Choosing the Right Tool for the Job: A Framework to Compare the Effectiveness of Problem Structuring Methods in System Dynamics Modeling

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Abstract

The understanding embedded in the mental models of participants in organizations is considered a crucial source of information for building system dynamics models. However, System Dynamics (SD) as a modeling methodology has not developed a standard way of eliciting and recording such understanding. Currently several methods of elicitation known as *problem structuring methods* (PSMs) are employed in the SD community to facilitate problem situation conceptualization in group model building (GMB). Despite a growing literature on the application of PSMs, very limited research has been undertaken to assess and compare the relative effectiveness of alternative PSMs. In this paper, we apply theoretical insights from cognitive science, in particular Cognitive Fit Theory, and visual notation analysis to suggest the characteristics of a PSM that are likely to be cognitively effective in conceptualizing problem situations in building system dynamics models. We then provide a preliminary report on an exploratory laboratory test of our predicted characteristics on four PSMs that are widely used by the SD community: (i) Causal Loop Diagrams (CLDs), (ii) Influence Diagrams (ID), (iii) Cognitive Maps, and (iv) (Magnetic) Hexagons. In the problem situation conceptualization used in our test, IDs were found to have the highest cognitive effectiveness, followed by CLDs, (Magnetic) Hexagons, and Cognitive Maps.

Keywords: Cognitive Effectiveness, Cognitive Fit Theory, Problem Structuring Methods (PSMs), System Dynamics (SD)

1. Introduction

In system dynamics (SD) modeling, the information contained in the organizational participants' (hereafter "participants") mental models is considered as a crucial source of information (Forrester 1961). Increasingly, system dynamics simulation models are built in close cooperation with participants in order to elicit and capture the understanding embedded in their mental models and thereby improve decision-making or problem-solving performance. In the SD literature, this process is usually referred to as “group model building” (GMB) (Andersen et al. 1997; Vennix 1996). By involving participants and facilitating collaborative modeling processes with these parties, GMB is intended to create a shared perspective on a problem at hand and on potential solutions by surfacing implicit assumptions and beliefs held by participants (Richardson and Andersen 1995; Vennix et al. 1996; Vennix 1996).

Richardson and Pugh (1981) outline SD modeling as a seven-step process that begins with identification of a problem followed by system conceptualization. In the conceptualization phase, the modeler observes some aspect of a situation that is then referred to as the “universe of discourse” (UoD). The modeler then tries to distinguish a set of entities that compose the universe of discourse and the relationships between them. Such conceptualizations are, in effect, a lens through which the modeler observes phenomena of interest in a UoD (Tarski and Corcoran 1983). Next, the modeler develops a model in the representation domain. The model is composed of modeling constructs intended to represent observed entities in the UoD. The conceptualization lens adopted by a modeler determines the kinds of modeling constructs that will be used in the representation domain and enables a mapping of the entities observed in the universe of discourse onto constructs in the representation domain. The conceptualization lens adopted by the modeler thereby determines the modeling constructs that are intended to lead to a "real-world" interpretation of the problem situation. Figure 1 represents this process.

Prior to the emergence of GMB, an SD modeler formed his/her conceptualization of a situation; increasingly today participants are directly involved in mapping aspects of a problem situation into “modeling constructs” used in the representation domain. The involvement of participants is widely regarded as resulting in models that deliver better representations of problem situations (Lane and Oliva 1998).

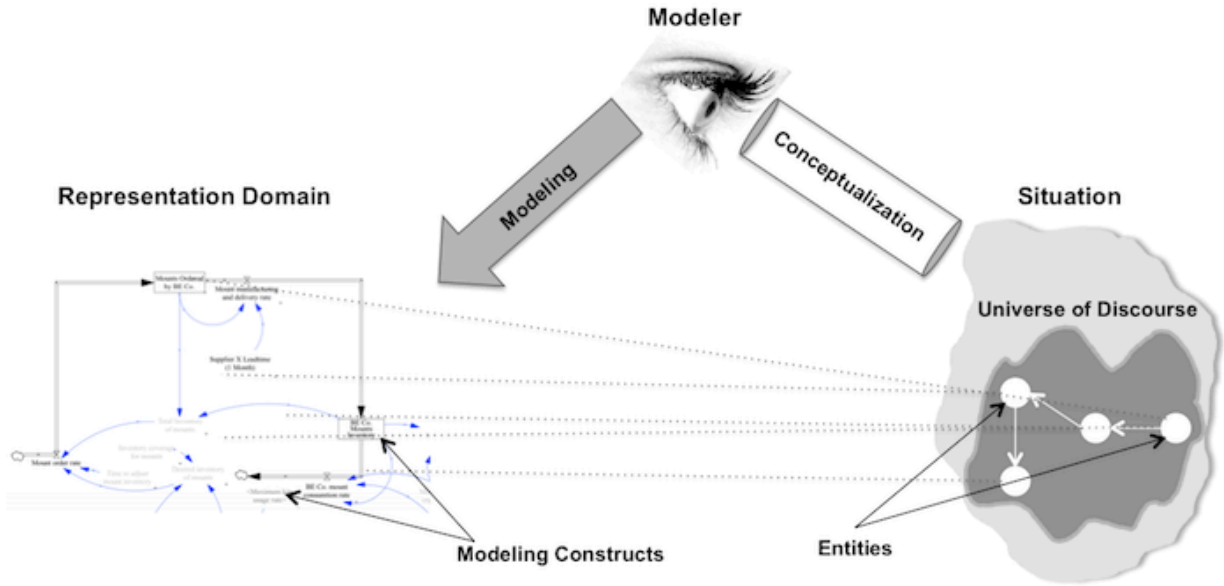


Figure 1: Conceptualizations in the Modeling Process

Nevertheless, the SD literature offers few insights into the relative merits of alternative ways of eliciting and recording participants' understandings in the SD modeling process (Lane and Oliva 1998; Lane 1994). We suggest that SD should begin to take more seriously and address more actively the strengths and weaknesses of alternative approaches to helping participants surface and articulate their understanding relevant to a problem situation.

This conceptual gap in SD modeling methodology has precipitated increasing interest among the SD community in developing frameworks and tools that can facilitate and improve the conceptualization phase of model building. Several tools and techniques have been developed inside the SD community to assist in eliciting participants' understanding. Such tools and techniques are commonly referred to as problem structuring methods (PSMs) (Rosenhead 1996; Mingers and Rosenhead 2004). PSMs developed and used in the SD community include Cognitive Maps (Eden 1994) and (Magnetic) Hexagons (Lane 1993; Hodgson 1992; Wong et al. 2011). Moreover, a number of hybrid approaches integrating elements of system dynamics and other PSMs have also emerged to support problem conceptualization. Lane and Oliva (1998), for example, develop a theoretical framework (i.e. Holon Dynamics) that integrates system dynamics and soft systems methodology. Lane (1994) provides a detailed description of PSMs employed in SD modeling.

We suggest that a key research question facing the SD community is how it can usefully compare and assess the relative performance of these actual and other potential PSMs, given the potential impact of PSMs on the quality of the communication between participants and SD modelers (Akkermans and Vennix 1997). Moreover, as noted by Franco and Montibeller (2010), this question takes on greater importance as PSMs are increasingly being taught to participants to enable conceptualization of problem situations without requiring facilitation by a modeling expert.

Further concepts and theory from the cognitive sciences are clearly not only relevant but also needed in order to analyze this important aspect of PSMs. To address this gap, in this paper we develop a framework to assess the performance of PSMs used in SD group model building, whether undertaken with SD modelers or autonomously. We invoke a theoretical perspective from cognitive science -- Cognitive Fit Theory -- related to dual task problem-solving (Vessey 1991; Shaft and Vessey 2006) as well as the work of Larkin and Simon (1987) to suggest how the gap between the conceptualizations of participants and the representations of SD modelers can be bridged to increase problem-situation modeling and problem-solving performance.

