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Simulation of Qualitative Models to Support Business Scenario Analysis

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Abstract

When we look at the research that is concerned with the modeling and analysis of business scenarios, we can recognize an unfortunate yet profound dichotomy of research methodologies; qualitative versus quantitative research. There seems to be an almost unbridgeable gap between the two approaches, which has also errected high barriers for communication between the two corresponding research communities. On the one hand, we have the "qualitative" or "behavioural" people who criticize quantitative methods as inapplicable and far removed from most of the real-world situations that are observed in organizational environments, and, on the other hand, we have the "quantitative" or "mathematical" people who only believe in numbers and equations and accuse any research that is not somehow based on a mathematical theory as unscientific. In the following discussion we try to show that qualitativeness and quantitativeness are not mutually exclusive concepts. Quite the contrary, we argue that they are, in many ways, closely related and that they form the two ends along a common dimension of knowledge discovery and knowledge representation. Based on recent work in qualitative reasoning, a newly emerging field in artificial intelligence, we present a system that offers modeling and simulation capabilities while only requiring qualitative information about the variables and relationships included in a model.

1. Introduction

The domains of the organizational sciences, management and economics are immensely complex. Most theories describe just a small segment of the real world by abstracting from it certain system entities and relate them in some way in order to explain or to predict a particular economic phenomenon. Our knowledge about the real world is mainly derived from perceptions and empirical observations. A theory can be viewed as an abstract system that describes some well-defined real-world phenomenon which reveals implications of its underlying assumptions and hypotheses. The principles of scientific deduction only allow us to draw conclusions that can be deduced from the assumptions included in a theory. In order to be meaningful, a theory has to be general, but at the same time specific enough to be amenable for empirical testing. For example, a general theory that explains the behavior of all consumers of an economy at all times and places is more relevant than one that is exclusively concerned with the behavior of a particular consumer at a particular time and place. Theories of the former kind, although conceptually ideal, do not exist in most problem settings or, at least, are not likely to be found. For that matter, theories usually need to be restricted to certain classes, such as collections of consumers with certain properties acting in some specific type of economy. According to Popper (1959), a theory should be constructed in a falsifiable manner, that is, it must be specific enough to refute it if empirical testing indicates that the hypotheses underlying a theory are not consistent with observed data. A theory containing a hypothesis of the sort *"at any time all x of a certain kind will choose a particular action a under some specific circumstances"* is more meaningful than one which simply says *that "at some time some x will choose a,"* because the latter immunizes itself from falsification.

Performing scientific deduction requires a language to represent domain knowledge, and an inference mechanism to derive implications from the knowledge expressed in that language. Representation languages range from narrative languages, diagrams and other graphical representations, mathematical structures to modeling languages for computer software systems. Selecting the most appropriate representation language is task-specific and usually involves a tradeoff between the high expressiveness of informal languages and the strong inferential power of formalized languages. An important phase in the process of scientific reasoning is the translation of domain knowledge into a particular representation language, usually referred to as theory specification or model specification. This transition requires a good deal of abstraction, and is the most vulnerable one in the whole process. Is the problem description consistent with our perception of the real world phenomenon under study, and does it capture all its relevant features? If both questions can be answered with yes, we can select and apply a suitable inference method, and deriving the implications of the model or theory is then merely a technical task which makes information implicitly encoded in the problem description explicit, that is, deriving implications neither adds nor subtracts any information.

Typically, an economic (or organizational) system is modeled by identifying a set of relevant system variables and specifying relationships among them. Once a model is set up in a particular representation language we can pose questions, and analyze the model by selecting an adequate solution method, which may include linguistic analyses, and interpreting the results. However, our knowledge about economic systems is inherently incomplete and full of uncertainties. Hence, developing an economic model requires some sort of abstraction and/or approximation. Since quantitative solution methods provide the most powerful inference mechanisms, it is desirable to represent the particular system under consideration as a quantitative model. But this is only possible if the real-world phenomenon under study can be expressed within the strict confines of a formal, quantitative representation language, and necessitates precise knowledge about the involved relationships, which usually means that we need to be able to formulate exact, and possibly tremendously complicated, functional relationships between the system variables. Assuming that there is indeed a true model exactly describing the behavior of the real world economic phenomenon, it is, in general, too complex to be discovered and remains unknown to the modeler.

