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The application of restructuring of knowledge in civil engineering

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In this paper, it is shown how knowledge theories and knowledge acquisition techniques are integrated by contextualisation to lead to the drawing of concept maps that can be used in civil engineering design, and to analyse and record specific experience. The concept maps form part of concept-based ontologies that are analysed to identify problems and constraints. Solutions to these problems and constraints create new knowledge and can be reported and linked to the world-wide-web. This linkage is made possible by utilising the Top-Level-Ontologies or Upper-Level-Ontologies to link to existing or new ontologies on the world-wide-web. The logic base acts as a procedure to lead and integrate all the above-mentioned aspects into three modules. These modules of the logic base are described and simple examples are given of how the logic base functions. The logic base is a technique to bring knowledge closer to the practising engineer, and facilitates thinking processes that will greatly assist in systematising knowledge, the analysis thereof and making it accessible on the word-wide-web.

INTRODUCTION

The word-wide-web and numerous publications offer virtually unlimited scope for obtaining information on engineering matters. Engineers, having to work in a world of increasing complexity, find it almost impossible to access, analyse and study vast amounts of complex information. This situation is exacerbated by a shortage of experienced engineers (Elliott 2017; Lawless 2005; Department of Higher Education and Training 2014). A dichotomy, therefore, exists between the knowledge sources and the demands for knowledge by practising civil engineers. In order to address this dichotomy, extensive research was carried out to find ways of addressing this problem (Verbeek 2018). Resulting from this research, knowledge restructuring is done. The applications of restructuring knowledge are discussed in this paper, whilst the theoretical aspects are discussed in Verbeek and Bothma (2018). The restructuring is done by adopting knowledge theories and repackaging knowledge into ontologies. Ontologies represent categories of concepts, their properties, the values of the properties, events and their causes and effects, processes and time (Gašević *et al* 2009). Concept maps are used to represent and analyse knowledge. The restructuring of knowledge is done by using what is called a "logic base" to represent a model to guide and integrate various knowledge restructuring processes. The goals of restructuring knowledge are to make knowledge explicit, to analyse and enhance knowledge, to structure knowledge into ontologies and to facilitate linkage and interoperability of knowledge structures with other ontologies on the world-wide-web. In this paper, applications of the logic base are discussed by first considering a very brief overview of the theory of the restructuring process and then to look at a few examples.

The application of the logic base is based on a civil engineering environment, but may also apply to other engineering fields. The point of departure of the restructuring discussed in this paper is to consider any matter or case that is placed in focus by the engineer to deal with. The architecture and operation of the logic base are described in the sections to follow.

THE ARCHITECTURE OF THE LOGIC BASE

The knowledge base integrates, in a single model, the processes relating to knowledge theories, knowledge acquisition, concept maps, relationship analysis and reporting. The complete architecture of the logic base is shown in Figure 1 and is referred to in subsequent sections.

Figure 1 shows that the logic base has three modules (or functional units), namely,

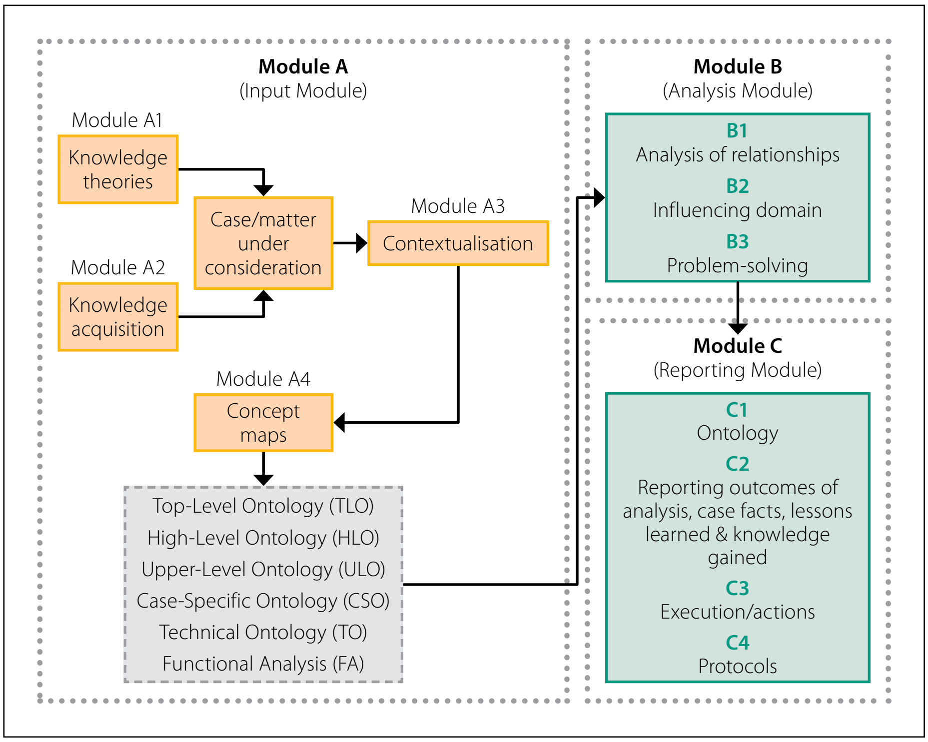

Figure 1 The architecture of the logic base

Table 1 Summary of knowledge theories

Knowledge theory	Brief summary of main points
Theory of cognition (Kellogg 2002; Sternberg 1999)	Involves mental processes and representations. Humans have a natural tendency to categorise concepts.
Theory relating to knowledge hierarchy (Pomerol & Brézillon 2001; Wallace 2007)	A distinction is made between data, information and knowledge. Information is contextualised data. Knowledge is when reasoning is done and the information is made ready for taking decisions and actions.
Theories of types of knowledge (Gašević *et al* 2009; Zack 1999)	The following are different types of knowledge: ■ Procedural knowledge (how to do something) ■ Declarative knowledge (details of concepts or objects) ■ Meta-knowledge (knowledge about knowledge) ■ Heuristic knowledge (rules of thumb, guiding problem-solving) ■ Structural knowledge (mental knowledge and the organisation thereof) ■ Inexact and uncertain knowledge ■ Common-sense knowledge (knowledge that cannot easily be put into precise theories) ■ Ontological knowledge (provides meaning to various kinds of categories)
Theory of knowledge conversion (Nonaka 1994; Nonaka & Tacheuchi 1995; Pomerol & Brézillon 2001; Polyani 1958)	Tacit knowledge resides in the individual and functions in the unconscious domain. Explicit knowledge is knowledge that is communicated (or coded) for purposes of sharing. Knowledge can be converted through the processes shown in brackets. ■ Tacit to explicit (Externalisation) ■ Tacit to tacit (Socialisation) ■ Explicit to tacit (Internalisation.) ■ Explicit to explicit (Combination)
Theory of knowledge creation, metaphor and reuse (Harsh 2009; Nonaka 1994; Sfard 1998)	As knowledge conversion increases, so do knowledge reuse and knowledge creation. Metaphor combines a group of concepts into a single word and helps to make knowledge explicit.
Theory of redundancy of information (Nonaka & Takeuchi 1995)	Conscious, intended overlap of information across organisational or discipline boundaries.
Sense-making theories (Browning & Boudès 2005; Kurz & Snowden 2003; Snowden 2013)	Model for sense-making. Domains defined as the known, knowable complicated, complex and chaotic domains.

modules A, B and C, being the input, analysis and output modules respectively.

Module A (the input module) is divided into four sub-modules, namely, Module A1 that covers the theories of knowledge, Module A2 that deals with knowledge acquisition, Module A3 that discusses contextualisation, and Module A4 that covers concept maps. Each sub-module is discussed in the sections to follow.

MODULE A

Module A1: Knowledge theories

This first module of the logic base contains fundamental theories of knowledge on which the logic base is built. These theories show the thinking required to enable the restructuring of knowledge. In Table 1, a summary is given of these theories.

In summary, knowledge is founded on the theories of cognition. It is also necessary to understand what knowledge is, how knowledge can be classified and how knowledge is made explicit. Sense-making provides the necessary tools for handling complex situations and identifying knowledge and relationships. These theories assist in widening the user's approach to enhance knowledge and to convert tacit knowledge (that functions in the unconscious domain in a person's mind) to explicit knowledge (that is systematically organised or arranged, i.e. coded to be easily communicated and shared) so that knowledge can be reused. Knowledge acquisition is dealt with in the following sub-module.

Module A2: Knowledge acquisition

The term knowledge acquisition, as used in this paper, represents "internal" processes in the human mind. It does not necessarily mean to acquire knowledge from external sources. The user reflects on other cases, looks at the evidence and own experiences. In this way, a user can relate more effectively to the case in hand and find solutions to problems and challenges. A selection of knowledge acquisition techniques is shown in Table 2.

The knowledge acquisition techniques in Table 2 can be summarised as follows:

- Comparisons are made of the matter or case in hand with previous cases or actions (prior knowledge). The similarities invoke previous reasoning processes, and inferences are drawn. These processes add to a person's knowledge.