Applying Cognitive Fit Theory and insights form cognitive science enables us to identify some characteristics of PSMs that should result in improved problem solving performance in group model building. These predicted characteristics were tested by conducting an exploratory laboratory study involving 12 groups of participants, each consisting of two PhD or MSc students in the field of computer and communication sciences at Ecole Polytechnique Fédérale de Lausanne (Switzerland). The groups were asked to develop conceptualizations of a pre-defined problem situation using four problem structuring methods widely used in the SD community: (i) Causal Loop Diagrams (CLDs) (Stermann 2001; Senge 1990); (ii) Influence Diagrams (Coyle 1998; Diffenbach 1992; Coyle 2000); (iii) Cognitive Maps (Eden 1994); and (iv) (Magnetic) Hexagons (Lane 1993; Hodgson 1992; Wong et al. 2011). We chose these four PSMs because they are currently being used in the SD community for group model building and because they lead to a diagrammatic representation of a problem situation.

This paper is structured in the following way. In section 2 we briefly discuss the underlying theory of Cognitive Fit in dual task problem-solving, delineating the role of external and internal representation in problem-solving. We then apply Cognitive Fit Theory to analyze a SD modeling process. Building on the theoretical insights developed, in Section 3 we suggest the characteristics of effective PSMs. Section 4 reports some results of our exploratory laboratory study to test our predictions. Section 5 includes conclusions and suggestions for further research.

2. Cognitive Fit Theory Applied to System Dynamics Modeling

Cognitive Fit Theory (Vessey 1991) can be applied to shed light on the cognitive processes involved in carrying out tasks such as constructing SD models. It proposes that achieving a good "correspondence" between a problem situation and the representation of the problem situation leads to superior problem-solving task performance. Vessey (1991) defines mental representation as “the way the problem is represented in human working memory” and suggests that in carrying out a problem-solving task, individuals create mental representations of the problem that incorporate the characteristics of both the representation of a problem and the representation of the problem-solving task (Vessey 1991). When individuals need to solve problems in a certain domain, their performance will be enhanced if their representation of a problem corresponds well to the problem-solving task. Figure 2 summarizes these tenets of Cognitive Fit Theory.

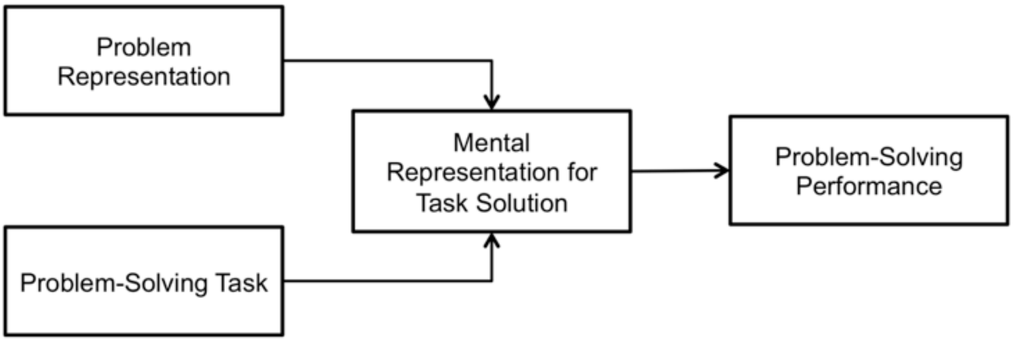


Figure 2: Cognitive Fit Model for Problem-Solving (Vessey, 1991)

From the perspective of Cognitive Fit Theory, SD model building entails two distinct tasks: one related to problem situation conceptualization, and the other related to SD model construction. Thus, SD model building involves a dual-task problem solving. Looking at SD modeling as a dual-task problem-solving exercise helps us to understand the interrelationships between a problem-solving task and the cognitive processes of participants involved in the task.

Shaft and Vessey (2006) extended Cognitive Fit Theory to address dual-task problem solving, which they characterize as occurring "when problem solvers perform two (or more) tasks simultaneously where each task is referred to as subtask." Drawing on the work of Zhang and Norman (1994) and Zhang (1997) on distributed cognition, Shaft and Vessey modified their original model to include the concepts of external and internal representations, as noted in Fig 3.

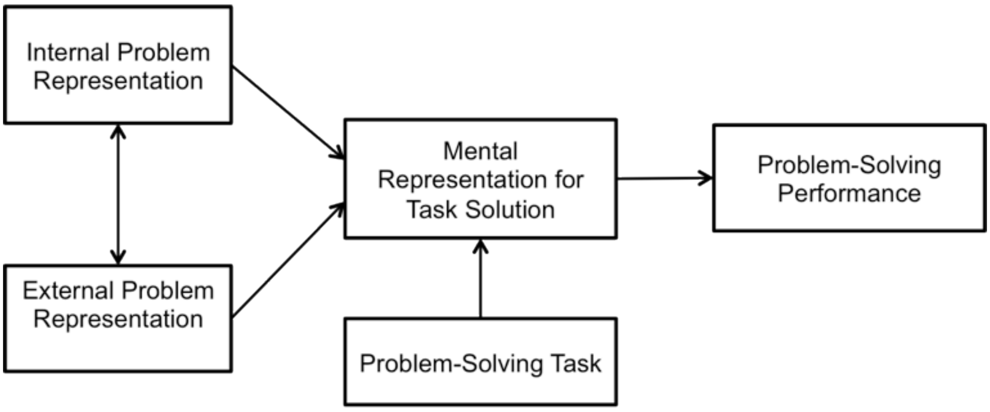


Figure 3: Extended Cognitive Fit Model for Dual Task Problem-Solving (Vessey,1996)

Zhang (1991:1) defines internal and external representations in the following way:

> Internal representations are the knowledge and structure in memory, as propositions, productions, schemas, neural networks, or other forms. The information in internal representations has to be retrieved from memory by cognitive processes, although the cues in external representations can sometimes trigger the retrieval processes.
>
> External representations are the knowledge and structure in the environment, as physical symbols, objects, or dimensions (e.g., written symbols, beads of abacuses, dimensions of a graph, etc.), and as external rules, constraints, or relations embedded in physical configurations (e.g., spatial relations of written digits, visual and spatial layouts of diagrams, physical constraints in abacuses,

etc.)". For example, problem solvers use external representations when they use a list for grocery shopping or when they use graphs to understand economic trends.

A dual task problem-solving model reflects the fact that both *internal* and *external representations* and the interactions among them contribute to the *mental representation for task solution* developed to solve a problem. Zhang (1997:2) explains the interaction between the internal and external representation by considering multiplication as a problem-solving task:

> "Let us consider multiplying 735 by 278 using paper and pencil. The internal representations are the meanings of individual symbols (e.g., the numerical value of the arbitrary symbol "7" is seven), the addition and multiplication tables, arithmetic procedures, etc., which have to be retrieved from memory; the external representations are the shapes and positions of the symbols, the spatial relations of partial products, etc., which can be perceptually inspected from the environment (Zhang and Norman, 1994). To perform this task, people need to process the information perceived from external representations and the information retrieved from internal representations in an interwoven, integrative, and dynamic manner."

Figure 4 represents SD model building as dual-task problem solving. As illustrated, the performance of SD models in capturing a problem situation and helping to develop solutions that improve the problem situation requires carrying out "problem situation conceptualization" and "SD model construction" subtasks.