The purpose of this paper is to examine the needs for representing qualitative relationships when developing models or formulating theories in the organizational sciences, information systems, management and economics. In the remainder of the paper, we will review current approaches of treating qualitative knowledge, identify existing shortcomings, and suggest a somewhat more formal methodology which enables theorists to do a more rigorous analysis of qualitative theories and qualitative model using the support of modern computing technologies.

2. The Representation of Organizational Relationships: Qualitative versus Quantitative Approaches

When we look at the research that is concerned with problems from the business domain, we can recognize an unfortunate yet profound dichotomy of research methodologies; qualitative versus quantitative research. There seems to be an almost unbridgeable gap between the two approaches, which has also errected high barriers for communication between the two corresponding research communities. On the one hand, we have the "qualitative" or "behavioural" people who criticize quantitative methods as inapplicable and far removed from most of the real-world situations that are observed in organizational environments, and, on the other hand, we have the "quantitative" or "mathematical" people who only believe in numbers and equations and accuse any research that is not somehow based on a mathematical theory as unscientific. In the following discussion we try to show that *qualitativeness* and *quantitativeness* are not mutually exclusive concepts. Quite the contrary and similar to Coyle (1999), we argue that they are, in many ways, closely related and that they form the two ends along a common dimension of knowledge discovery and knowledge representation.

When dealing with partially known systems, there are several approaches one might take in coping with incomplete and uncertain knowledge. Quantitative analysis restricts itself to well known mathematical structures, like linear equation systems or mathematical optimization models, and tries to find an approximate model that is close enough to the true model to give useful insights. Stochastic methods treat system variables as random, or impose error terms in order to cover the true relationships. The latter approach requires additional assumptions about the probability distribution of random variables which is often beyond the knowledge available. For that reason, and to keep the model tractable from a computational point of view, random variables are usually chosen to be normally distributed; a commitment that has to be justified but is too often neglected. Quantitative approaches have the advantage of producing precise results, but frequently one lacks confidence in the appropriateness of the underlying model. Precise answers, on the other hand, are often not even of primary interest when conducting organizational studies; qualitative information like signs of impacts and effects, ranges and directions of change of goal variables can be sufficient for satisfactorily explaining and predicting the behavior of organizational systems. In many situations most of the knowledge at hand is of a qualitative nature; for example, knowledge of the signs or possibly magnitudes (e.g., low/medium/high) of variables rather than exact numerical values, or partial knowledge of the shape of functional relationships (e.g, monotonicity).

Reasoning with incomplete or qualitative information has actually a fairly long tradition in the area of economis; see, for example, Samuelson (1947) and Lancaster (1962). Because qualitative economic analysis had been essentially developed prior to the era of modern computer technology, it was limited in scope by the absence of computational power. Recent research in qualitative reasoning, a new field that has emerged from artificial intelligence, see Weld and deKleer (1990), is based on a similar motivation as qualitative economics. Qualitative reasoning attempts to provide a framework that allows one to model dynamic systems in qualitative terms. Basically unaware of the related work in qualitative economics, qualitative reasoning has developed a small number of representation languages and computer-supported inference mechanisms for qualitative modeling in the physics and engineering domains, sometimes reinventing techniques already known in the economics literature. Iwasaki and Simon (1986) first recognized the link between qualitative reasoning and qualitative economics. The research in qualitative reasoning has raised new interest in qualitative analysis in economics and first applications can be found in Farley and Lin (1990), Berndsen and Daniels (1991), and Lang et al (1995). A more comprehensive discussion of qualitative modeling and reasoning issues which extends into the management area is presented in Lang (1993).