Table 2 Knowledge acquisition techniques

Knowledge acquisition techniques	Summary description	Application
Case-based reasoning (Aamodt & Plaza 1994)	Knowledge from previous cases are retrieved and selectively applied to new cases (e.g. in the field of law, case histories are of utmost importance).	Essential for not re-inventing solutions and to extrapolate knowledge gained in previous cases to apply to the case in hand.
Evidence-based management (Rousseau 2006)	Outcomes of previous actions are evaluated and used in new designs (e.g. in the medical field this is applied to prescribe treatments, based on responses of patients on previous treatments).	This is a useful knowledge-building technique and action-based learning technique.
Experiential learning (Kolb *et al* 2001)	New inferences are drawn from reflections on observations of past experiences.	Cause and effect relationships can be evaluated to assess applicability to the case in hand.
Reflective learning (Boyd & Fales 1983)	Used to internally examine, explore and develop thinking, triggered by experience. Keeping journals is a useful way to retain and record knowledge and experience within context.	Uncovering of problems and constraints through the knowledge that resides in the tacit domain and can become known through the thinking process.
Critical thinking (Kuhn 1999; Kurfiss 1988; Norris 1985)	Rationally deciding what to do or to believe. It answers questions for which information may not be available. It explores, questions, hypothesises and integrates available information.	An analysis is done to arrive at rational conclusions.
Knowledge spill-over (Carlino 2001)	It involves an exchange of ideas among individuals and crossing boundaries into other fields. Exaptation (alternative applications to original intention) helps to overcome challenges.	This expands knowledge and applications to other fields.

- Rationalisation takes place where a person examines, explores and integrates information to come to a belief.

The above techniques guide the user to identify, dissect, review and sort knowledge (referred to as "knowledge units") to enable contextualisation of knowledge at hand. It contributes to the search of solutions to problems and constraints.

A systems approach is fundamental to the handling of cases to be studied, and also for the restructuring of knowledge (Blanchard & Blyler 2016; Haines 1998). The theories of knowledge and of knowledge acquisition are part of a system approach and need to be placed in that context. These are dealt with in the following section.

Module A3: Contextualisation

Knowledge acquisition deals with the way people think and how they understand the cases/matters under consideration. However, the foregoing needs to be rationalised and put into practice by doing the following:

- Examine a case and identify as many uncertainties as possible.
- Identify the significant external influences on the system under consideration.
- Identify the various phases (past, current and future, as well as development phases, such as conceptual, feasibility, detailed design, implementation, operations and retirement phases).
- Identify the main issues to explore.

The above process provides context to the case in hand and is termed contextualisation.

The processing of knowledge is depicted by the knowledge processing framework in Figure 2.

Once the contextualisation is done, the next step in the restructuring of knowledge is the drawing of concept maps. This is shown in the following section.

Module A4: Concept maps

Concept maps are graphical representations of cognitive processes in the human mind (Borst 1997). The concepts are drawn in boxes and connected with lines or arrows, indicating some kind of

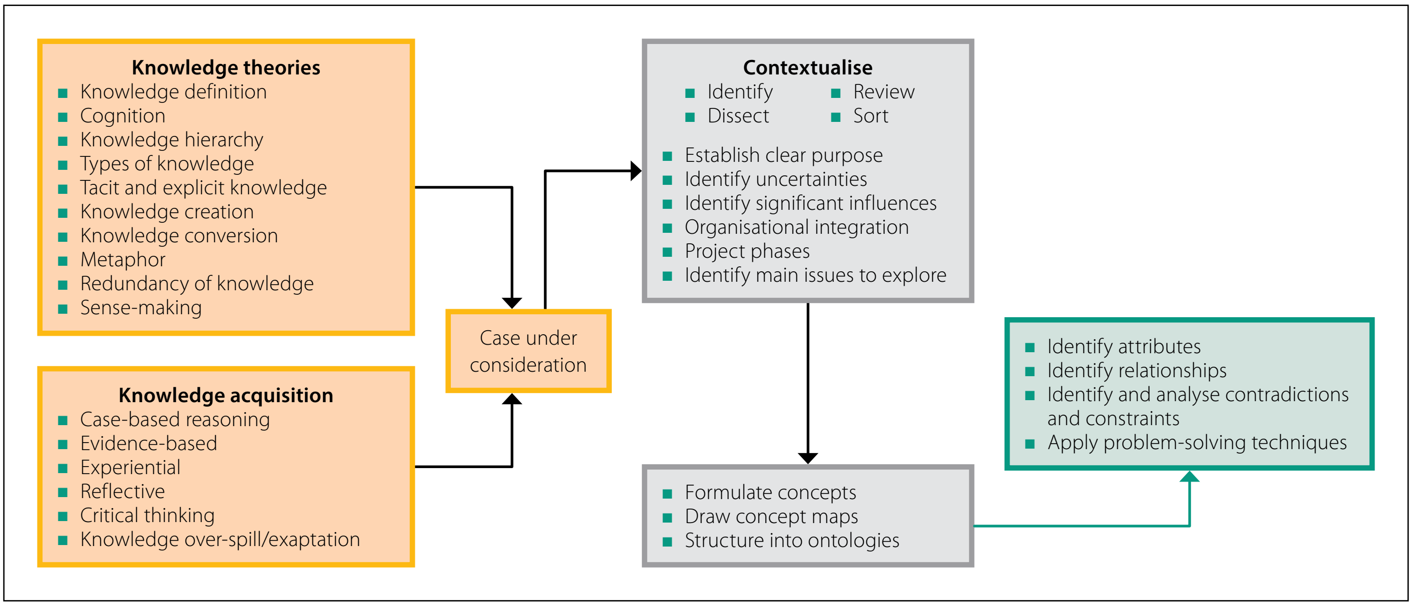

Figure 2 The knowledge processing framework

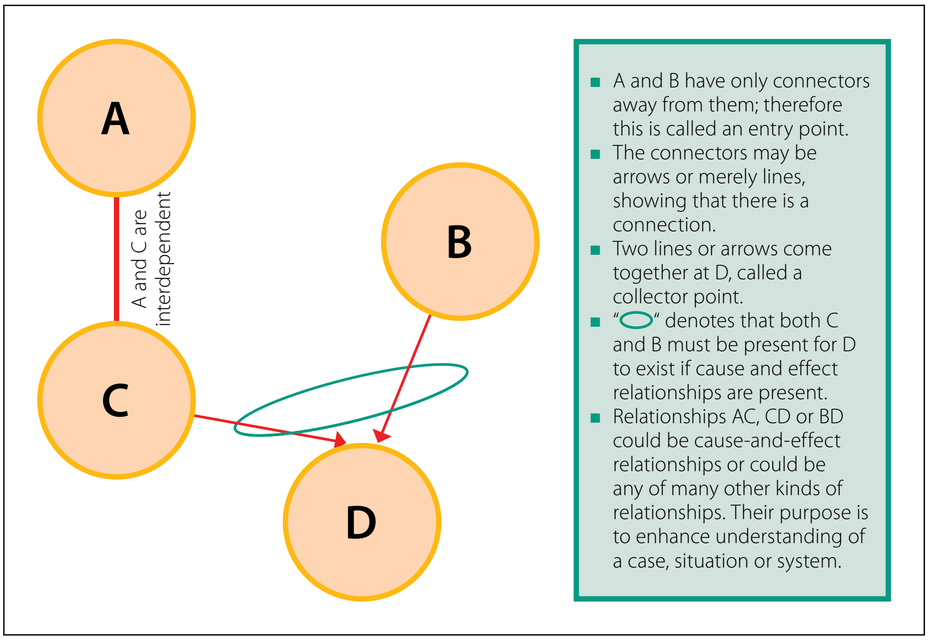

Figure 3 Example of a concept map

relationship between them. There is a hierarchy in the concepts, denoted by various ontological levels which will be shown in further sections.

Once a concept map has been drawn, the relationships between the concepts are analysed by the application of problem-solving techniques (Gruber 1993; Novak and Cañas 2008; Verbeek 2018).

A concept map is illustrated in Figure 3.

The concepts are denoted by A, B, C and D in Figure 3. These concepts could be the following:

- Concept A: The formwork for the bridge deck must be checked and signed off.
- Concept C: The rebar in the bridge deck must be checked and ready.
- Concept B: The trucks that transport the ready-mixed concrete must be ready (including all the logistics).
- Concept D: The process of concreting the bridge deck.

The relationships indicate that both the rebar and the trucks that transport the ready-mixed concrete (and the associated logistics) must be in place to do and complete a concrete pour.

The relationships between the various concepts can be analysed to get to a full understanding of the system's operation. This is discussed in subsequent sections.

Module A4: Ontologies

The linking of knowledge (i.e. the outputs from the logic base) to the world-wide-web, necessitates arranging the knowledge into ontological structures. Ontologies are similar to taxonomies where entities are classified according to strict hierarchical protocols (Cebrian-Tarrason & Vidal 2008; Noy & McGuinness 2001). Ontologies have a wider content and additional characteristics to those of taxonomies (Verbeek 2018).

The basic ontological structure

In research conducted (Verbeek 2018), it was found that the typical topics found in the reporting of a variety of case studies regarding engineering issues are the most appropriate basis for defining ontologies. The following topics are typically found in case studies involving engineering issues and are derived from the format found in a large number of case studies (Delatte 2009; Jones 1998; Jones 2001; LePartner & Johnson 1982).

