incorrect situation recognition leads to the renewed data evaluation. Decision-makers needs to elaborate situation (recognition), add missed data and modify the strategy when there is: insufficient situations awareness, incomplete information or conflicted differences between alternatives (metacognition). The R/M model reconciles both pattern-matching recognition and problem solving strategies (Azuma, Daily, & Furmanski, 2006).

METHODOLOGY

We conducted eleven interviews and two workshops with decision-makers (designers and contractors), as well as with operators, data specialists, network operators and developers of applications for construction engineering industry.

Interviews for the first stage of project were held between March and June 2016. We prepared a set of questions and asked interviewees to prepare example(s) of projects that they found interesting regarding locating test trenches. To extract information about the user experience, practice rules, decision results and strategies we questioned each specialist about the number and location of test trenches, the reasons for decisions, opinions, support aids, results, communication and suggestions about changes. Each interview session took approximately two hours.

Workshops were divided into two sessions; one with six designers and (afterwards) one with six contractors. This division resulted from interviews when we noticed that the decisions made by designers and contractors were different (due to different stages of project). The first session took place in July 2016 and the second in October 2016. Both were based on serious gaming techniques (Schell, 2015) to check the behaviour of decision-makers when taking decisions under uncertainty. This approach was challenging as the participants had to face situations they were not prepared for and to explain their choices. We provided them with a map of underground utilities, extracted from Cadastre's klic system on which we superimposed the following projects: (1) build a new parking place, (2) place new fibre cables and connect them to houses and (3) replace an old sewage system. For each project, they had to decide how to locate test trenches and place them on map using transparent foils. We included obstacles, such as trees and waste containers, to make the assignment more difficult and influence the utilities path. The game board, together with examples of the results, are shown in Figure 20.

Figure 20. Workshop session with decision-makers

To analyse the collected data and information we used analytical and cognitive approaches to provide us with interesting results to generate further ideas about DSS design. In addition to the NDM model described earlier we also used the following methods: (1) The Design Process Unit (DPU) and Design for eXcellence approach (DfX) (Becker Jaruregui & Wessel, 2013), (2) System Engineering (Blanchard & Fabrycky, 2011), (3) Simon's Rational Decision-Making Model (Simon, 1977), and (4) Multi-criteria Decision Analysis (Ishizaka & Nemery, 2013). We discuss our results and adopt a NDM perspective in the following section.

RESULTS

During the interviews and workshops we observed a number of good and bad practices. The best practices showed that, in order to decide about the number and location of necessary test trenches, the following techniques needed to be combined:

- Data analysis (i.e. maps of underground utilities);
- Site analysis (i.e. ground conditions and obstacles);
- Detection tools (i.e. ground scanning tools);
- Use of best practices (i.e. provided by guidelines);
- Computer support (i.e. visualization tools and data bases to store data).

Only a few companies we interviewed used the combination of these methods, with others using just one or two methods. Clearly, using judgments is not incorrect. The experience, skills and knowledge of decision-makers are important to the decision process. Nevertheless, all best practices (experience, computer support, ground scanners, and utilities maps) can and should be joined together and used, not only by experts, but also by novices who might otherwise assess the excavation case wrongly.

It was interesting for us to check why damages still occurred, despite the fact that test trenches were dug. We analysed the most frequent cases of damage to assess whether the errors were due to poor risk assessment, a lack of data or due to rushed activities. The damage to utility services that occurred most often were: (1) mechanical damages, (2) damages to house connection, (3) damages while fibre cables were connected to houses, (4) damages to data-transport cables, (5) damages due to lack of information on utilities maps, (6) damages to disconnected utilities, (7) damages when tree was pulled together with utilities, (8) damages due to absence of Network Operator supervisor, (9) damages due to ground conditions (soil type, reduce visibility), and (10) damages while digging test trenches.

Those results directed us towards an analysis of decision-makers' behaviour. The interviews and workshops uncovered that decisions about the number and location of test trenches depended on the following factors: (1) stage of the project (orientation test trenches during design, test trenches dug before starting the excavation or test trenches dug when the reparation to the utility is necessary due to system failure), (2) type of work (i.e. building a new road or replacing the sewage system), (3) actions taken (i.e. drilling, open excavation or trenchless methods), and (4) decision-makers' and their experience.