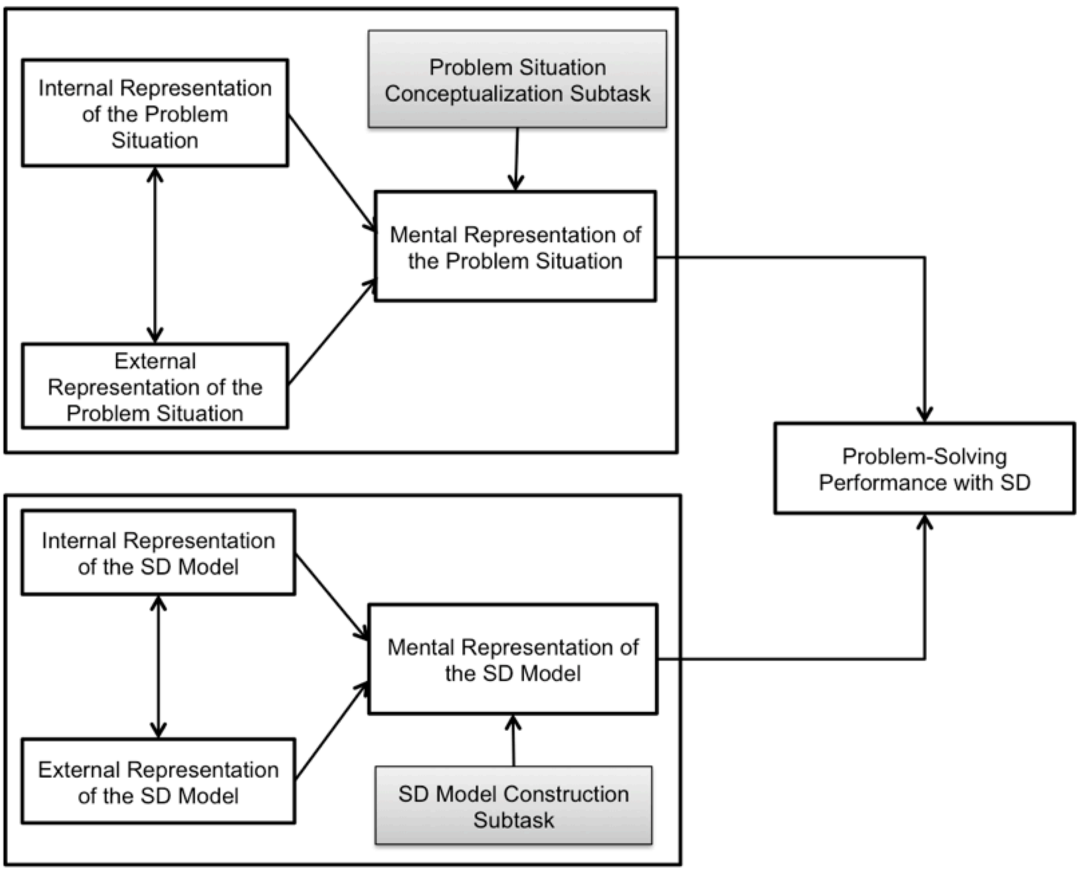


Figure 4: Cognitive View of SD Modeling as a Dual Task Problem-solving

In effect, participants apply a PSM to develop a conceptualization of the problem situation. The PSM enables the participants to develop an external problem representation in the problem situation conceptualization sub-task. Then, using this external representation, the participants form internal mental representations of the problem situation. These two representations then go through interactive iterations until a shared mental representation of the problem situation is achieved among the stakeholders and the problem situation is considered adequately represented. An SD modeler may then employ this representation of the problem situation as an external representation in the modeler's SD model construction subtask in the process of building an SD model, as suggested in Figure 4.

3. Characteristics of Effective PSMs

In this section, we draw on Cognitive Fit Theory (Vessey 1991) and visual notation analysis Moody (2009) to develop a view of SD modeling that suggests how specific tools and techniques applied to conceptualize a problem situation can in fact improve the problem-solving performance of the SD models. In the subsequent section, we describe the exploratory laboratory study we conducted with student subjects at Ecole Polytechnique Fédérale de Lausanne between February and March 2012 to test these predictions.

Vessey (1991: 3) states that:

> “Matching representation to tasks leads to the use of similar problem-solving processes, and hence the formulation of a consistent mental representation. There will be no need to transform the mental representation . . . to extract information from the problem representation and to solve the problem. Hence, problem-solving with cognitive fit leads to effective and efficient problem-solving performance."

In other words, if participants' internal and external representations, do not correspond well to a problem situation and problem-solving task (i.e., Problem Situation Conceptualization and SD Model Construction), there is likely to be little or nothing to guide the SD Modeler or the participants in deriving a task solution, and both must then exert greater cognitive effort to try to transform their respective representations into a form suitable for solving the problem specified in the task. This excessive effort will result in decreased problem-solving performance (Vessey and Galletta 1991).

From the perspective of problem situation conceptualization, SD models should result in higher performance in problem-solving if the representations of participants' understanding emphasized in the PSM as an external representation in the Problem Situation Conceptualization subtask triggers the elicitation and retrieval of participants' tacit knowledge, mental models, and causal structures. Larkin and Simon (1987) suggest that the *ease*, and *accuracy* with which a representation can be processed by the human mind determines the cognitive effectiveness of the representation. The cognitive effectiveness of a PSM therefore reflects the ability of a particular PSM to communicate or "connect" cognitively with a given group of participants.

A PSM provides a problem situation conceptualization that is then used by the SD modeler as an external representation in the SD model construction sub-task. The SD model can be expected to result in higher performance in the problem-solving task if the format and the type of the participant understanding addressable through the PSM (i.e. the problem situation conceptualization) matches the entities and relationships incorporated in an SD stock and flow simulation model. In this case, a given PSM may effectively support an SD model construction subtask, and the SD modeler does not need to try to transform the “problem situation conceptualization” subtask to become compatible with the “SD model construction” subtask. Exploring the cognitive fit of different PSMs and the SD model construction sub-task is a part of our future work.

In our experiment, we sought to assess empirically the impact of PSMs that have been widely applied in the SD community on the conceptualization of a problem situation, choosing PSMs that create a diagrammatic or graphical representation of a problem situation conceptualization. The Graphical and diagrammatic representations are argued to be superior to other forms of representation such as verbal representations. Graphical representations can give participants access to understanding that can’t be accessed by internal representations (Zhang 1997; Scaife and Rogers 1996). Larkin and Simon (1987) state that diagrams help to facilitate problem solving by bringing together all pieces of information related to a situation and thereby reducing the time required to make inferences. Moreover, diagrams support cognitive operators that can recognize features easily and make inferences directly. Thus, a graphical representation method may result in better representation of a problem situation by making the relationships between the entities in a problem situation explicit and visible. Therefore, in our study we focus on the PSMs to which diagramming is central.

The four PSMs employed in our study are: Causal Loop Diagrams (CLDs) (Stermann 2001; Senge 1990), Influence Diagrams (Coyle 1998; Diffenbach 1992; Coyle 2000) Cognitive Maps (Eden 1994) and (Magnetic) Hexagons (Lane 1993; Hodgson 1992; Wong et al. 2011). While CLDs and Influence Diagrams have been developed inside the SD community, (Magnetic) Hexagons and Cognitive Maps have been borrowed by SD modelers from "Systems Thinking" and “Soft Operations Research” fields. Diagramming is integral to all these methods.

A diagraming notation (i.e. a visual notation) is composed of syntax and semantics. The graphical symbols (visual vocabulary) and the compositional rules (visual grammar) form the syntax of a diagraming notation. Semantics of a diagraming notation include the definitions of the meaning of each symbol. The cognitive effectiveness of the graphical representation is inversely related to number of graphical symbols (i.e. visual vocabulary) and their compositional rules. In Table 1, we compare the syntax and the semantics of the four PSMs we employed in our study.

In the next section, we illustrate how the cognitive effectiveness of the four PSMs can be measured by the ease and accuracy with which the participants can understand and employ the their syntax and semantics. We also explore the relationship between cognitive effectiveness of a PSM and the conceptualization of the problem situation.