- Introduction and scope
- Design
- Construction/manufacturing
- Operations and maintenance
- Setting and context/narrative/role players and relationships/real examples
- Sequence of events and causal path
- Investigation, problems, constraints and issues
- Interpret actions, solutions and actions taken
- Technical, legal and ethical lessons learned
- Educational aspects, extrapolation and replication
- References
- Influencing domain (which includes variables such as time, pace and resource capacity).

Various levels of ontologies are defined as follows:

Top-Level Ontology (TLO)

This is the foundational ontology and is also linkable to other ontologies on a world-wide-web. (This linkage might have to be via the introduction of several links to suit the external ontology.) The TLO is made up of concepts derived from the typical topics found in case studies. The topics of case studies represent a logical grouping of concepts and cover most reported case studies in industry. Furthermore, when considering the approach to engineering matters, these can be restructured by categorisation in one or many TLO concepts.

The concept map for the Top-Level-Ontology (TLO) is shown in Figure 4.

High-Level Ontologies (HLO)

For every concept in the TLO, a breakdown of concepts can be done and these are grouped into different HLOs. This breakdown of concepts in the HLOs provides a series of concepts put together to support various aspects in a civil engineering environment. An example of an HLO is shown in Figure 5.

Upper-Level Ontologies (ULO)

The ULO is an ontology made up of selected concepts from the HLOs and is used for customisation to meet user requirements. A ULO has exactly the same hierarchical status as the constituent HLOs. It should be noted that the concepts in this HLO may be defined to suit the user requirements and could be rather flexible. It is only with the Top-Level Ontology (TLO) that one would prefer to keep the concepts the same to enable easier linkage to a web environment.

Case-Specific Ontology (CSO)

The CSO is defined by a user and has its own selection of concepts. A unique concept map can be drawn to represent a specific case study or any specific civil engineering matter under consideration. An example could be when considering earthworks construction. When such a specific case is analysed, it is the easiest to first draw a CSO to represent the case (doing earthworks). By then referring to the HLOs or the appropriate ULO, the gaps between the CSO and the HLO (or ULO) can be identified. The HLOs can act as checklists to ensure complete treatment. It is important to link the CSO to the appropriate HLOs from where they link to the TLO, and therefore also to the world-wide-web. An example of a simple CSO relating to earthworks is shown in Figure 6.

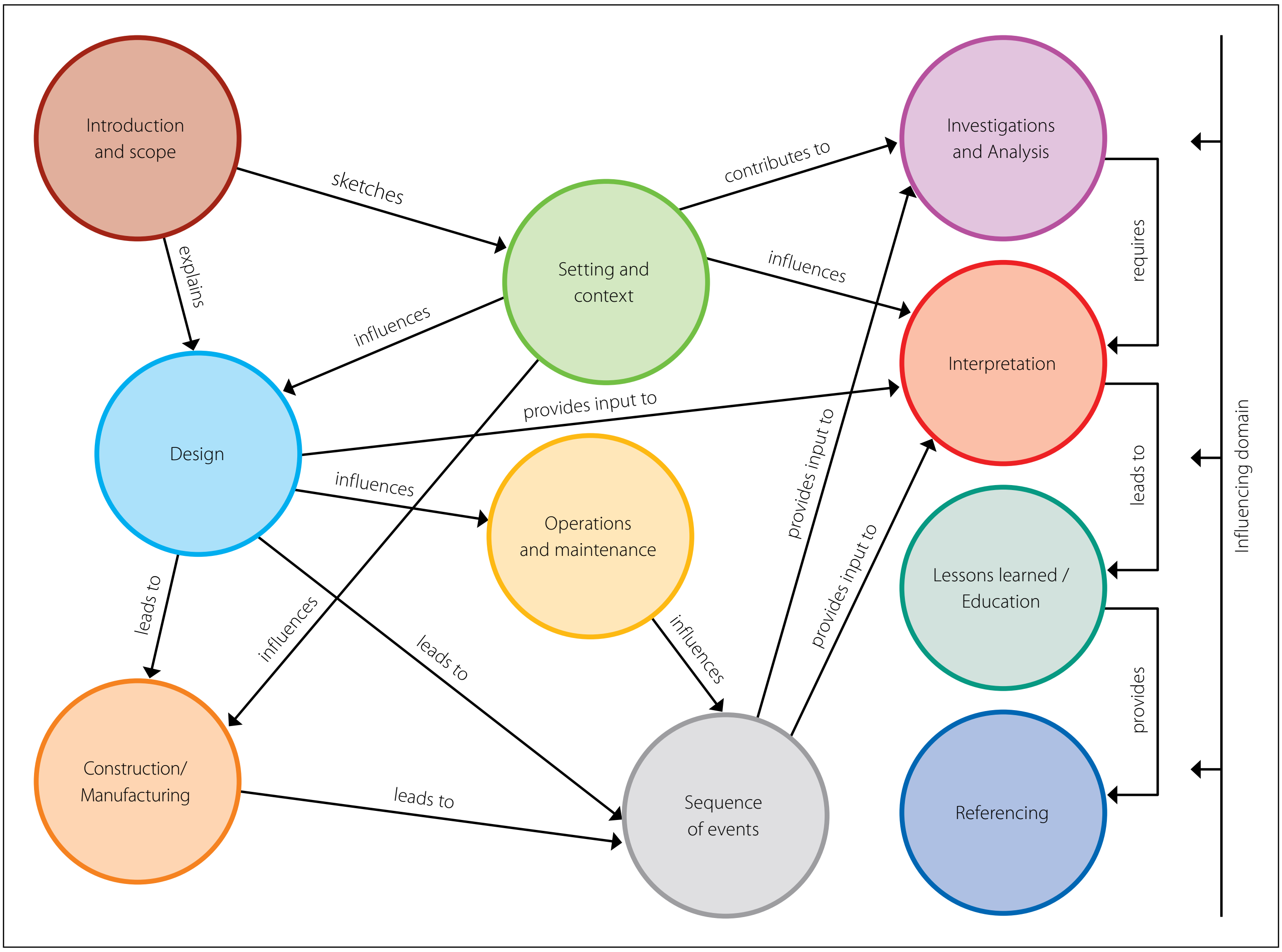

Figure 4 Top-Level Ontology (TLO) concept map

Technical Ontology (TO)

Engineering cases often have a discipline-analytical content and concept statements contain discipline-specific content.

Relationships between technical parameters or concepts are studied and these "technical" relationships are mostly computational of nature. However, in civil engineering, relationships are not necessarily computational. A technical ontology is designed to cater for the quantitative and qualitative requirements. The ontology has two parts, namely a TO that links to the CSO and to a Functional Analysis (FA) component. A TO contains qualitative concepts that link to a specific FA. There could therefore be several TOs, each linking to a particular FA. The TOs then link to a CSO. All the parameters that may be involved in achieving a specific goal or function are taken into account and analysed in the FA (Mann 2009; Scheinkopf 1999; Suh 2001).

Functional Analysis (FA)

An FA entails listing of all the parameters that may contribute to particular functions. First of all, the Main Useful Function (MUF) or ultimate goal of the system must be defined. In order to achieve the MUF, sub-requirements (or specifications) termed the Upper-Level Functional Requirements (ULFR), must be satisfied. To satisfy a ULFR, there could be a large number of parameters that contribute to the end result of the ULFR. The Lower-Level Functional Requirements (LLFRs) are all the contributing parameters that cumulate to determine the value of the ULFR. The LLFRs can be qualitatively or quantitatively interrelated. In quantitative relationships, the LLFRs are variables in equations of which the ULFR is the dependent variable. The FA accommodates the parameters (which are also concepts) to enable analysis. This is best illustrated by way of an example in Table 3 where a functional analysis matrix and an example are shown.

The ULFRs are shown in the columns, and the rows of the matrix show the LLFRs. In the example there are two ULFRs, namely discharge volume and the limitation on the width of the canal. The main contributory parameters are the LLFRs, Manning's roughness coefficient "*n*-value" (LLFR1). The second is the ratio between the area and the wetted perimeter, constituting LLFR2. The third is the slope of the canal, LLFR3. The matrix shows which LLFRs participate to yield the desired ULFR. There are mathematical/empirical relationships that would determine the value of the attributes. In order to satisfy the MUF, both the ULFRs must be met. The potential impact of the area development plan is not listed in the table, but it will have to appear in the TO where there could be a specific concept, named "Future developments". In the HLOs, time, space and capacity have to be superimposed in all the analyses and will be captured in the influencing domain in the TLO. This "future development" concept has a direct relationship with the ULFRs and its LLFRs. (The slope, roughness and infiltration can all be influenced by aspects of the future developments.) In this way, a systematic analysis can be done to arrive at the problems, constraints and outputs from the analysis. The FA serves as an excellent source of knowledge and record of experience.

