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# 42. THEORY DEVELOPMENT THROUGH SIMULATION: EXTENDING COORDINATION THEORY IN CRISIS RESPONSE

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## Abstract

As a research method, simulation can be useful in coping with the lack of data or in designing experiments that would be too costly or risky otherwise. This is especially relevant in the domain of crisis response, where on top of the difficulty of controlling data gathering and experiments there is also a lack of theory, particularly in terms of coordination. We present a framework that guides the use of simulation as a method for theory development in this domain. We illustrate this framework with research in progress aimed at extending the theory of coordination in crisis response. A simulation model is built to operationalize the theory and enable improved understanding of coordination in crisis response.

## Keywords

Simulation, research methods, coordination, crisis response

## 1. Introduction

Simulation is "the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and/or evaluating various strategies for the operation of the system" (Shannon, 1998). When the modeled system is complex (as opposed to a simple physical system) we cannot expect the model to predict, so the object is to understand (Lyons, Adjali, Collings, & Jensen, 2003). We adopt this view of simulation – for understanding and evaluation – by using it as a method of theory development in the domain of crisis response. This, however, does not imply that simulation cannot be used for prediction and theory development in other contexts.

Simulation can be used as a research method in different disciplines (Becker, Niehaves, & Klose, 2005). In the domain of crisis (emergency) response, simulation is widely used. The difficulty in gathering data and the limited possibility of designing controlled experiments is partly the reason for this. But the use of simulation is not limited to methodological convenience, it is also due to its inherent capabilities: simulations can be used to illustrate the patterns and pathologies of crisis decision making; they can create a great opportunity for getting acquainted with all aspects of crisis management; and they can help bridge the gap between theory and practice (Boin, Kofman-Bos, & Overdijk, 2004). Computer-based simulations have the further added-value of allowing the study of dynamics of highly-complex crisis scenarios. This kind of simulation can

yield very cost effective and time efficient insight into emergency response organizations (Robinson & Brown, 2005).

Agent-based simulation in particular can be used to develop domain-specific theory in the field of coordination (Dooley & Corman, 2002; Macy & Willer, 2002). Such theory-building stems from a particular class of research question: it addresses the "what-if" of simulation in general, together with the interaction between: local and global, micro and macro, individual and emergent behavior, structure and chaos (Davis, Eisenhardt, & Bingham, 2007; Louie & Carley, 2008; Macy & Willer, 2002). Scientific questions are typically positive (explanatory) or normative (prescriptive). Somewhere in between lay questions about what is plausible (what might be). Simulations are particularly useful in this context (Louie & Carley, 2008).

The rest of this paper presents two background frameworks for the use of simulation in section 2. On section 3 it presents a combined framework for simulation as a method of theory development in the domain of crisis response, followed in section 4 with a brief description of its use in developing coordination theory in the domain of crisis response. The last section presents some final discussion and limitations of the approach so far.

## 2. Background for simulation

In this section we present two methods for using simulation. The first offers a roadmap for simulation as a method for theory development, while the second offers a set of activities within a design-oriented, problem-solving approach.

### 2.1 Simulation as a Method of Theory Development

One of the uses of simulation is theory discovery, under the understanding that a simulation model is the codification of a set of theoretical propositions equivalent, for example, to operationalizing constructs into survey items (Dooley, 2002). According to (Davis et al., 2007), simulation as a research method can provide superior insight into complex theoretical relationships among constructs, especially when challenging empirical data limitations exist and can provide a powerful method for sharply specifying and extending extant theory. The roadmap for using simulation to develop theory is presented below (see Table 1).

| Activity | Result |
|---|---|
| D1. Determine theoretically intriguing research question. | Research question |
| D2. Identify Simple theory that addresses the research question and for which data is challenging to obtain. | Simple theory |
| D3. Choose simulation approach that fits question and theory. | Simulation approach |
| D4. Create conceptual representation operationalizing theoretical constructs. | Computer based simulation model |
| D5. Verify computational representation of theory and conduct robustness checks | Internal validity (verified simulation model) |
| D6. Experiment to build novel theory | Experimental design |
| D7. Validate with empirical data | External validity (valid results) |