The motivation for taking a qualitative perspective has various reasons. Firstly, for many problems there is simply not enough information available to formulate a quantitative model, thus prohibiting the application of quantitative methods. We call this situation modeling systems with incomplete knowledge or information. Secondly, partially known systems encompass imprecise and uncertain information. This is called modeling systems with imprecise knowledge or information. Thirdly, even if it were possible to acquire complete and precise knowledge, the modeler is often not really interested in the details of the system, in other words, the modeler prefers a qualitative description. The latter case adopts a point of view which is typical for a top level management perception of an organization, and is especially suited for addressing strategic business issues. Fourthly, research in, for example, organizational science and economics, pursues as one of its main goals the development of general theories about certain classes of firms. In this context, one might be interested in a qualitative framework that allows you to abstract knowledge from a collection particular organizations, which might be fairly specific, into more general descriptions, retaining the qualitative information that represents only significant distinctions and characterizes all members of the class. Analyzing such a generalized, qualitative model draws implications that hold for all specific, possibly quantitative, models that are instances of this class.

In business related areas like organization science, management, business communication, and others, qualitative approaches are widely used in order to investigate problem scenarios and to develop theories. Work in the management science (MS) and decision support systems (DSS) areas, on the other hand, have traditionally been emphasizing quantitative methodologies. A common pitfall of traditional MS/DSS approaches is their rigid representation of modeling information. Usually, modelers are forced to formulate the relationships of a model as a set of quantitative constraints, typically constraints of one specific kind such as algebraic or differential equations. However, the importance and relevance of a more formal treatment of qualitative knowledge representations and qualitative inference methods has recently been recognized in the MS/DSS literature as well (Hamscher et al, 1995, Stein and Zwass, 1995, and Hinkkanen et al, 1995).

From an opposite angle on the subject, Monge (1990) and Weick (1989) have observed that theoretical and empirical organization science and management (OS/MT) research has been impeded by the lack of appropriate conceptual and computational tools to model inexactly, vaguely, incompletely or, in other words, qualitatively specified systems. In most cases qualitative descriptions are presented as purely verbal formulations, that is, in an informal manner. Despite the usefulness of verbal formulations, additional more formal methods are often desired in order to overcome certain vaguenesses in describing complex systems. The absence thereof has contributed to a dominance of linguistic analyses in most of the theoretical OS/MT research, and also to numerous ill-advised applications of statistical test methods and regression analyses in empirical work (Weick, 1984). Hence, Monge (1990) has concluded that current research in the social sciences is suffering from the lack of computational systems for processing qualitative information. He calls for a mathematical representation language that provides a useful compromise between expressiveness and inferential power. Emphasizing the modeling of dynamic systems he describes crucial features of such a hypothetical language including provisions for continuous as well as discrete processes integrating qualitative and quantitative information. Present qualitative OS/MT studies rely chiefly on verbal discourses or other informal approaches, but in order to formulate, test and verify theories more formalized methods are needed. Therefore we argue that organizational computing systems must be able to represent and process qualitative information more thoroughly than present MS/DSS systems.

3. A Formal Specification of Qualitative Relationships

Before we propose a formal approach for specifying qualitative relationships we need to discuss in more concrete terms what we mean by qualitativeness. We are not aware of a commonly accepted definition of the the term “qualitative” in the context of research methods. Common folklore sometimes suggests that qualitative research refers to methodologies that don’t involve mathematical terms. While this may be true in many cases it, in our opinion, oversimplifies matters and unnecessarily limits the scope of qualitative research. From the above discussion it should be clear that mathematics is a neutral formalism and can simply been viewed as a language for expressing knowledge about this world, a language, or rather a set of languages if we want to distinguish different mathematical disciplines, that does not have to be but certainly can be useful when developing scientific theories. Rather than trying to resolve the difficult task of presenting an explicit definition of qualitativeness, we introduce a couple of examples, requiring only a minimal amount of mathematical formalism, which will illustrate what kind of relationships we have primarily in mind when we talk about qualitativeness.