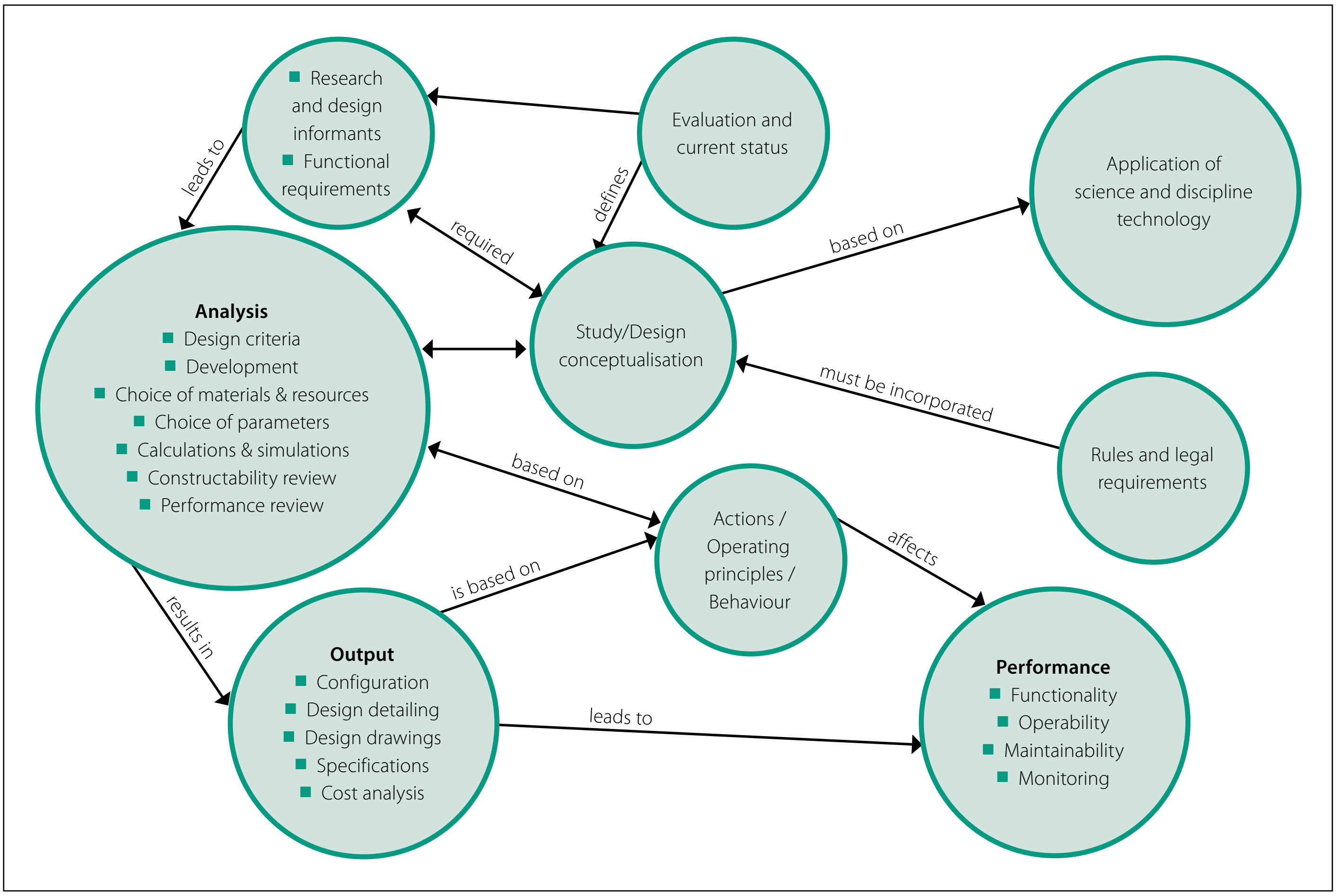

Figure 5 High-Level Ontology (HLO) concept map

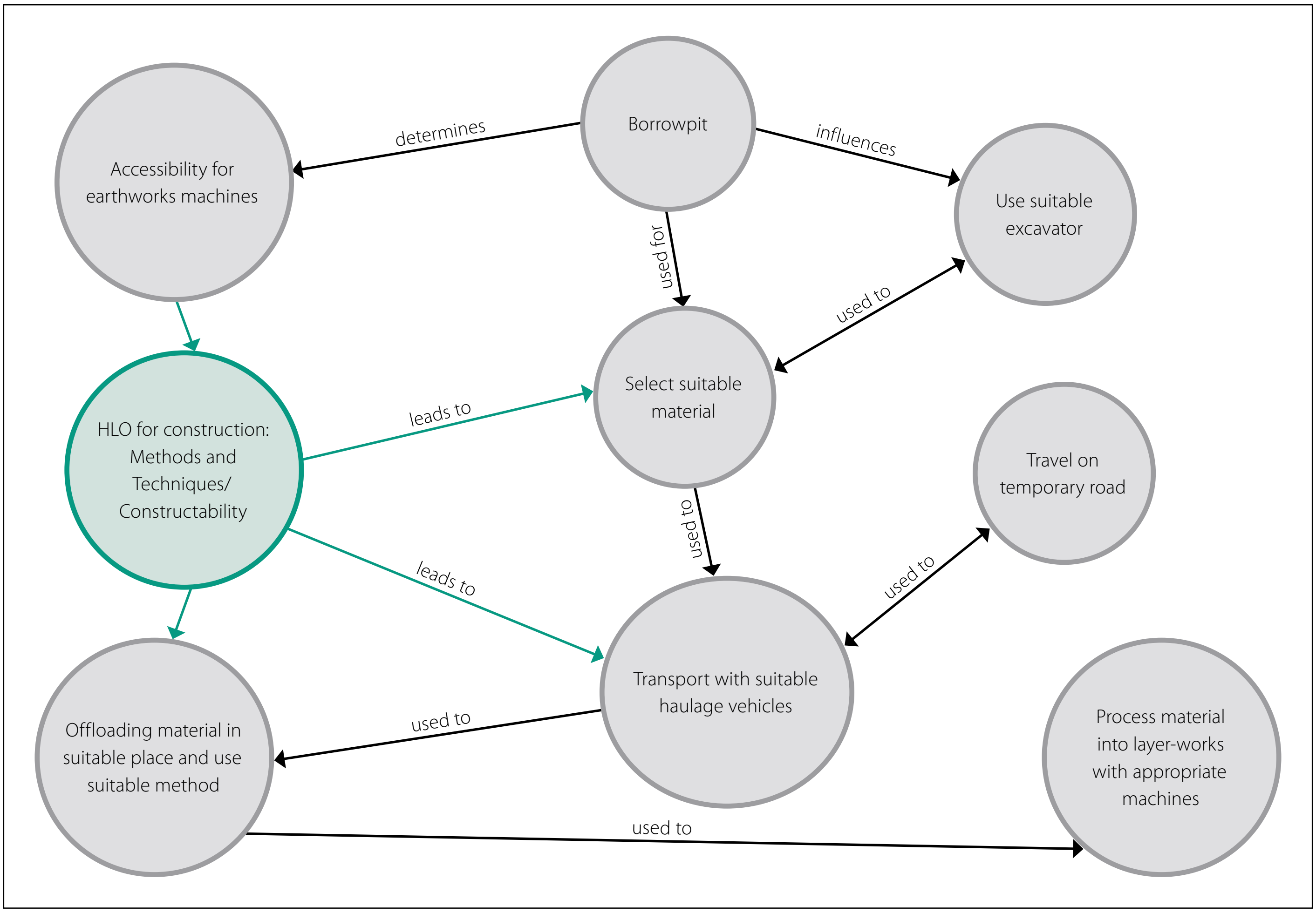

Figure 6 Case-Specific Ontology (CSO) concept map

Table 3 Functional Analysis Matrix

Main Useful Function (MUF) (this links to the TO)		
LLFR (Generic matrix)	Upper-Level Functional Requirements (ULFRs)	
	Requirement 1 ULFR1	Requirement 2 ULFR2
Lower-Level Functional Requirements (LLFR)	Containing elements, attributes and values	
LLFR1	Attribute 1	Attribute 1
LLFR2	Attribute 2	Attribute 2
LLFR3	Attribute 3	Attribute 3
Example: Open channel flow		
Main Useful Function (MUF): Cater for discharge of flood water through a residential development		
Lower-Level Functional Requirements (LLFR)	Parameters, Attributes and Values	
	Upper-Level Functional Requirement ULFR 1	Upper-Level Functional Requirement ULFR 2
	Discharge volume (Manning) (ULFR) of a certain amount	Constraints on the available space (width of the canal)
LLFR1	Manning's *n*-value	
LLFR2	Area-wetted-perimeter ratio	Canal width
LLFR3	Slope of canal	Slope of canal

The overall structure of ontologies is shown in Figure 7. The figure shows where each level of ontology fits into the total framework. On the right-hand side of Figure 7, the linkage to external ontologies is shown. It also illustrates how one can start an ontology in a hierarchical way with the natural sciences, followed by engineering, civil engineering and then discipline-specific ontologies such as structures, geotechnical, roads, transportation, water resources, hydrology and other civil engineering disciplines.

The purpose of the ontologies is to create a functional structure (restructuring of knowledge from original word-descriptions to concept maps and ontologies) for analysis and reporting. The next module is the analysis module, Module B, which is discussed in the following section.

MODULE B – ANALYSIS

In this analysis module, knowledge creation takes place through the application of problem-solving techniques. A selection of appropriate problem-solving techniques are summarised in Table 4.