**Table 1**: Activities for developing theory through simulation methods
Adapted from: (Davis et al., 2007)

## 2.2. Simulation as a method of inquiry

To further inform the process of conceptualizing, building, and evaluating a simulation model, we also consider the use of simulation as a method of inquiry (Sol, 1982). This approach consists of conceptualizing a system, creating a model to represent it and subsequently experimenting with the model to generate alternatives for changes to the real system. The activities are presented below (see Table 2).

| Activity | Result |
|---|---|
| S1. Conceptualization: Choice of context; Identification of entities and action patterns; and specification of base model | Base Model |
| S2. Construct an executable simulation model, along with an experimental frame. | Simulation Model |
| S3. Conduct experiments, followed by verification and validation. | Results |
| S4. Evaluate the different alternatives and choose target system | Target System |

**Table 2**: Activities of simulation as a method of inquiry
Adapted from: (Sol, 1982, p. 44)

# 3. Framework for Simulation as a Method of Theory Development

The first method for using simulation is focused on theory. Its objective is to build a model that operationalizes theoretical constructs to conduct experiments that contribute to the theory (Davis et al., 2007). However, it is not explicit about how to connect the theory to a particular situation under study. The second method, focuses on using simulation as an inquiry into a real situation, following a design-based approach in which simulation aides in the evaluation of alternatives for change (Sol, 1982). Its objective is framed as a design, problem-solving or decision-making problem and need not entail theory development.

We combine the two methods into a single framework for simulation as a method to develop theory that considers conceptualizing and building the model as an inquiry into a real problem situation. Although, the object of the simulation is not to change an existing system directly, but rather to extend existing theory. We begin with a research question and end with a development or extension of extant theory. The activities are combined into a single simulation method, presented below (see Figure 1), where each activity is represented by a box and each outcome as a parallelogram.
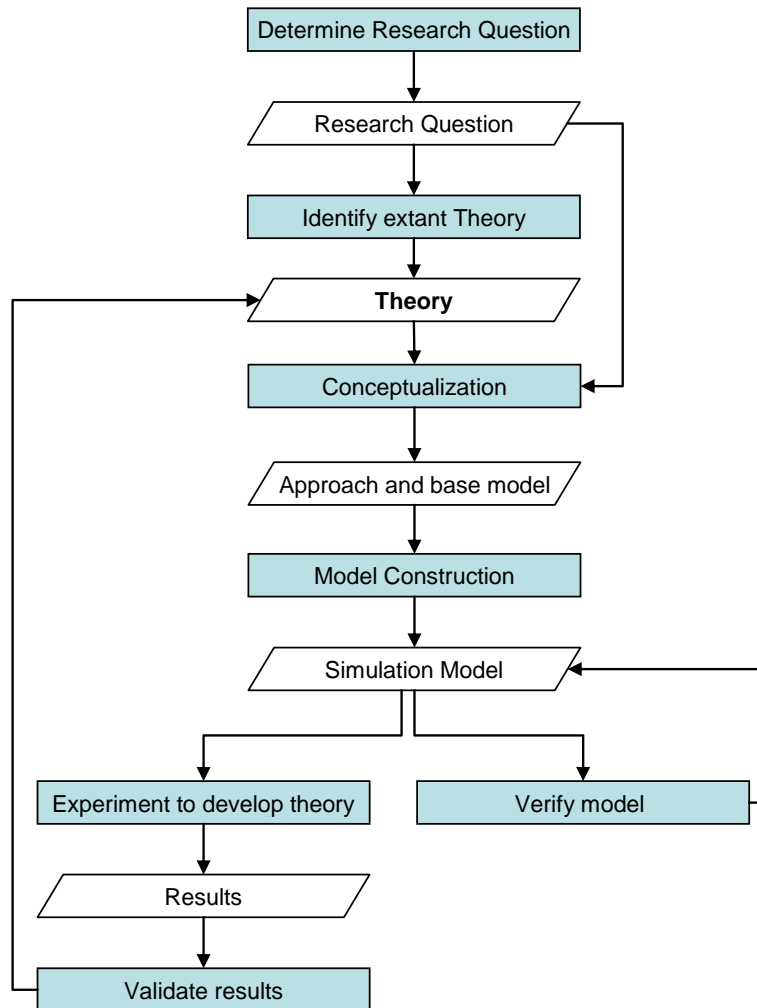
**Figure 1**: Framework for simulation as a method of theory development