Decision-makers used a set of good practices, such us digging test trenches, when there are doubts about the accuracy of utility maps, or when high risk utilities, such as gas pipelines, are present in the excavation area or many cables and pipes cross over one another. Designers dig test trenches to check if there is enough space to perform the project and to avoid unnecessary cost and changes. In contrast, contractors dig test trenches because they want to keep deadlines and to perform their work safely. To achieve this, they have to confirm, not only the location and depth of the utilities, but also check their material (e.g. resistance for vibration) and type of connections (e.g. can have impact on utilities depth).

During the workshop, we noticed how fast some decision-makers took decisions. This was clearly related to the knowledge and experience they had. In some cases, they could directly decide if the test trench was necessary or not, because they had faced similar situations before. For example, if on the excavation area a water pump station was present, the experienced decision-maker knew the depth of associated utilities can differ. Some decisions, such as checking the area up to 1,5 m from the excavation place, were influenced by (legal) rules (Crow, 2013) established according to best practices. Nevertheless, designers and contractors can face situations new to them. Furthermore, the decision as to whether an excavation should happen should not be made in a hurry, but proceed only after careful case-by-case analysis. If information was insufficient, then the information gaps need to be addressed before taking a decision so as to reduce uncertainty (R/M model). Thus, the situation should be well identified, the tasks made clear and planned properly using the best available techniques (i.e. maps, ground radars and best practices).

The current behaviour of decision-makers is presented using the SRK model in Figure 21.

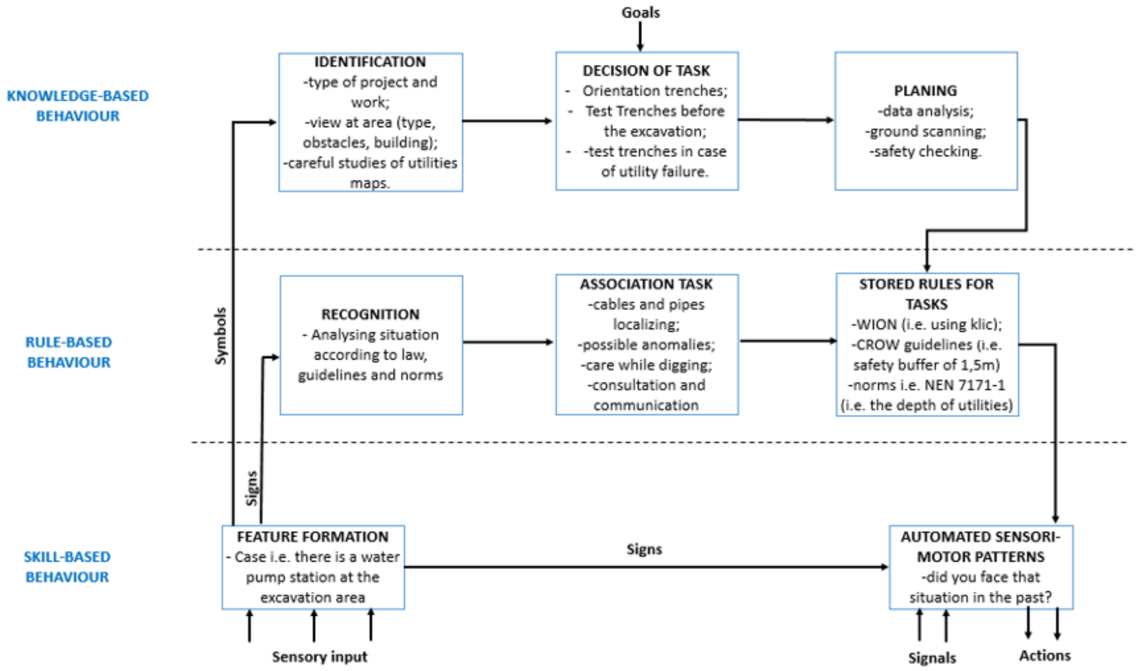


Figure 21. Rasmussen's model of cognitive control SRK for test trench location process (adopted from Rasmussen (1983))