Summarising from Table 4, various problem-solving techniques can be classified as follows (Verbeek 2018):

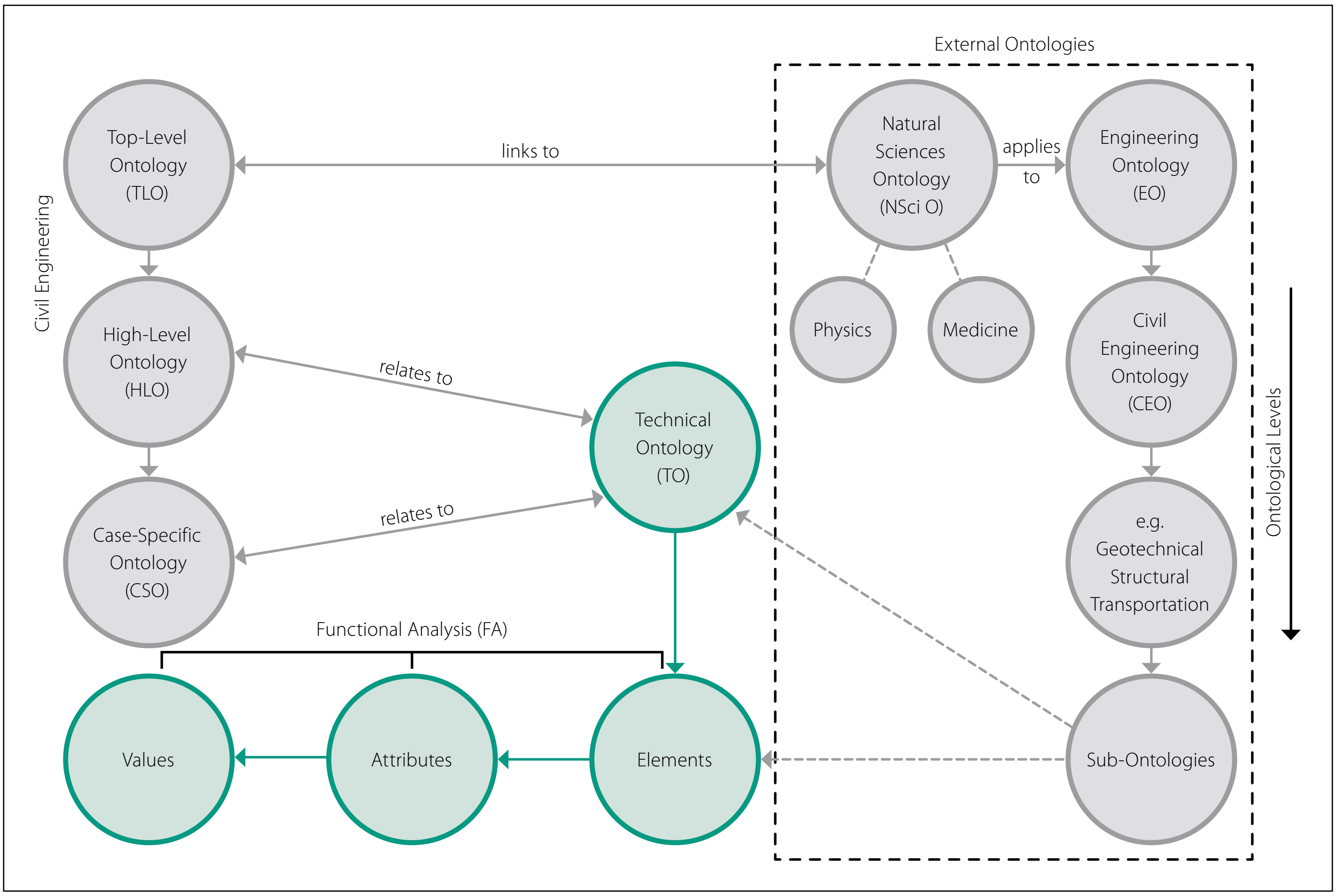

Figure 7 The overall framework of ontologies

Generation/ discovery of new thoughts	Trigger-word technique, brainstorming, synectics morphological analysis.
Synthesis and analysis	Attributes are identified and analysed.
Methodical parametric studies	RCA, FMECA, FAST, HOT, TRIZ and TOC, as defined in Table 4.

The second module, Module B, represents the analysis part where relationships are studied, and contradictions and constraints are identified. A useful way to study relationships is to compile a Concept Matrix (CM) to identify all the possible relationships. The effects of all the concepts on one another and the effects of factors in the influencing domain on each relationship can be studied. All the concepts are listed in a spreadsheet. Pairing the concepts in each row and column with one another, ensures that all the possible relationships are noted and considered. When a problematic relationship is discovered, that relationship can be given a particular reference number to a description and analysis of the problem. All the outcomes of the previous modules are reported in Module C.

MODULE C – OUTPUT MODULE

In this module, the outcomes of the preceding sections are reported and discussed.

The reporting format in Module C is as indicated in Table 5.

Table 5 shows that the various ontology levels are used to lead to the case knowledge and vice versa.

Example: Structural beam

In order to illustrate the foregoing, consider an example of the strength design of a simply supported steel beam, spanning between two supports, bolted into position. (Serviceability considerations can also be included.) Table 6 applies.

Module A1

The comments on the RHS column represent important issues that should all be determined and decided at the beginning of the project.

The next module considers knowledge acquisition.

Module A2

In this module, the various knowledge acquisition techniques are considered. Table 7 applies.

Table 4 **Summary of selected problem-solving techniques**

Problem-solving techniques	Description	Application
Trigger-word technique (Gick & Holyoak 1980; Sarkar & Chakrabarti 2008)	Trigger ideas invoke thought processes.	Thought processes are invoked and broadened.
Checklist technique (Rossiter & Lilien 1994)	Many types of checklists, e.g., criteria, tasks, coordination, trouble-shooting, discipline, procedural, communication, projects.	Checklists serve as reminders of what to consider; however, the actions to follow are of importance and knowledge is required to take action.
Morphological analysis (MA) (Ritchey 2002; Zwicky 1949)	Problem structuring and non-quantifiable relationships to reduce sets of possible configurations. Study relationships.	This is a useful method to only consider the important relationships in an analysis.
Attribute-seeking technique (AST) (Govindaraju & Mital 2008)	Evaluate each attribute of an object or system for meeting functional criteria.	The method goes into detail to look at the attributes. Assist in a systems approach.
Brainstorming technique (B-S) (Silverstein *et al* 2012)	Generation of numbers of ideas and evaluation (ranking) of these ideas.	This group method widens the field of ideas and assists with prioritisation.
Synectics (Seligmann *et al* 2007)	More formalised type of brain storming. Use analogies and metaphor. Forms of metaphor used are a direct analogy, personal analogy and compressed conflict (creating contradicting words or analogies).	This method supports many ideas, and groups sets of ideas to render them explicit. Analogies are also very useful to create more understanding.
Analysis and synthesis (A&S) (Ritchey 1991)	Look for laws of mutual interaction.	This assists to establish clear cause-and-effect relationships.
Root-cause analysis (RCA) (Rooney & Van den Heuvel 2004)	Structured evaluation to establish what, how and why a detrimental event happened.	Essential method to focus on solutions to the correct or fundamental problems. Answers repeated questions of "Why?"
Failure-modes, effects and criticality analysis (FMECA) (Silverstein *et al* 2012; Luthra 1991)	Used to review the effects of a probable failure of components and assemblies on system performance.	This method evaluates different scenarios or systems responses and consequences.
Functional analysis systems technique (F.A.S.T) (Bartolomei & Miller 2001; Grönqvist *et al* 2006; Kardos 1993)	Functions and dependencies are identified and analysed.	This method answers the questions: "How?" "Why?" and "When?"
Hierarchy of objectives technique (H.O.T) (Youker 1998; Hugo 1991)	Related to F.A.S.T and used to analyse and communicate project objectives.	Also answers the "how" and "why" questions. It has a simple structure and is useful for communication. It is used to record and structure methods and experience. Often applied to constructability analysis.
TRIZ Technique (Mann 2009; Gadd 2011)	Inventive problem-solving. Analysis methods used to identify contradictions and using standard inventive principles to solve contradictions.	An investigation technique that offers standard solutions and is used as a basis for the development of solutions of contradictions in relationships between concepts.
Theory of constrains (TOC) (Scheinkopf 1999)	The theory of constraints deals with systems analysis with the view of increasing throughput.	Systems are analysed to identify constraints in throughput and to resolve the root causes of constraints.

Table 5 Module C: Layout of reporting document

Ontology			Case facts and lessons learned – knowledge gained from the case	Output protocols
Narrative/story	Large concrete pours to be done at a bridge			
TLO	HLO	CSO		
Design	Rules and legal requirements	Concrete delivery trucks	Unroadworthy delivery trucks delay concrete pour	Ensure all logistics are in place when doing a significant concrete pour.
	Configuration	Cranage position	Crane movement fouls with another building	Ensure crane position makes allowance for adjacent structures that may be erected during a project.

The above knowledge acquisition techniques can be applied throughout the design process and are part of knowledge enhancement. The next module consolidates the knowledge in hand by contextualisation.