	Syntax	Semantics
Cognitive Maps		
	Phrases with (contrasting) poles	
	Arrows with +/- polarity	Causality
Magnetic Hexagons		
	Phrases, Clusters	
	Arrows	Relationship
Causal Loop Diagrams		
	Noun variables	
	Arrows +/-	Causality
	Balancing and reinforcing Feedback Loops	
Influence Diagrams		
	Noun variables	
	Arrows +/-	Causality
	Balancing and reinforcing Feedback Loops	
	Causal chains	

Table 1: Syntactical and Semantic Characteristics of Four PSMs

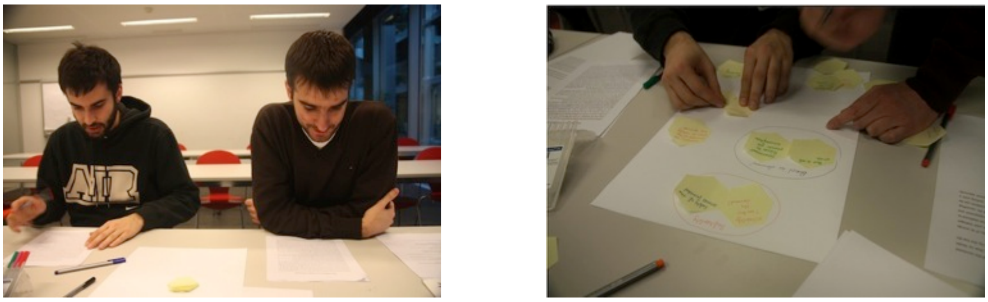
4. Exploratory Laboratory Studies

An exploratory laboratory study was designed to gain an understanding of the cognitive effectiveness of the PSMs subject to the study and the relationship between the problem situation conceptualization and the cognitive effectiveness of a certain PSM. Twelve groups of participants, each consisting of two PhD or MSc students in the field of computer and communication sciences at Ecole Polytechnique Fédérale de Lausanne, took part in the experiment. A PSM was assigned to each group (each PSM was used by three groups). As the participants shared the same academic background, their familiarity with the diagrammatic representations was roughly the same. None of the subjects had a prior knowledge of the PSMs used in the study.

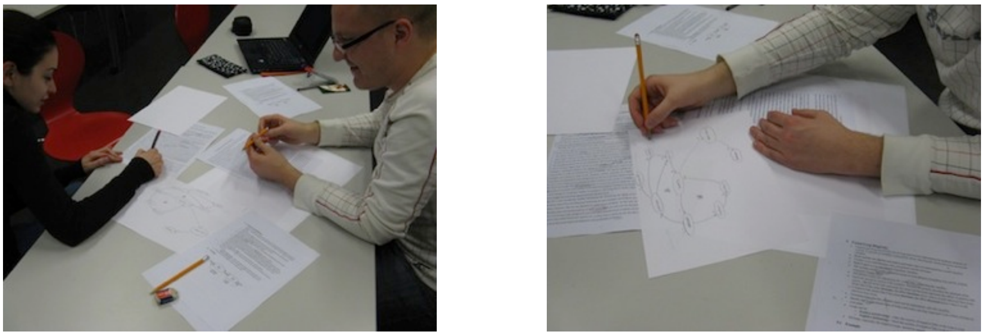
4.1 Study Procedures

Each group was provided with a description of a problem situation (see Appendix 1) and a set of guidlines (see for e.g Appendix 2) on how to represent the problem situation using a certain PSM. The guidlines were extracted from the seminal papers published on the methods. The experiments were done one at a time and during the sessions a facilitor was present and interacted with the participants. Some pictures from the modeling sessions are shown in Figure 5.

Each modeling session lasted for around one hour. At the beginning of the modeling sessions the facilitator gave a brief explanation of the PSM as well as a usage example. During the sessions the participants asked questions to check their understanding of the problem situation as well as the syntax and semantics of the PSM.



(Magnetic) Hexagons Experiment



Causal Loop Diagrams Experiment

Cognitive Maps Experiment

Influence Diagrams Experiment

Figure 4: Pictures from the modeling sessions

See Appendix 3 for a sample of the questions asked in the experiment. The models developed by the participants were then re-drawn using the software application specific to the PSM (for e.g Vensim in case of the CLDs and Decision Explorer in case of Cognitive Maps) or general purpose applications such as Microsft Powerpoint. See Appendix 4 for some sample models.

4.2 Study Results

As mentioned earlier *ease*, and *accuracy* with which a representation can be processed by the human mind determines the cognitive effectiveness of the representation (Larkin and Simon 1987). In our study we measured the ease and accuracy with which the PSMs we defined the following two constructs:

- Level of facilitation: this construct represents syntactical and sematic ease of a representation. The more facilitation required in a session (i.e. measured by the number of questions asked by the participants), the more complex the syntax and the semantics of the PSM. We employ this construct to measure the *ease* with which the participants in the study could process a PSM.
- Model correctness: this construct represents the correctness of the models developed by the participants from the perspective of the syntax and the semantics. This construct is employed to measure the *accuracy* with which the participants in the study could process a PSM.

Based on the constructs defined, we calculated the cognitive effectiveness of a certain PSM using the following formula.

$$CE = \frac{SEM + SYN}{FL}$$

Where, CE is Cognitive Effectiveness; FL is the facilitation level (FL); SEM and SYN are the semantic and syntax correctness. FL ranges from 1 to 5 (low to high facilitation) and SEM and SYN range from 1 to 5, (low to high syntactical/sematic correctness).

In order to understand the relationship between CE and the problem situation conceptualization, we developed the conceptualizations of the problem situations using the four PSMs. As we did not have enough experience using the (magnetic) hexagons and cognitive maps, the models we developed along with the description of the problem situation were sent to the developers of the modeling technique and were modified based on the recommendations to give a better representation of the problem situation (see Appendix 5 for a sample of the models we developed to capture the problem situation). Next, the models developed by the participants were compared to the models developed by us and were graded on a scale of 1 to 10 (10 being the best representation of the problem situation). In comparing and ranking the models we did not look for a one-to-one mapping, as no single correct model of a situation exists. Rather, we checked for the main variables, issues and concepts (depending on the modeling framework) and their interactions. In Appendix 6 we document how the Causal Loop Diagrams were graded with respect Problem Situation Conceptualization, LT, SYN and SEM. In Figure 5, we compare Model Correctness (i.e. SYN+SEM), Level of Facilitation and Cognitive Effectiveness for the four PSMs.