Theories in management typically encompass general statements which apply to whole classes of organizations. Hence, management theories try to discover commonalities among all organizations (of a certain class) with general validity, which can sometimes only tenuously be described as certain trends, influences or tendencies. A widely used practice in research areas such as organization science, management, and behavioral information systems is to use qualitative descriptions in order to formulate causal and functional relationships as general propositions. Qualitative statements are typically based on hypothesized monotonic relationships of the form *if variable X is increased (or decreased) then variable Y will increase (or decrease).* As an illustration take, for example, (a) Cooprider (1990) who states the qualitative proposition "*Increasing the level of partnership among organizational units leads to an increase in the productivity of the entire organization*", and (b) Huber (1990) who hypothesizes that "*For a* *highly centralized organization, use of computer-assisted communication and decision-support technologies* (that is, information technology (IT)) *leads to more decentralization.*". Each of these two propositions verbally expresses a monotonic relationship between two variables, which is very common in the OS/MT literature. Qualitative relationships of this kind can very well be represented as so-called *(increasing) monotonic function constraints (*M^{+}*constraints)*. Thus, we propose represent this kind of qualitative knowledge and specify relationship (a) as a qualitative QSIM constraint

(a) PRODUCTIVITY = M^{+}(PARTNERSHIP),

and relationship (b) similarly as

(b) DECENTRALIZATION = M^{+}(IT).

Another type of qualitative relationship, called *qualitative derivative,* arises when the rate of change of one variable determines the value of another. In cash-flow management, for example, one might say that the *cash-netflow,* that is, the difference between *cash-inflow* and *cash-outflow,* is determined over time by the rate of change of *cash* held by a company. Research in the finance area typically employs quantitative methods when developing and analysing cash-flow models although the precise rate of change of cash funds or other system variables can only be guessed crudely. In a qualitative approach one would simply specify

(c) CASH-NETFLOW = f'(CASH),

without having to detail the exact nature of this functional relationship.

Examples (a)-(c) show how an important set of hypotheses and propositions can be expressed slightly more formal and concise as corresponding qualitative relationships. This reformulation would provide little leverage if was not possible to do something with these qualitative relationships. As it turns out, it is essentially this representation that forms the basis for qualitative reasoning systems. A theory expressed as a qualitative model consisting of a set of such qualitative relationships, can be analyzed with qualitative reasoners, which will derive implications entailed by the proposed relationships. The qualitative inference mechanism will detect potential conflicting statements or plain contradictions, and will reveal possible outcomes conistent with the specified theory. Qualitative Analysis is characteristically different from its quantitative counterpart in its more liberal information requirement and its inherently ambiguous inferences. The next section will briefly overview the work in the qualitative reasoning field before we present, in the following section, a little illustrative example of a qualiative reasoning study.

4. Qualitative Reasoning - A Brief Review

Original research in qualitative reasoning in artificial intelligence, respectively qualitative physics as it was often called, was driven by the question how do humans reason about the physical world? The observation was made that humans function quite successfully in daily situations like boiling water in a tea kettle, pouring into a cup, avoiding car collisions while driving, etc,. without fully understanding these phenomena. This observation led to the conclusion that it must be possible to develop a qualitative physics, which would not require complex equations as in standard physics, and to build commonsense reasoning systems that would be able to explain and predict the behavior of physical systems.

In order to give a rough picture of the behavior of a physical system, which is all what is often needed, it is not necessary to provide a complete and precise mathematical description of the system. Many insightful concepts can be described by qualitative distinct behaviors of a physical system. Representation languages of qualitative reasoning systems are based on high abstractions of real systems as a model representation. This means that some information is lost, thus the answers derived by the inference mechanism cannot be exact. To resolve this intrinsic ambiguity, more knowledge would be required.