Module A3

This contextualisation is done from the preceding knowledge theories and the knowledge acquisition techniques as described in the previous section. Table 8 applies.

The above contextualisation shows the relationships between the knowledge theories and knowledge acquisition techniques and how contextualisation is done. The concept maps can now be drawn.

Module 4: Concept maps

From the contextualisation, the CSO (Case-Specific Ontology) map for the design of the steel beam can be drawn. A TO (Technical Ontology) can also be drawn to accommodate specific concepts related to the FA (Functional Analysis).

The main concepts are as follows (also see Figure 8):

- MUF (Main Useful Function). Structural support (first concept).
- Effective span. (This will depend on the chosen steel section, other connections to the beam, and the end conditions or fixation.)
- Loading conditions. (This is specified by the owner. However, uncertainties are often encountered with loading conditions that often change over time.)
- Supports and fixation – including lateral support. (These conditions need to be understood, including requirements for installation (constructability) and possible effects of fatigue due to cyclic loading.)
- Beam type, dimensions and configuration. (The floor clearances need to be taken into account.)

The concept map in Figure 8 reflects the main concepts for the design of the steel

Table 6 Example of structural beam – knowledge theories

Knowledge theory	Comments
Theory of cognition	A beam in its final position is visualised and sketches are made to ensure that the position of the beam and its surroundings are clear.
Theory of knowledge hierarchy	Is what is known, data, information or knowledge.
Theories on types of knowledge	What is known about the procedural, declarative, heuristic, common-sense, inexact, uncertain and ontological issues?
Theories of knowledge conversion	How are design philosophies structured, documented and communicated? Is there a central repository for documenting design details?
Theory of redundancy	Is there any spill-over of information from other disciplines? For example, consider the requirements for supporting electrical cable racking to the beam.
Sense-making theories	Is everything that is needed to be known currently in the "known" domain? Are there complex issues that need to be handled?

Table 7 Example of structural beam – knowledge acquisition

Knowledge acquisition technique	Comments
Case-based reasoning	Consider previous successful designs in relation to the current. What can be learned from the previous cases?
Evidence-based	Evidence-based learnings could be that the grades of bolts are often incorrect, since historically all bolts on the site were grade 4.8 and not grade 8.8 as may be specified. The design may have to rather use grade 4.8 bolts instead.
Experiential	Reflect on experience in beam design and loading conditions actually encountered on sites. Allow for appropriate conditions identified.
Reflective	Reflect on design methods and procedures, including available construction methods and constructability issues.
Critical thinking	Critical thinking is required during a design process to ensure that all factors are considered.
Knowledge spill-over/ exaptation	Ask the question if the beam is in fact necessary. Speak to the owners of the building or plant to see if all alternatives were considered.

Table 8 Example of structural beam – contextualisation

Action	Comments
Establish clear purpose	The purpose of the beam – uses and requirements must be clear. In the concept map, it ties up with the TLO scope and user requirements. (Cognition)
Identify uncertainties	Are the loading conditions clear? What about possible future changes to plant and equipment? (Critical thinking, knowledge hierarchy)
Identify significant influences	Significant influences could be the intensity of corrosion in the location of the beam. Refer also to the issue about the grade of bolts. (Redundancy of information)
Organisational integration	Does the installation of the beam affect production? (Critical thinking, knowledge spill-over, experiential learning)
Project phases	Is the beam a part of a future installation? (Uncertainties)
Identify main issues to explore	The main issues could be the loading conditions and the beam dimensions due to limitations in vertical space. (Experiential)

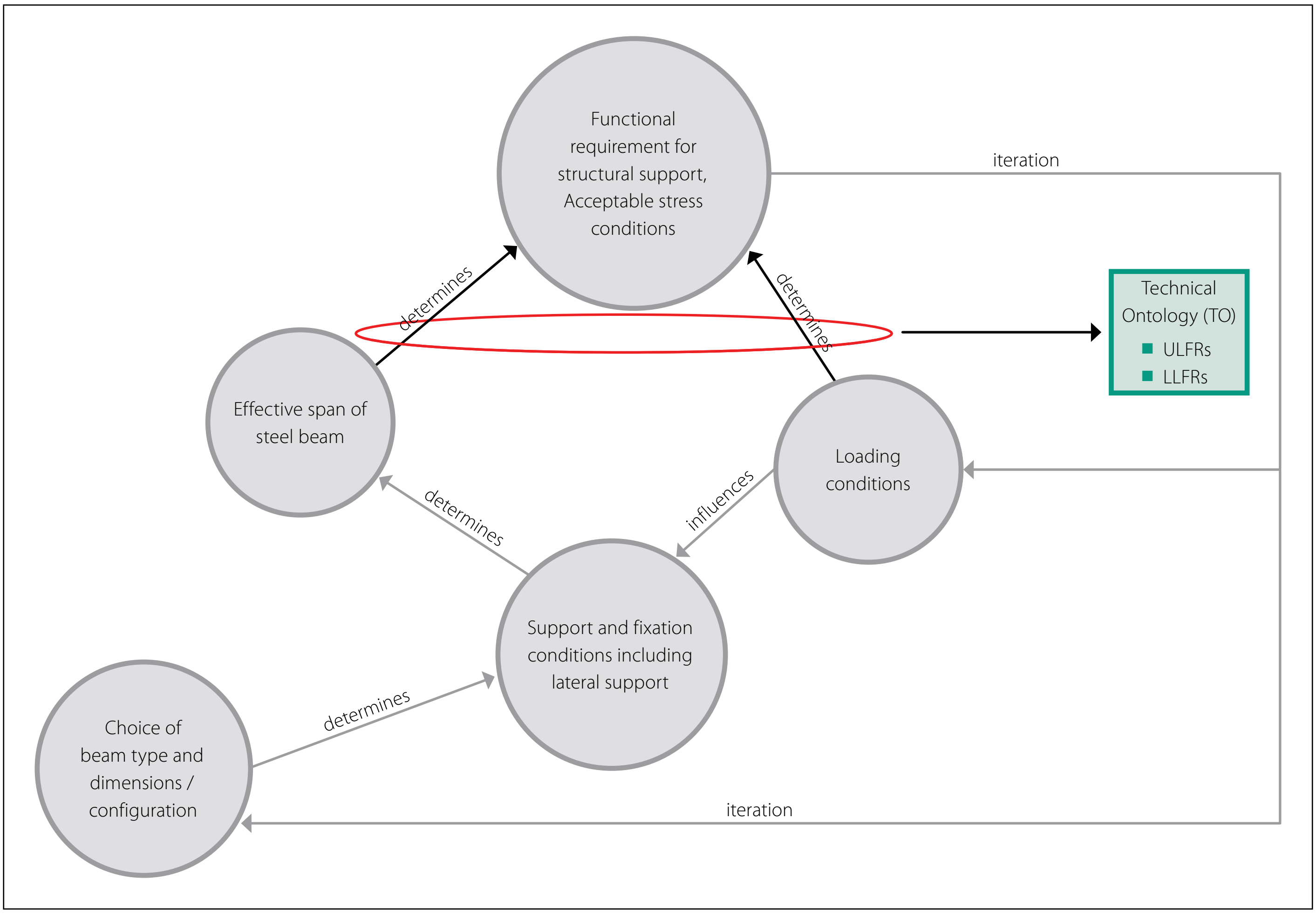

Figure 8 Case-specific concept map for design of a steel beam

Table 9 Example of a structural beam: Functional Analysis Matrix (FAM)

Main useful function (MUF) structural support		
	ULFR1 (Upper-Level Functional Requirement no 1) Functional requirement: Load resistance (stress conditions)	ULFR2 (Upper-Level Functional Requirement no 2) Span of beam (fixed span)
LLFR1 (Lower-Level Functional Requirement no 1)	Parameter	Parameter
LLFR2	Load characteristics	
LLFR3	Fixation details at the supports	
LLFR4	Lateral support of top flange	
LLFR5	Geometry of chosen steel section	
LLFR6	Material properties of the steel	

beam. (This is for illustration purposes only. In practice, both ultimate and serviceability limit states would have to be considered). The next part is the analysis part, Module B.

The concept map illustrates that both the span and the loading conditions are crucial performance characteristics or "demands" constituting the MUF (Main Useful Function) of the beam. The question is: how can these demands or ULFRs (Upper-Level Functional Requirements) be met? The answer lies in the definition of the LLFRs (Lower-Level Functional Requirements) pertaining to each ULFR.

For the ULFR "Span", the clear span between the supports is fixed in this example.

The ULFR for "Loading" is determined by the serviceability limits criteria represented by the stress conditions in the steel when loads are applied. The stress conditions in the beam will be determined by a number of parameters (LLFRs), as indicated in Table 9, the FAM.

The relationships between the ULFR and every LLFR can be calculated or determined from empirical relationships. The results of the calculations can be stored in calculation sheets as reference documents attached to the logic base. The relationships can also be studied by using a CM (Concept Matrix), as shown in Table 10.

Only six relationships, as denoted by the numbers in Table 10 (the X symbols denote complementary relationships that are already numbered) are possible and can be determined by equations or empirical relationships applicable to the discipline of structural engineering.