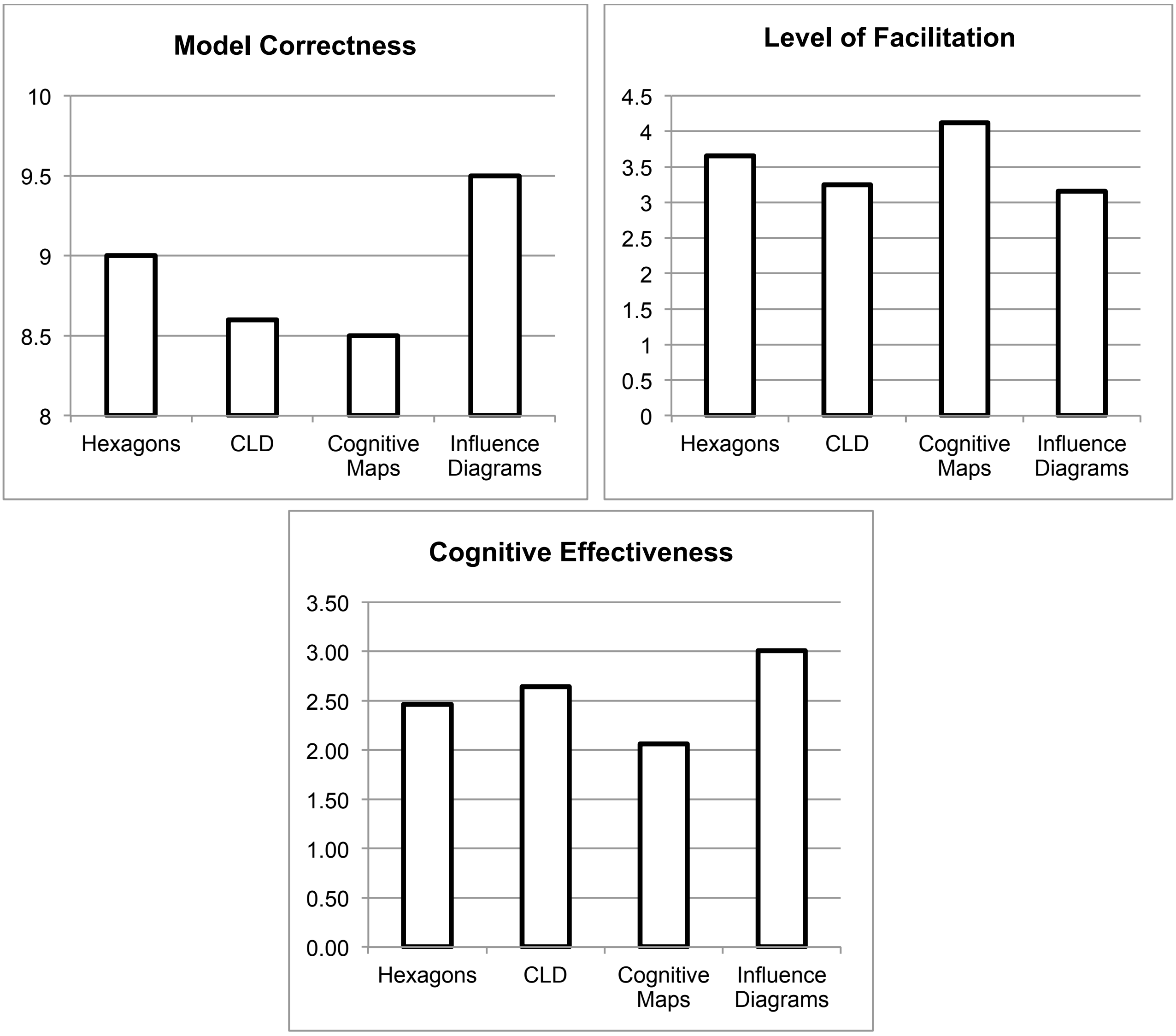


Figure 5: Model Correctness, Facilitation and Cognitive Effectiveness for the four PSMs

The results reported in Figure 5 suggest that Influence Diagrams have the highest Cognitive Effectiveness among the PSMs used in our study. Based on our observations, the participants managed to build their representations of the problem situation using Influence Diagrams without much facilitation and the models they constructed were syntactically and semantically superior to other PSMs. The difference between Influence Diagrams and Causal Loop Diagrams, is the existence of influenced-only factors or variables. This means a causal chain should not necessarily be a part of a causal loop (Diffenbach 1982).

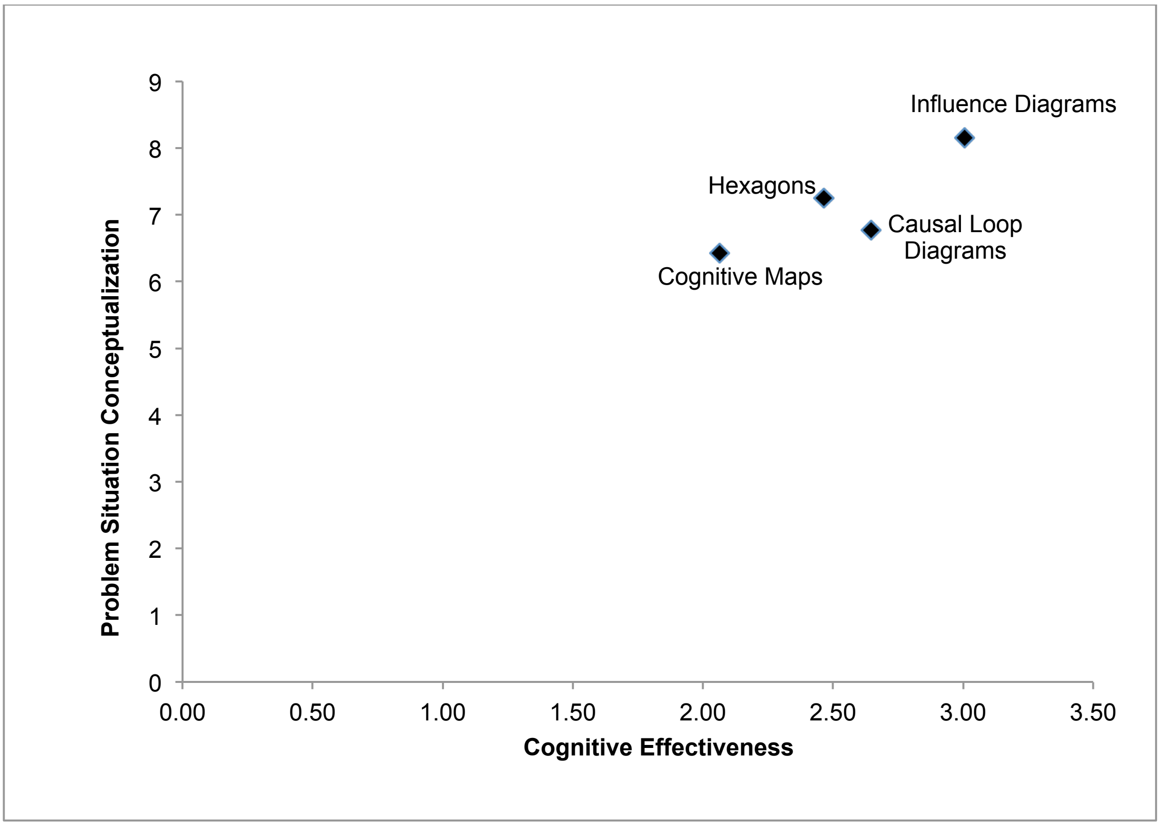


Figure 6: the relationship between Cognitive Effectiveness and the Problem Situation Conceptualization

Finally, in Figure 6 we illustrate the relationship between Cognitive Effectiveness and the Problem Situation Conceptualization. As it can be seen the Cognitive Effectiveness of a PSM is positively linked to the quality of the Problem Situation Conceptualization. In other words, the participants can construct better models of the problem situation when a cognitively effective PSM is employed in the group model building.

5. Conclusions and Suggestions for Further Research

In this paper, we applied theoretical insights from cognitive science to gain an understanding of how PSMs can improve problem-solving in group model building with system dynamics modeling. We predicted the key characteristics of a cognitively effective PSM that can lead to a better conceptualization of the problem situation by the participants in group model building sessions and thus improve problem-solving performance. We conducted an exploratory laboratory study to gain an understanding of the theoretically developed insights on the characteristics of a cognitively effective PSM. The results show that problem structuring with influence diagrams has the highest cognitive effectiveness followed by CLDs, (Magnetic) Hexagons and cognitive maps. We also concluded that the cognitive effectiveness of a PSM is directly related to the quality of the representation that captures the problem situation conceptualization. In our future research we will focus on understanding which PSM results in a better cognitive fit from the perspective of System Dynamicist who constructs the stock and flow simulation model on the basis of the problem situation conceptualization captured by the four PSMs.

In a parallel stream of research, we are in the process of developing a cognitively effective PSM for group model building with SD. Our PSM is based on the Systemic Enterprise Architecture Methodology (SEAM) (Wegmann 2003). Developed at École Polytechnique Fédérale de Lausanne (EPFL), SEAM is a modeling technique that since 2001 has been used for teaching (Wegmann et al. 2007) and consulting (Wegmann et al. 2005) in the field of enterprise architecture and requirements engineering. SEAM is rigorously defined based on General Systems Thinking (GST) (Weinberg 1975), organizational Cybernetics (Beer 1979,1984) and federates multiple modeling techniques (such as discrete behavior, goals or quantitative models). (Golnam et. al, 2010) is our first effort to explore the applicability of SEAM as a PSM in SD modeling process. In the next iterations we have focused more on modeling the cognitive processes in terms of the goals that are based on the perceptions of facts (known as beliefs). The results of our first stream of research inform us about the improvements and the modifications that should be made to SEAM, so that it results in a cognitive fit when applied in the SD modeling process.

References

Akkermans, H. A. and J. A. M. Vennix (1997). "Clients' opinions on group model-building: an exploratory study." System Dynamics Review **13**(1): 3.

Andersen, D. F., G. P. Richardson, et al. (1997). "Group model building: adding more science to the craft." System Dynamics Review **13**(2): 187.

Beer, S. (1979). The heart of enterprise, John Wiley & Sons.