Qualitative simulation [Kuipers, 1989], the best known and most widely used qualitative reasoning system, describes a system in terms of qualitative quantities and functional relationships from which it generates all consistent behaviors of the system. QSIM was specifically designed to model continuous dynamic systems traditionally formulated quantitatively as a set of algebraic or differential equations. The general goal of QSIM is to represent the structure of a mechanism or system (modeling), and to predict its possible behaviors (simulation), that is, reasoning from structure to behavior. QSIM was designed with the following requirements in mind:

- Models should express what is known about a system
- Models should not require assumptions beyond what is known
- Models must be tractable to derive useful predictions
- Model predictions must match actual behaviors

A QSIM model comprises qualitative constraints plus an initial state from which it predicts possible behaviors. A system is described in terms of qualitative variables called *quantities* . A quantity is defined as a finite, totally ordered set of symbolic *landmark values.* Landmarks are qualitatively distinct values such as, for example, low/medium/high or negative/zero/positive. The user needs to provide a model specification that includes the definition of all system variables. Qualitative *constraints* describe relationships among quantities. QSIM offers qualitative arithmetic constraints like addition, multiplication etc,. qualitative classes of functional relationships like the class of monotonically increasing or decreasing functions (M^+/M^- functions), and the class of constant functions.

All qualitative reasoning systems are founded on a qualitative mathematics that was basically developed in the economics field decades ago [Samuelson 1947, p.23-29]. Table 1, for example, depicts qualitative addition of two variables, x and y. In this basic qualitative description variables can assume the qualitative values positive (*pos*), zero *(zero)*, or negative (*neg*). Adding two positive variables, that is, $x=pos$ and $y=pos$, definitely yields a sum that is positive as well, $x+y=pos$ (row I of table 1). The sum of a negative term, say $x=neg$, and a positive term, say $y=pos$, on the other hand, is indetermined and can be positive, zero or negative. This is exactly the inherent ambiguity in qualitative analysis resulting from incomplete knowledge, ambiguity which coincides with the real world whenever two conflicting forces, which cannot be precisely described in numerical terms, are simultaneously at work. Quantitative approaches claim time and again precise scientific results while problem-intrinsic ambiguity is simply swept under the carpet and not shown in the quantitative model specfication. Recently, qualitative calculi have been extended to allow reasoning systems to represent qualitative values of more finely grained magnitudes.

		$x+y$	*pos*	*zero*	*neg*	*(y)*
I		*pos*	*pos*	*pos*	*pos/zero/neg*	
II	*(x)*	*zero*	*pos*	*zero*	*neg*	
III		*neg*	*pos/zero/neg*	*neg*	*neg*	

Table 1: Qualitative Addition

5. Conclusion

In this paper, we have discussed major assumptions underlying quantitative and qualitative research methodologies and have put a special focus on the representation of organizational relationships which can be used as the basis of specifying models and theories in management and economics. We have suggested a qualitative modeling approach which would allow researchers to use computational software tools in order to derive automatically the implicit consequences of a proposed theory.

In future research we would like to connect qualitative reasoning particularly to system dynamics modeling. The reason for this twofold. First, system dynamics is a major modeling framework in management and organization science. Second, and more importantly, system dynamics include influence diagram as an important tool for modeling complex and poorly understood systems. It often used as a first effort to structure and organize the system variables and relevant relationships that have been extracted or derived from an original problem description. For that purpose, the relationships in influence diagrams are typically at a qualitative level, similar to those described in section 3 of the current paper. Hence, we believe that qualitative reasoning techniques can be applied to provide both a representational and a computational tool to support the analysis of influence diagrams. In some cases, perhaps, it wouldn’t be necessary to specify a fully quantified simulation model in order to derive useful predictions for policy making or other modelling purposes. Combining the flexibility and expressiveness of the graphical representation of influence diagrams with the computational power of qualitative reasoning systems could provide a significant enhancement of the system dynamics modeling approach.

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