Figure 21 is based on the example of the water pump station, which was discussed during workshop sessions. Only four of the twelve decision-makers decided that it was necessary to dig test trenches near the pump because the depth of the utilities can differ relative to the other parts of the excavation area. They supported their choice by using an example from their past experience (*skill-based behaviour*). Other participants agreed with their suggestion. The decision was also influenced by the set of rules (*rule-based behaviour*). To reduce the risk of failure, decision makers used, for example, the 1,5 m buffer. This ensures that no utility will be damaged while executing the work. Nevertheless, new situations could be identified using available technologies *(knowledge-based behaviour*). During the interviews, we observed cases where damage occurred because of a lack of a correct situation assessment. For instance, in one case, the age of buildings influenced the material and depth of the utilities and this was not taken into account by decision-makers.
Many strikes are attributable to the lack of the information on the utilities maps. However, the relation between SRK behaviours and the failures can be noted as well. The damages to the utilities caused by:

- removing the trees ;
- absence of the network operator supervisor,
- excavation machines (if utility marked on klic), and
- misunderstandings;

could be avoided by correct assessment of the situation.

Experience sharing could be an interesting component part of a future DSS. The excavation case could be analysed using, not only data from radars, maps, documentation and observations, but also by matching the situation to ones that had occurred in the past. The RPD and R/M models related to pattern-matching could be used by creating an experience database within the DSS. The new situations faced by decision-makers and best practices could be collected and updated, for example: how obstacles can influence the location and depth of utilities, the resistance of the material for vibrations, and so on. Based on the input information, the tool could look for patterns (using the RPD model variations) using algorithms and to present this to decision-makers by (e.g. warning signals). The information about previously dug test trenches can be also collected. So, if it is necessary to dig new test trenches, the decision-makers can have an overview of the past decisions and findings. Together with other techniques, this would help generate a more reliable risk assessment. A combination of analytical and naturalistic decision-models clearly could support better situation awareness, help to collect enough reliable information and, last, but not least, reduce uncertainty related to conflicts between alternatives approaches (i.e. dig one, two or three test trenches).

CONCLUSIONS

Digging test trenches is one method used to confirm the exact location of the cables and pipes. Often, the decision about their number and location appears random and driven by the personal judgments of the individual decision makers. The interviews and workshops conducted uncovered strategies used by the decision-makers (designers and contractors). They used good practices, such as digging test trenches when there is uncertainty about the accuracy of utilities maps, when high-risk utilities are present, or when many cables and pipes cross over one another. The regulatory rules and other guidelines can also help to reduce uncertainty (e.g. the rule of adding the 1,5 m checking buffer to ensure that the excavation project will not damage utilities).

The knowledge and skills of decision-makers both play an important role in the decision-process. It influences how many test trenches will be dug and where they will be located. The use of different techniques, such as detection tools, utility maps, visualisation programmes and data management tools, can support decision process. However, decision-makers ultimately assess the risk of damage. Their experience levels differ. They often face new situations. These can involve poor decisions or incorrect assumptions if they are having to analyse large amounts of data. Many people involved in the excavation process are not sufficiently familiar with the use of ground scanning methods. This can result in further incorrect assumptions about the situation. Full automation of decision-making regarding how and where to locate test trenches appears to be untenable. Neither is it desirable, as it prevents leveraging expertise from those directly involved.

A combination of analytical and naturalistic decision-making elements within one DSS seems to be an interesting and viable option. Pattern-matching could give additional input for decisions, especially when decision-makers lack experience or when new situations have to be faced. An experience database could be created by the users and updated by adding information about the best practices, findings, failures, obstacles that influence the location of utilities and digging test trenches. The DSS could search the database to find similar cases to the project under consideration. Moreover, based on all collected data and conducted analyse, the risk of damage (including the case where test trenches are not used) can be calculated.

We argue that DSS which collects all the necessary data, analyses them, visualises them and, in addition, compares them with best practices and previous experience, can reduce all of the aforementioned three forms of uncertainty mentioned in the literature (Lipshitz et al., 2001) (inadequate understanding, lack of information and conflicted alternatives). The system of pattern matching within the tool can be based on the RPD model by comparing the current situation with others in the database (variation 1), requiring additional input information (variation 2), or informing about the necessity of "evaluation of course of actions" by, for instance, risk calculation of the generated scenario (variation 3). The RPD model can be supported by using the R/M model and inform the users about any deficiency in information which is needed to generate a viable solution. Of course, these ideas await further elaboration and testing. Nevertheless, we are confident that they will help shape the thinking about tomorrow's DSS for selecting the nest locations for test trenches.

ACKNOWLEDGMENTS

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(in his 1982 article, Newell confined these system levels to computer system levels, but it became apparent in his 1990 book that he meant these system levels to apply to all biological and artificial systems).
In the next paragraph, I will expand upon the notion of 'system levels', as I believe that the introduction of a new system level could bring significant advances to the study of artificial systems, going beyond macrocognition and current views of NDM.