Beer, S. (1984). "The viable system model: its provenance, development, methodology and pathology." Journal of the Operational Research Society **35**(1): 7.

Coyle, G. (1998). "The practice of system dynamics: milestones, lessons and ideas from 30 years experience." System Dynamics Review **14**(4): 343-365.

Coyle, G. (2000). "Qualitative and quantitative modelling in system dynamics: some research questions." System Dynamics Review **16**(3): 225-244.

Diffenbach, J. (1982). "Influence diagrams for complex strategic issues." Strategic Management Journal **3**(2): 133-146.

Eden, C. (1994). "Cognitive mapping and problem structuring for system dynamics model building." System Dynamics Review **10**(2-3): 257,276.

Forrester, J. W. and J. Wright (1961). Industrial dynamics, MIT press Cambridge.

Franco, L. A. and G. Montibeller (2010). "Facilitated modelling in operational research." European Journal of Operational Research **205**(3): 489-500.

Golnam, A., A. Van Ackere, et al. (2010). Integrating System Dynamics and Enterprise Modeling to Address Dynamic and Structural Complexities of Choice Situations. The 28th International Conference of The System Dynamics Society, Seoul, Korea, The System Dynamics Society.

Hodgson, A. M. (1992). "Hexagons for systems thinking." European Journal of Operational Research **59**(1): 220-230.

Lane, D. C. (1993). "The road not taken: observing a process of issue selection and model conceptualization." System Dynamics Review **9**(3): 239-264.

Lane, D. C. (1994). "With a little help from our friends: how system dynamics and soft OR can learn from each other." System Dynamics Review **10**(2-3): 101.

Lane, D. C. and R. Oliva (1998). "The greater whole: Towards a synthesis of system dynamics and soft systems methodology* 1." European Journal of Operational Research **107**(1): 214
Larkin, J. H. and H. A. Simon (1987). "Why a Diagram is (Sometimes) Worth Ten Thousand Words**." Cognitive science **11**(1): 65
Mingers, J. and J. Rosenhead (2004). "Problem structuring methods in action." European Journal of Operational Research **152**(3): 530 - 554.
Moody, D. (2009). "The "physics" of notations: Toward a scientific basis for constructing visual notations in software engineering." Software Engineering, IEEE Transactions on **35**(6): 756-779.
Richardson, G. P. and D. F. Andersen (1995). "Teamwork in group model building." System Dynamics Review **11**(2): 113,Äì137.
Richardson, G. P. and A. L. Pugh (1981). Introduction to system dynamics modeling with DYNAMO, MIT Press Cambridge, MA, USA
Rosenhead, J. (1996). "What's the problem? An introduction to problem structuring methods." Interfaces: 117,131.
Rouwette, E., S. Hoppenbrouwers, et al. (2008). Collaborative systems modeling and group model building: a useful combination.
Scaife, M. and Y. Rogers (1996). "External cognition: how do graphical representations work?" International Journal of Human,Computer Studies **45**: 185.
Senge, P. M. (1993). "The Fifth Discipline: The Art and Practice of the Learning Organization: Book review."
Shaft, T. M. and I. Vessey (2006). "The role of cognitive fit in the relationship between software comprehension and modification." MIS Quarterly **30**(1): 29,Äì55.
Sterman, J. D. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World, McGraw Hill Higher Education.
Tarski, A. and J. Corcoran (1983). Logic, semantics, metamathematics: papers from 1923 to 1938, Hackett publishing company .
Vennix, J. A. M. and J. Vennix (1996). Group model building: Facilitating team learning using system dynamics, Wiley.
Vessey, I. (1991). "Cognitive Fit: A Theory-Based Analysis of the Graphs Versus Tables Literature*." Decision Sciences **22**(2): 219.
Vessey, I. and D. Galletta (1991). "Cognitive fit: An empirical study of information acquisition." Information Systems Research **2**(1): 63.
Wegmann, A. (2003). On the Systemic Enterprise Architecture Methodology (SEAM). Proceedings of International Conference on Enterprise Information Systems. Angers, France, Citeseer.
Wegmann, A., G. Regev, et al. (2007). Teaching Enterprise Architecture And Service-oriented Architecture in Practice. Workshop on Trends in Enterprise Architecture Research (TEAR 2007)**:** 13.
Wegmann, A., G. Regev, et al. (2005). Business and IT Alignment with SEAM. Proceedings of 1st International Workshop on Requirements Engineering for Business Need, and IT Alignment, Paris.
Weinberg, G. M. (1975). An introduction to general systems thinking, Wiley-Interscience.
Wong, H., D. Morra, et al. (2011). "Using system dynamics principles for conceptual modelling of publicly funded hospitals." Journal of the Operational Research Society.
Zhang, J. (1991). The interaction of internal and external representations in a problem solving task. Proceedings of the Thirteenth Annual Conference of Cognitive Science Society.
Zhang, J. (1997). "The nature of external representations in problem solving." Cognitive science **21**(2): 179.

Zhang, J. and D. A. Norman (1994). "Representations in distributed cognitive tasks* 1." Cognitive science **18**(1).

Appendix 1

A Utility Company provides energy services (electricity, gas, etc.) to the residents of a city in Europe with the population of nearly 500 000 people. From an organizational perspective the Utility Company is divided into different business units (BUs): Gas BU, Electricity BU, etc. The Utility Company has so far been known by the stakeholders including the customer as a safe and reliable provider of energy services. The profitability of the Utility Company depends on the demand for its services which is influenced by the reliability and the safety of the services provided. Stakeholders' perception of safety is linked to the number of the incidents that occur due to the leakages in the pipes, and reliability is perceived by the stakeholders as the ability of the utility company to meet energy demand.

The Gas BU conducts the following important functions: the purchase of the gas, gas sales and distribution to the end users and management of the infrastructure. Recently, the rise in oil prices has made the government develop some policies and incentives to promote gas consumption against electricity consumption. Such incentives will boost gas demand. To remain profitable, the Gas BU has to maintain the reliability of its services by ensuring that the increase in the demand is met.

The easiest, fastest and the cheapest way for the Gas BU is to meet the demand by increasing the pressure in the pipes. Higher pressure in pipes means higher supply and thereby, meeting the increase in the demand. Therefore, the Gas BU and by that the Utility Company can maintain its identity as a reliable energy service provider. However, the increased pressure has its own drawbacks. This would be the first time that their system will be run constantly with a pressure higher than normal, so more leakages in the system are expected. Statistically, the number of leakages is positively linked to the number of incidents that occur, such as explosions. Leakages call for a quick intervention in order to minimize the risk of incidents. The Gas BU already has special teams of field technicians equipped and trained to take all the necessary security measures to mitigate the risk of incidents. The field technicians are dispatched to the leakage spot as soon as a customer reports a leakage through the BU call center. In the face of the rising pressure and the possible increase in the number of leakages, the company has to make sure that there are enough field technicians available to secure the spot by taking the necessary security measures. This might mean an increase in the number of the field technicians to counteract the drawback of the increased pressure. But, such increase in manpower implies an increase in the hiring that no doubt requires an increase in the human resource budget that should be approved by the Gas BU board.

The Gas BU is also considering another mechanism for maintaining the safety of its energy services. The initial analyses have shown that recording and monitoring the past leakages and incidents can help the BU in developing preventative measures that can be deployed to avoid future incidents. To this end, the BU should invest in the design, development and implementation of an IT system that can carry out the functions required for recording, analysis and monitoring of the incidents in such way that potential future incidents can be predicted and avoided. The approval of the initial investment required for putting such a system by the Gas BU's board of directors. Past experiences show that board approvals depend on the profitability of the BU.