There are other factors that play important roles in the LLFRs, such as the following:
- Micro-climate conditions
- Corrosion intensity and types
- Availability of steel sections
- Uncertainties concerning the loading conditions (this is often a rather problematic issue in industrial plants).

The above factors can influence the design. These factors are more of a qualitative nature and form concepts in the TO or the CSO, if appropriate.

Module C: Output of the logic base

The outputs of the logic base are summarised in Table 11.

Output protocols

An output protocol is defined as a suggested rule for practitioners to follow. It emanates from the analysis of cases and is put forward as general rules to follow, not limited to only the case study under consideration. The protocols should form part of the industry knowledge base for every practitioner to take careful note of.

Example: Mechanically Stabilised Earth (MSE)

This *descriptive* study informs readers of the method of functioning of Mechanically Stabilised Earth (MSE) and describes the applications and advantage of this method (Smith 2013).

Module A: Synopsis/narrative

This method was invented in 1957 by Henri Vidal, a French architect and engineer, whilst playing with pine needles and beach sand (Smith 2013). The method involves stabilising an earth embankment by means of tie-back strips inserted during the construction of an earth fill. Typically, flat metal strips are inserted perpendicularly to a vertical face of an earth fill. The metal strips are then tied to a facing material for the retention of earth on the vertical face of an embankment. This method of building stable-fill embankments has become popular and is used throughout the world. These fill embankments can be used successfully for the support of bridge decks. The sketch in Figure 9 illustrates a cross-section of the layout.

The layout shows how reinforcing strips are placed in a soil embankment during construction to reinforce the earth, thereby permitting a vertical face on the traffic side of the abutment. The Case-Specific Ontology (CSO) concept map is shown in Figure 10.

The CSO concept map in Figure 10 shows the main concepts of construction of an embankment by using Mechanically Stabilised Earth (MSE). The next step is to map the CSO with the generic HLO. This is described in the paragraphs below.

Table 10 Example of structural beam: Concept Matrix (CM)

	Loading	Span	Geometry	Fixation
Loading		1	2	3
Span	X		4	5
Geometry	X	X		6
Fixation	X	X	X	

Module B: Analysis

Note: Only some examples of HLOs are presented in this paper. For more comprehensive details, refer to Verbeek (2018).

The first five paragraph headings below represent concepts belonging to HLOs.

Purpose

The purpose of this method is to create a stable embankment, on which infrastructure can be constructed.

- Construction must be possible in poor founding conditions.
- The structure (both the abutment and the bridge) must not be sensitive to settlements.
- The construction duration must be as short as possible.
- There must be a smooth transition between the earth approaches and the concrete deck.

Configuration

In this method, horizontal reinforcement is placed in an embankment fill. The reinforcement is placed in alternating layers of compacted soil and soil where reinforcement has been placed. The face(s) of the embankment are typically vertical, and cladding is positively connected to the horizontal reinforcement to provide an aesthetically pleasing façade.

Mechanism of operation

The horizontal reinforcement in the fill restrains lateral strain by friction between the soil and the reinforcing elements in the soil. The effect is the same as if a lateral restraining load is applied to the soil. As the vertical stress is increased, so do lateral stresses increase in direct proportion. The horizontal strain in the earth is restrained by the reinforcing elements.

Operational principles

In soil mechanics, the volumetric stress-strain relationship is of importance (this is part of the TO). If a vertical stress is applied to a soil specimen, horizontal stresses increase in direct proportion (and vice versa). However, due to the behaviour of particulate media, such as compacted soil, a small lateral force or restraint would have a larger proportional effect on the vertical load-bearing capacity. (This is illustrated and can be calculated with reference to the Mohr-Coulomb failure criteria (Das & Sobhan 2014)).

Influencing domains

Geotechnical considerations

- Geochemical environment
- Construction quality control and assurance
- Seismic events

Relationships and possible failure mechanisms (combining it with problem-solving techniques)

Relationships are stated and evaluated according to the TRIZ method (substance-field relationships) (Mann 2009; Gadd 2011). Comments are given on each relationship that can be reported in the output module.

- *Relationship: Embankment and subsoil.* Potential failure of foundation soil and

Table 11 Example of a structural beam: Module C output

Ontology			Case facts and lessons learned – knowledge gained from the case or actions taken	Output protocols
Narrative/story	Design of a steel beam			
TLO	HLO	CSO		
Design	Analysis	Loading conditions	Due to future needs, loading unsure and further clarification needed.	Ensure that loading conditions are clarified at the onset of the design process.
		Span of the beam	This is a fixed entity.	

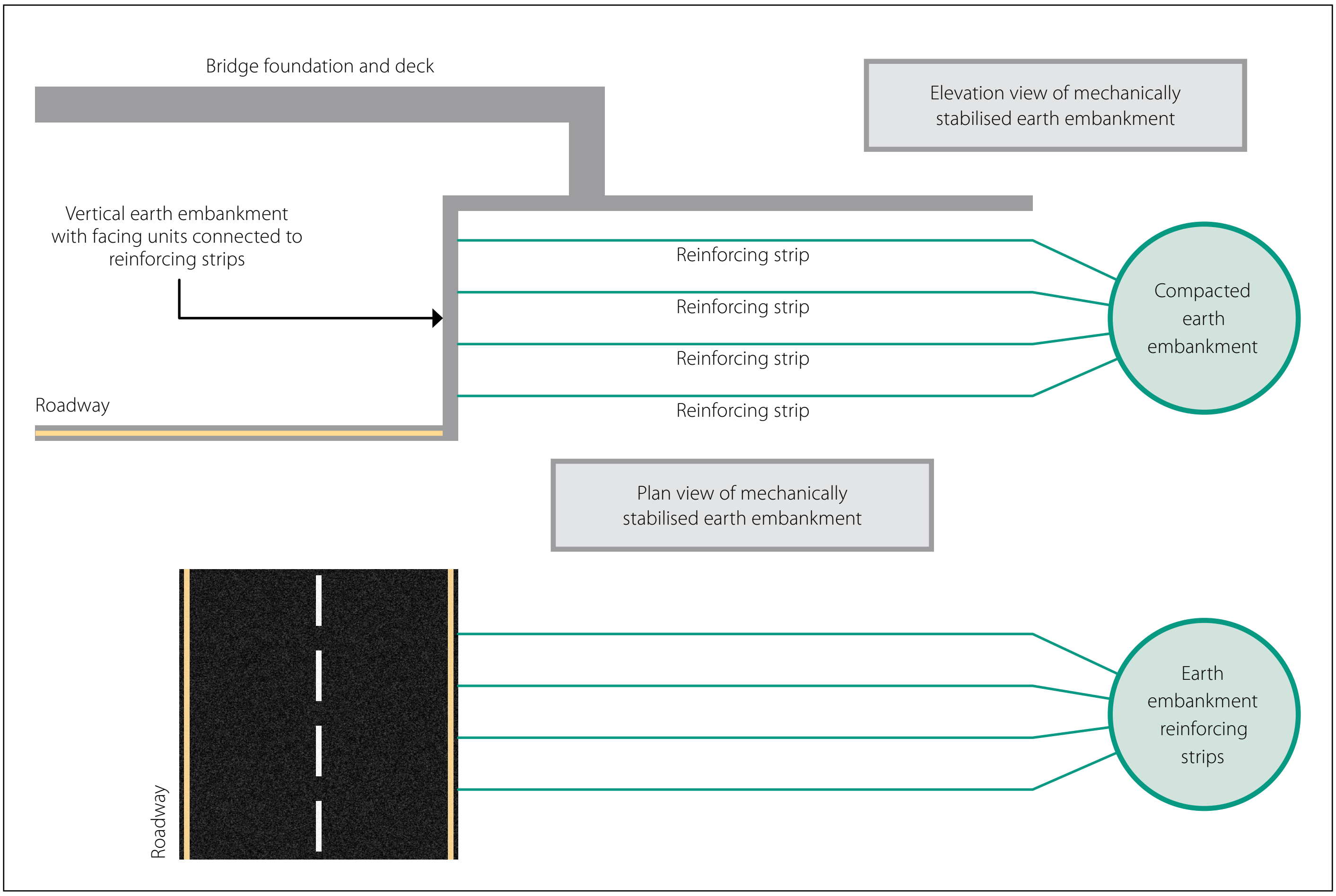

Figure 9 Layout of mechanically stabilised earth (MSE)