SYSTEM LEVELS

There are many definitions on what a 'system level' is. According to Newell (1982), a true system level is a reflection of the nature of the physical world, not simply a level of abstraction. It should be a specialization of the class of systems capable of being described at the next (higher) level. Aggregation occurs within each level and does not take us to the next level on its own; meaning should be added and some things therefore become invisible at the next level (this is another way of saying that phenomena at higher levels have emergent properties). Therefore, although the levels are ontologically irreducible to each other, each level may still be implemented at the next lower level.

Note that this view of system levels is quite different from what we normally take to be 'units of analysis'. For instance, the distinction between micro, meso and macro levels (individual, group, organization) is not a true system level description, in Newell's definition. For instance, Karsh, Waterson, and Holden (2014) proposed 'mesoergonomics' as a way to specify macro- and microergonomic integration. Their aim was to reveal cross-level interactions and to describe relationships between and among levels rather than describing phenomena that emerge from their components but that cannot be explained by them (Hackman, 2003). For instance, Carley and Newell (1984) described what a Model Social Agent would look like, in an attempt to make an individual agent behave like a social agent. They concluded that a Model Social Agent could be obtained by minimal requirements on information processing capabilities but with major extensions in the types and amount of knowledge required. Note this is a matter of aggregation and does not take us to a next system level on its own. We obtain social behavior by basically adding more knowledge to an existing system level (which Newell called the 'knowledge level' and later the 'rational band'). Newell (1990) even doubted whether a separate social band existed, due to the lack of invariants found up until then. In the paragraph below, I will note some general developments that justify the introduction of a new level, situated right above the knowledge level.

DEVELOPMENTS

In the past 15 years, some notable developments have taken place in the fields related to Cognitive Systems Engineering (CSE) and Naturalistic Decision Making (NDM), as well as in some other, unrelated, fields. Without being exhaustive, the following developments may be noted:

- The extension of NDM to macrocognition. Some particular models developed under the guise of macrocognition are the Data-Frame model of Sensemaking (Klein, Phillips, Rall, & Peluso, 2007) and the Flexecution model of Replanning (Klein, 2007a,b). These models depart from the linear Input-Output models and stress the dynamics of (re)framing, elaboration and preservation in cycles of macrocognitive activity.
- The extension of the situation awareness concept from being strictly 'in the head' to being a distributed, emergent process, arising from the dynamic interplay of humans and technological artefacts (e.g., Stanton, Salmon, Walker, & Jenkins, 2010).
- The Interactive Team Cognition approach (Cooke et al., 2013) provides a theoretical alternative to existing approaches that exclusively focus on individual team members' cognitive processes. Interactive Team Cognition views team cognition as context-dependent team interaction rather than a monolithic entity that a team can either have or not have. Rather than viewing team cognition as something that is shared among team members and then aggregated, it is viewed as an interdependent network that should be studied at the team level. Team cognition arises as an emergent property as team members communicate with each other (Walker et al., 2006).
- The move from a dyadic semiotic model of 'meaning' that views the mind as a symbol-processing system to a triadic semiotic model that suggests that a sign's meaning is grounded in the functional dynamics of the problem domain. This particular development can be traced back to ecological psychology (Gibson, 1979), and from this lineage to Rasmussen, Pejtersen, & Goodstein (1994) and Flach (2015). The implication of this philosophical view is that the focus of applied work has shifted from human-computer interaction to interactions between humans and work domains, mediated by interfaces and automation (Flach, 2015). The same shift may be noted when comparing (cognitive) task analysis with work analysis (Vicente, 1999).
- The shift from CSE to Resilience Engineering may be viewed as a shift from the engineering of cognitive systems to engineering with a particular purpose in mind, i.e. achieving sustained adaptability (Woods, 2015). The aim is still to 'outmaneuver complexity' by 'graceful extensibility', but the focus has shifted from cognitive systems to 'tangled layered networks'. There is evidence that the particular network structure that has evolved determines the long-term success of organizations to deal with disturbances (Rivkin & Siggelkow, 2007; Stanton, Walker, Sorensen, 2012). In a variety of domains, scale-free network structures

have been shown to be resilient architectures, in the sense of being robust to the (random) removal of nodes (Schraagen, 2015). Specifically, in such resilient architectures the degree distribution of nodes follows a power law.