Appendix 2

Guidelines for Developing Cognitive Maps

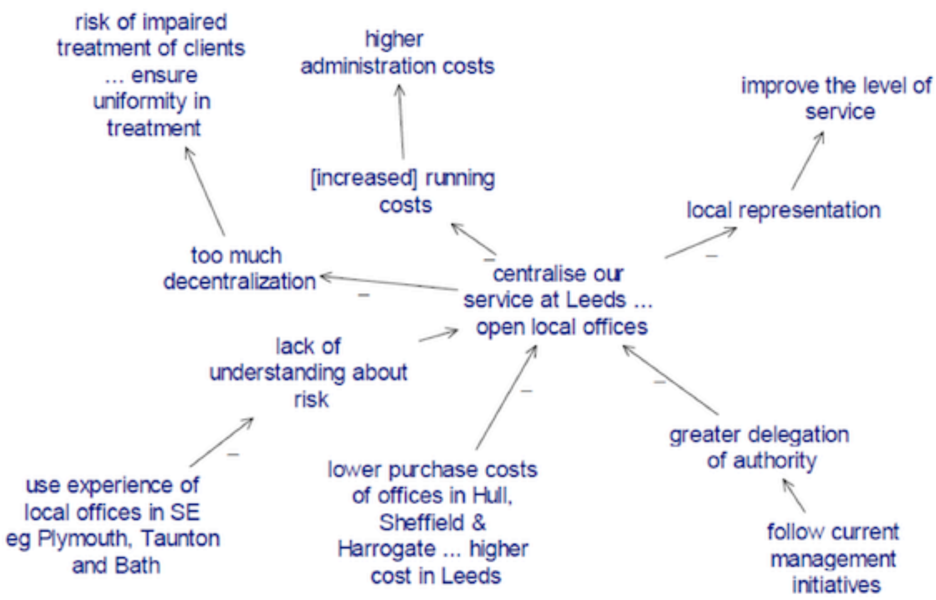
- Read carefully the problem description and make sure you understand the overall situation.
- Confirm your understanding with your partner and the facilitator
- Read it again so you can identify important sentences
- You can write them down, underline them directly in the text, etc.
- Separate these sentences into distinct phrases, and make concepts from these phrases.
- A pair of contrasting phrases may be united in a single concept by using contrasting pole of a concept (the meaning is retained through contrast).
- By discussion with your partner, try to find and write this kind of contrasting poles in the concepts.
- If you cannot find a contrasting pole for an important concept, write it down anyways.
- The concepts (with or without contrasting poles) should be phrases no longer than 10-12 words which together explain the problem.
- These phrases should retain the language from the problem description (avoid abbreviating).
- If you believe that one concept is the cause of the other, connect them by an arrow, where the cause is at the tail of the arrow.
- A network of nodes (concept) and arrows as links should be formed, by connecting the concepts, where the direction of the arrow implies believed causality. The arrows indicate perceived cause and effect relationships and they are of two types:
  - The arrow with no sign (or rarely a + sign) means that the positive pole of the first concept pairing is associated with the positive pole of the second pairing (also for negative with negative)
  - The arrow with a negative sign indicates that the positive pole of the first pairing tends to lead to the negative pole of the second pairing (also negative to positive)
- Cognitive maps should be characterized by a hierarchical structure where goal type statements are at the top of the hierarchy.
- Often it can be found circularity in the map in which a chain of means and ends loops back on itself and this is often regarded as a fundamental structural characteristic of a map.

Example

Example of a cognitive map from an interview transcript (taken from [Getting started with cognitive mapping]) [2]:

"We need to decide on our accommodation arrangements for the York and Humberside region. We could centralize our services at Leeds or open local offices in various parts of the region. The level of service we might be able to provide could well be improved by local representation but we guess that administration costs would be higher and, in this case, it seems likely that running costs will be the most important factor in our decision. The office purchase costs in Hull and Sheffield might however be lower than in Leeds. Additionally we need to ensure uniformity in the treatment of clients in the region and this might be impaired by too much decentralization. However we are not sure how great this risk in this case; experience of local offices in Plymouth, Taunton and Bath in the south east may have something to teach us. Moreover current management initiatives point us in the direction of greater delegation of authority."

The final and complete map from this interview text:



[1] Robert T. Hughes et al., The use of causal mapping in the design of management information systems

[2] Fran Ackermann, Colin Eden and Steve Cropper, Getting Started with Cognitive Mapping

[3] Colin Eden, Analyzing cognitive maps to help structure issues or problems, European Journal of Operational Research 159, pg. 673-686, 2004

Appendix 3

Are incidents and leakages the same thing?

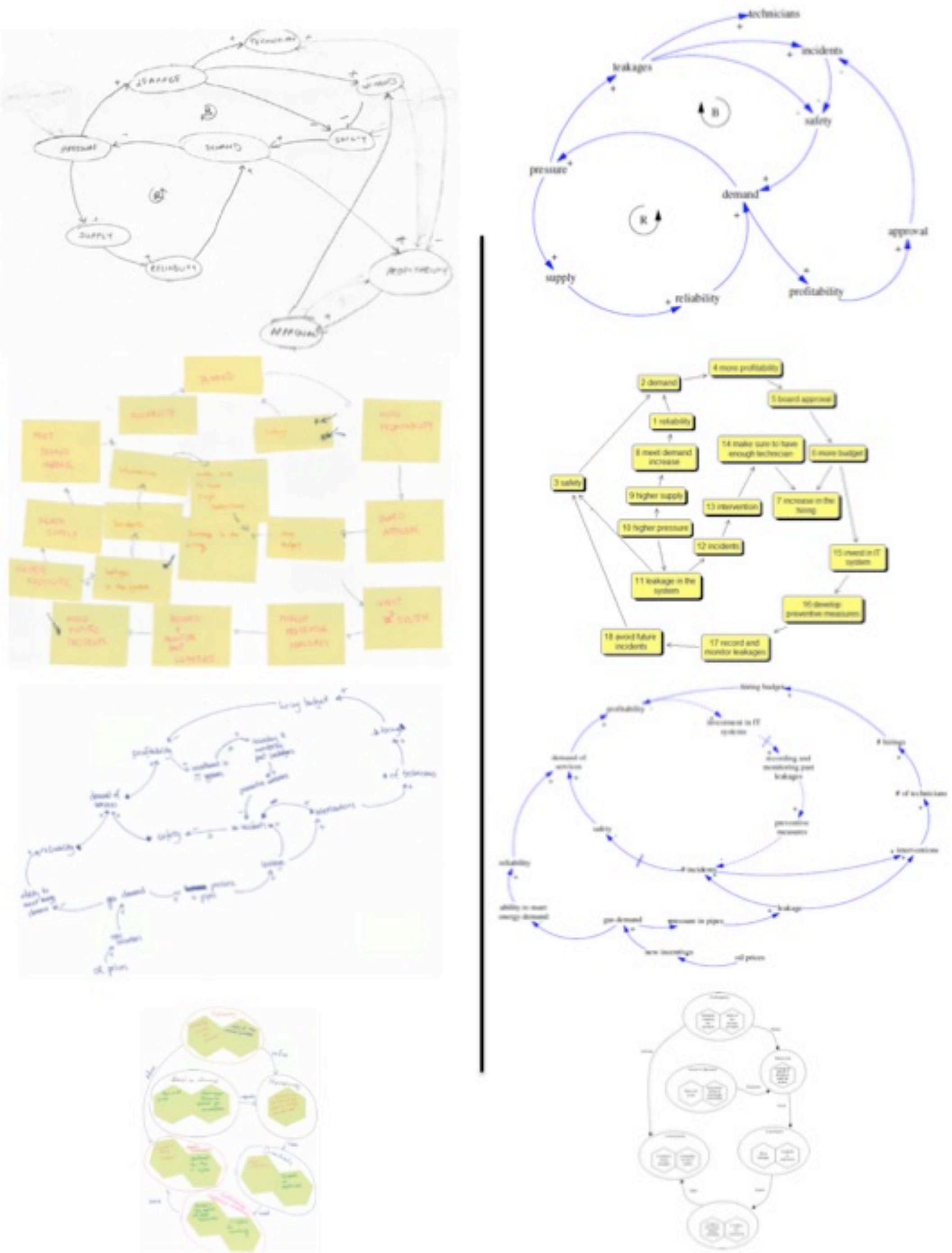
Hexagons:
Do we need to define the clusters first?
Can we have the same hexagon twice?
Can we have only one hexagon in a cluster?
Can there be a cluster within a cluster?