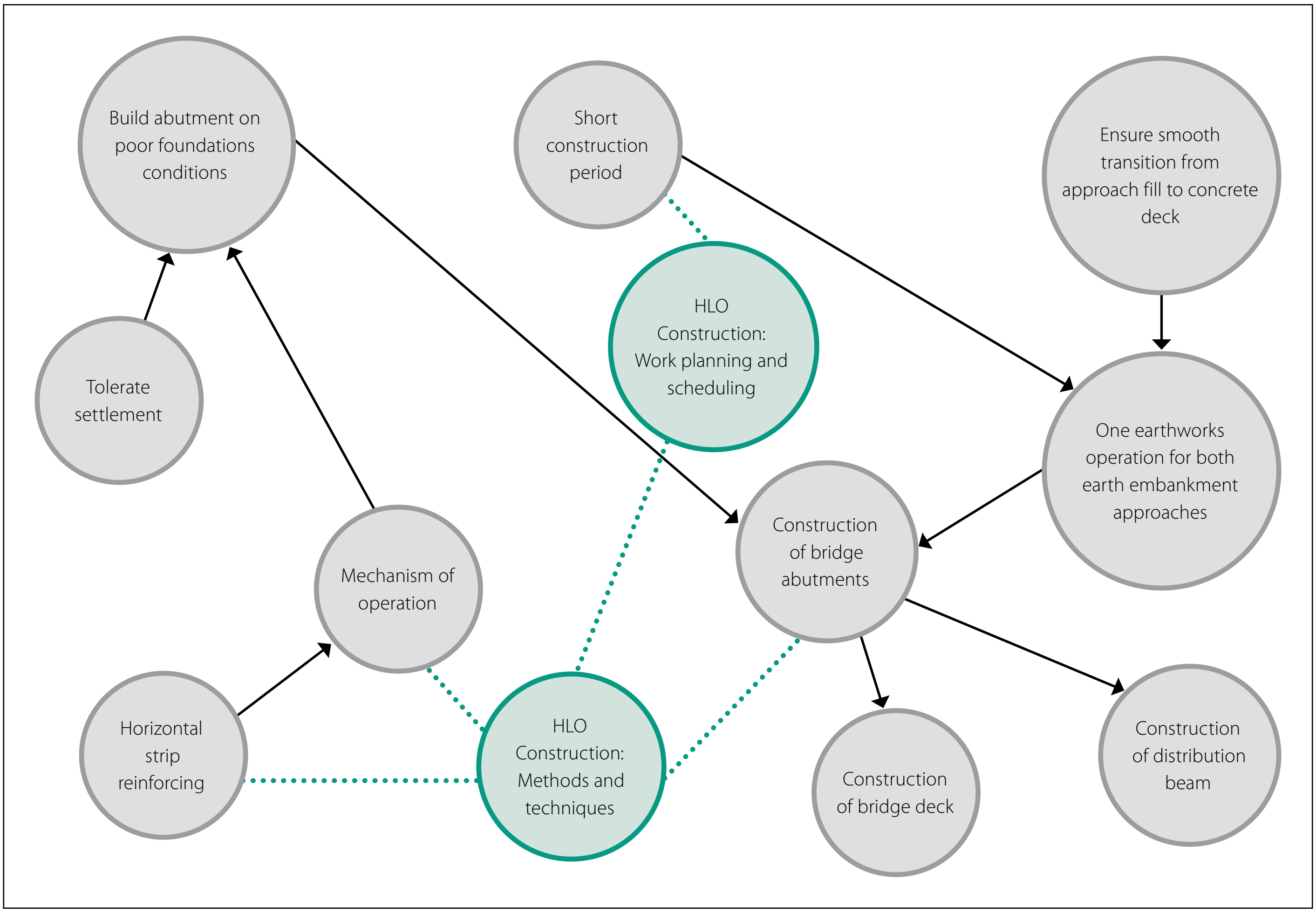

Figure 10 Case-Specific Ontology (CSO) concept map for mechanically stabilised earth (MSE) for bridge abutment

potential settlement – both conditions can adversely affect the mechanically stabilised earth embankment.

- *Relationship: Soil and compaction equipment*. It might not be possible to properly compact poor soil to the required specification.
- *Relationship: Metal or polymer strips and soil*. Strips may slip due to insufficient friction between strips and poorly compacted soil.
- *Relationship: Metal or polymer strips and moisture in soil*. The frictional resistance between the metal or polymer strips and the soil can reduce due to a reduction of effective stress as a result of excess pore pressure (a phreatic surface may form in the fill). Moisture could also, through the transportation of ions, cause corrosion that could destroy the metal strips.
- *Relationship: The extensivity of the metal or polymer strips and the lateral strain in abutment fill*. Extension of strips such that lateral forces cannot be mobilised.
- *Relationship: Metal or polymer strips and facing material connections*. Possible failure of metal connections at the cladded face due to poor design/manufacturing or due to corrosion on soil/air interface.
- *Relationship: Bridge foundation and soil embankment*. Soil in MSE may settle and cause excessive settlement of bridge.
- *Relationship: Rainfall and embankment*. Rain can dam up on the embankment and saturate the soil, weakening the soil structure as a result of excessive pore pressure (phreatic surface may form). Insufficient drainage of fill, as well as surroundings, can result in failure of the embankment.

The above set of relationships are deduced from the case study and are not directly reported in the script of the study.

Technical Ontology (TO)

The functioning of the metal strips relative to the soil can be expanded in a Technical Ontology (TO). For example, the shear resistance of the strips can be considered. There is a functional relationship between the soil properties and the vertical-effective stress and the shear that can develop between the soil at particular points along the strips. The relationships can be determined by laboratory testing. There are also other important relationships that may need further elaboration. These are conceptually shown in Table 12. Each FR (Functional Relationship) represents a concept statement that can be further expanded in a TO.

The FAM (Functional Analysis Matrix) can also be compiled to extend the analysis as shown in Table 12, in a slightly different format than previously. (The relationships are sequentially numbered.)

Each individual cell should have a reference number, as indicated in Table 12. Each relationship can be referenced, listed, described and analysed. For example, relationship 1 denotes the relationship between soil type and settlement. In this case, the clay content, type of clay, thickness of the clay, stress history and changes in stress conditions in the clay are important considerations. The perceived important relationships are marked with bold numbers. These may need special attention by way of, for example, laboratory analysis of the interface of the reinforcing material with the compacted soil. A database with typical friction values may be of great assistance in this regard and can be linked to this item in the logic base (for example through the H.O.T. technique).

This case study is, in fact, a descriptive study and does not present specific experience or convey knowledge other than introducing the technicalities of employing mechanically reinforced earth for use in bridge abutments.

Table 12 Example mechanically stabilised earth: Functional Analysis Matrix (FAM)

Attributes	Upper-Level Functional Requirements (ULFRs)		
LLFR	Tolerance to settlement	Limiting lateral restraint	Stable facing of retaining wall (vertical facing)
Soil type	1	**2**	3
Strips type	4	**5**	6
Friction between strips and soil	7	**8**	9
Extensiveness of strips	10	**11**	12
Foundation strength	**13**	14	15
Foundation settlement	**16**	17	18
Horizontal strain of embankment	**19**	20	**21**
Connections between strips and front facing	23	23	**24**

Module C: Reporting

Reporting in the logic base is done as in Table 13.

CONCLUSIONS

In this paper, it is shown how knowledge theories and knowledge acquisition techniques are integrated by contextualisation to lead to the drawing of concept maps that can be used in civil engineering design and to analyse and record specific experience. The concept maps form part of concept-based ontologies that are analysed to identify problems and constraints. Solutions to these problems and constraints create new knowledge and can be reported and linked to the world-wide-web. This linkage is made possible by utilising Top-Level-Ontologies or Upper-Level Ontologies to link to existing or new ontologies on the world-wide-web. The logic base acts as a procedure to lead and integrate all the above-mentioned aspects into three modules. These modules of the logic base were described and simple examples were given of how the logic base functions. The end result in Module C (output module) contains all the outcomes of the processes and can provide valuable knowledge. In essence, the original words and descriptions of a case or matter under consideration are restructured into ontologies, and analysis is done. This enhances knowledge and makes it, in a succinct way, more readily available for reuse.

The logic base is a technique to bring knowledge closer to the practising engineer and facilitates thinking processes that will greatly assist in systematising knowledge, the analysis thereof and making it accessible on the word-wide-web.

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Table 13 Example of mechanically stabilised earth Module C: Output from logic base

	Ontology (TLO/HLO/CSO)	Case facts and lessons learned – knowledge gained from the case	Output protocols
1	User requirements (HLO for introduction and scope).	■ Rapid embankment construction. ■ Construction on a relatively weak foundation (foundation strength to be assessed vs loading and rate of loading). ■ Structure not very sensitive to settlements. ■ Smooth transition between approaches and concrete bridge.	Design to accommodate reasonable tolerances for relative movement between soil and concrete structures.
2	Configuration (HLO for design).	■ Friction strips built into fill to retain vertical face. ■ Strips made of steel or polymers.	Complement natural material with steel or polymers for construction.
3	Governing laws (HLO for design)	Friction, consolidation settlement and collapse of soil, compatibility of soil, chemical resistance.	
4	Principles of operation (HLO for design)	■ Friction between strips and soil develop horizontal forces, resisting lateral movement. ■ Friction between steel/polymer strips to be assessed, and spacing between strips determined.	
5	Events (HLO for sequence of events)	Possible failure mechanisms: ■ Weak compaction – low density. ■ Slip between strips and soil. ■ Loss of effective stress due to water ingress and the establishment of a phreatic surface. ■ Strips extensiveness too large to mobilise lateral forces. ■ Failure of connections of facing to strips.	
6	Operations and maintenance (HLO for operations and maintenance)	Very little, if any, maintenance is required. Occasional inspections should be conducted.	
7	System response and controls (HLO for system response and control)	Only drainage and settlement need to be monitored.	
8	Influencing domains (list of possible influences)	Corrosion / chemical attack	
9	Element/parameter analysis (FA)	Refer to Table 12.	

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