- The introduction of the network and relational perspective in management science (Hollenbeck & Jamieson, 2015) and the social sciences in general (Borgatti, Mehra, Brass, & Labianca, 2009) and the concomitant rise of social network analysis as a methodology (Wasserman & Faust, 1994).

Summarizing these developments, we may note that there is a move away from viewing cognitive agents as independent units to viewing them as part of larger networks of interconnected units of adaptive behaviour. These networks are constrained by factors external to them, including time, physical constraints, task, technology, social structure, and culture. The networks are cross-cutting, embedded in each other, and heavily intertwined. As units of adaptive behaviour interact over time, regularities in behavior emerge. These regularities may be visible in the form of 'patterned interactions' and may be studied by methods such as social network analysis. The implications of these developments for NDM have not yet been discerned. In the next paragraph, I will connect the micro-macro cognition distinction to Newell's system level constructs and then build up to the new "Transaction level".

MACROCOGNITION AND MICROCOGNITION AS SYSTEM LEVEL CONSTRUCTS

Macrocognition as a field has defined itself as an extension to the Naturalistic Decision Making field, in the sense that its focus is on a broader set of macrocognitive functions than merely decision making. For instance, it also distinguishes sensemaking, planning, adaptation, problem detection and coordination as important macrocognitive functions. Macrocognitive functions need to be performed by individuals, by teams, by organizations, and by joint cognitive systems that coordinate people with technology. It is the study of cognitive adaptations to complexity (Schraagen, Klein, & Hoffman, 2008).

Macrocognition is distinguished from microcognition primarily by its time scale of analysis. Whereas microcognition focuses on cognitive processes in the time band of 100 msec up to 10 sec., macrocognition focuses on cognitive processes from minutes to hours. The preferred means by which these processes are studied then also varies, with microcognition frequently opting for constrained tasks in confined environments with high experimental control, while macrocognition opting for real-life tasks under actual working conditions with less experimental control (Cacciabue & Hollnagel, 1995; see Hoffman & McNeese, 2009 for a historical overview).
Interestingly, although macrocognition in principle extends to the organizational level, in practice there are very few studies that adopt the methods employed by organizational scientists, nor are the time scales adopted in macrocognitive studies weeks or months or years, but rather hours at the upper level. Methodologically, then, an important shortcoming in current macrocognitive studies is the lack of longitudinal data collection, which prohibits the discovery of emergent behaviors at longer time scales.

If microcognition is equated with Newell's cognitive band and macrocognition with Newell's rational band, then it follows that macrocognition is a 'knowledge level' construct (Newell, 1982). At the 'knowledge level', the principle of rationality applies: if an agent (e.g., an expert) has a goal and knows that knowledge A will bring him or her closer to that goal, then the agent will choose knowledge A. From the outside, the behavior of the expert is highly predictable, once we know the expert's goals and the knowledge that is required to attain those goals. For the NDM community, the principle of rationality should look familiar: it is functionally, if not logically, equivalent to the RPD model. The expert has a representation that can be accessed without any computational costs, or, in Newell's (1982) 'slogan equation': Representation = Knowledge + Access. The representation consists of a system for providing access to a body of knowledge. Access is a computational process, hence has associated costs. Thus, a representation imposes a profile of computational costs on delivering different parts of the total knowledge encoded in the representation (Newell, 1982). But if we look closer, we notice that this equation generalizes beyond the RPD model. In fact, the RPD model is a special case that applies when computational costs are low, i.e., the knowledge can be accessed highly efficiently to make selections of actions in the service of goals. In other (unfamiliar, non-routine) cases, knowledge may not be accessed as efficiently, and it is here that the macrocognitive 'deliberative search' processes are put to work to access the knowledge.

A NEW LEVEL

I now propose that there does exist yet another system level, which I will call the *transaction level*. It is a true systems level in Newell's sense, that is, it is a reflection of the nature of the physical (and social!) world and not just a point of view that exists solely in the eye of the beholder. It is not a level of analysis that can be applied to any unit of analysis, as, for instance, a network perspective that can be applied to both brains and societies. It is not an aggregation of knowledge, so its behavior cannot be obtained by expanding agents at the knowledge level with simply more knowledge. Rather, no amount of knowledge added will yield the transaction level properties that are characteristic of this level.