CLD
How many nodes can there be in a loop?
Does the diagram have to be very detailed (more than 6 nodes)?
Can there be two outgoing links from one variable?

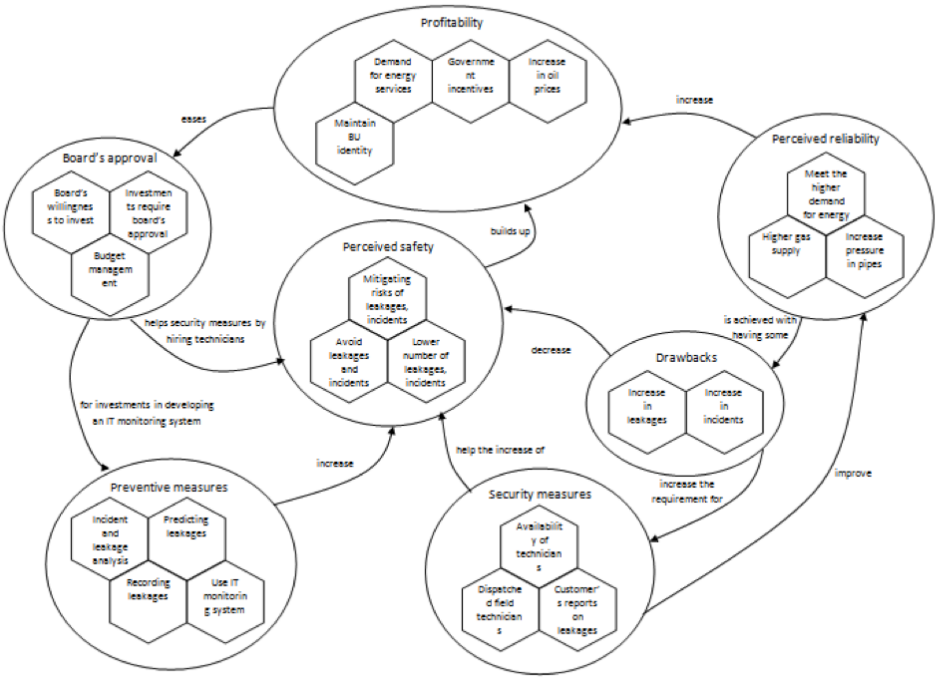
Cognitive Map
Does +/- mean consequence?
Does the - link has a negative meaning?
Does each issue must have a contrasting pole?

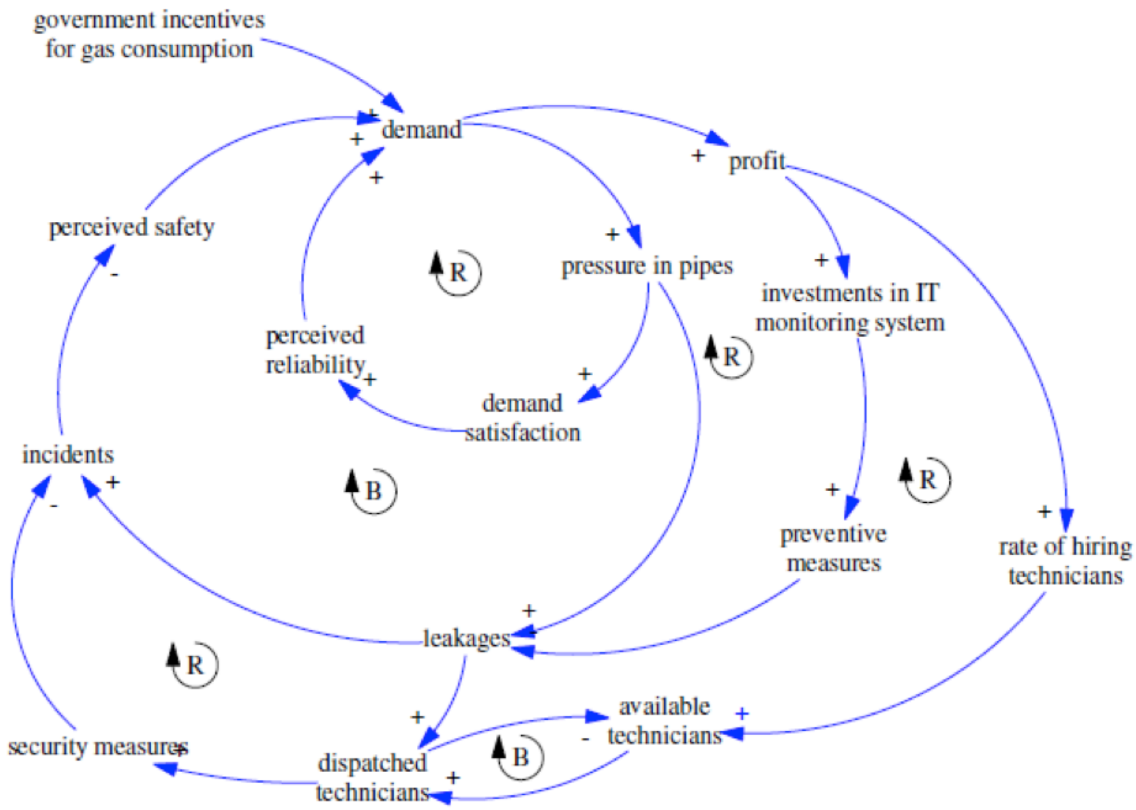
ID
What does the dashed lines mean?
Can there be an arrow going outside the loop?

Appendix 4


technicians
leakages
incidents
B
safety
pressure
demand
R
approval
supply
reliability
profitability
4 more profitability
2 demand
5 board approval
1 reliability
14 make sure to have enough technician
8 meet demand increase
6 more budget
3 safety
9 higher supply
13 intervention
7 increase in the hiring
10 higher pressure
12 incidents
15 invest in IT system
11 leakage in the system
16 develop preventive measures
18 avoid future incidents
17 record and monitor leakages

Appendix 5


Profitability
Demand for energy services
Government incentives
Increase in oil prices
Maintain BU identity
eases
increase
Board's approval
Board's willingness to invest
Investments require board's approval
Budget management
builds up
Perceived safety
Mitigating risks of leakages, incidents
Avoid leakages and incidents
Lower number of leakages, incidents
Perceived reliability
Meet the higher demand for energy
Higher gas supply
Increase pressure in pipes
helps security measures by hiring technicians
decrease
is achieved with having some
Drawbacks
Increase in leakages
Increase in incidents
for investments in developing an IT monitoring system
increase
help the increase of
increase the requirement for
improve
Preventive measures
Incident and leakage analysis
Predicting leakages
Recording leakages
Use IT monitoring system
Security measures
Availability of technicians
Dispatched field technicians
Customer's reports on leakages


government incentives for gas consumption
demand
profit
perceived safety
pressure in pipes
investments in IT monitoring system
perceived reliability
demand satisfaction
incidents
preventive measures
rate of hiring technicians
leakages
security measures
dispatched technicians
available technicians
R
B

Appendix 6

	Main Variables	Group 1	Group 2	Group 3	
1	Demand	1	1	1	
2	Supply	0	1	0	
3	Profitability	1	1	1	
4	Technicians	1	0,5	1	
5	Preventive measures	1	0	0	
6	IT investments	1	0	1	
7	Leakages / incidents	1	1	1	
8	Security	0	0	1	
9	Safety	0.5	1	1	
10	Reliability	1	1	0,5	
	Total (10):	**7.5**	**6,5**	**7,5**	
	Pts for loops:	0,5	1	1	* 1 pt equals 2 loops
	Total (13):	**8.0**	**7,5**	**8,5**	**6,77**
	Facilitation (1=good, 5=bad):	**2**	**3**	**3**	**2,66667**
	Semantic correctness (5 good):	**4**	**3**	**4**	**3,66667**
	Correctness of syntax (5 good):	**5**	**5**	**5**	**5**
					3,25