*Determine a research question*. As other methods of scientific inquiry, this one starts by delineating a research question of interest. On one hand, the question is motivated by a study of literature in which an intriguing tension is sought (Davis et al., 2007). On the other hand, the question is explored out of observation of a real problem situation (Sol, 1982, p. 43). The outcome of this activity is a research question that guides the inquiry in a particular domain.

*Identify extant theory*. Because the research question is informed by studying existing theory, the second activity in the method consists of selecting the most appropriate extant theory – or *simple theory*, according to (Davis et al., 2007) – among that body of knowledge. Such theory needs to shed light on the research question, highlighting the identified tension and complexities of the domain of application. It should also present challenges that are limited by the availability of data, making the inquiry suitable for a simulation treatment. The selected extant theory is an un(der)developed theory with only a few constructs and related propositions with modest empirical or analytical grounding, such that the propositions are likely correct but conceptually weak (Davis et al., 2007). Revising, developing or extending this theory is the outcome of the

whole simulation method. This progress can be understood in terms of Lakatos as a use of simulation to test the 'protective belt' around the 'hard core' of a research programme (Lakatos, 1978). We identify the 'hard core' theoretical concepts, and around them place potential anomalies which become the object of testing and adjustment.

*Conceptualization*. This activity begins by determining the context and the simulation approach that most adequately fit the research question and the extant theory. Conceptualization should include a context, an identification of entity-categories and a base model (Sol, 1982, p. 43). The choice of context for conceptualization determines the language for conceptual modeling. Accordingly, a simulation approach that fits this context should also be chosen, between for instance discrete-event, system dynamics and agent-based simulation (Dooley, 2002). The base model is then built in line with the context for conceptualization and is an implementation-independent representation of the problem situation.

*Model construction*. Using the selected context and approach, a computer-based simulation model is built. This model should express the base model in computer-readable language. It should also express the theoretical concepts and relationships that are to be experimented with.

*Verification*. This activity is about checking the internal validity of the theory and the correctness of the model. Simulation model verification is substantiating that the model is transformed from one form to another as intended, with sufficient accuracy (Balci, 1994). The result is a verified simulation model, which implies iterating between this activity and the previous one, until the model is sufficiently verified for experimental purposes.

*Experimentation*. This activity takes place in order to produce results that test the protective belt of the theory, emphasizing the tensions addressed by the research question. Using simulation for theory development in crisis management might entail probing certain aspects of crises by simulating them under controlled conditions: keeping some conditions constant and manipulating others in successive runs, allows observing and measuring the potency and assumed relationships between certain variables (Kleiboer, 1997). The experimental design depends on the selected approach and desired outcomes, but in any case simulation means experimentation and experimentation calls for statistical analysis (Kleijnen, 1999).

*Validation*. The validation of the simulation model is aimed at substantiating that it behaves with satisfactory accuracy within its application domain and consistent with the study objectives (Balci, 1994). However, the extent or rigor of this step is contingent on the pre-existing extant theory, because when the starting propositions are grounded on empirical evidence, external validity is already embedded into such theory (Davis et al., 2007). In a sense, validating the simulation model is a recognition that it is like a miniature scientific theory and as such subject to the problem of induction – inferring from real world observations that the model (or theory) captures essential structures and parameters of the real system (Kleindorfer, O'Neill, & Ganeshan, 1998). This difficulty is especially relevant because, as stated before, the simulation is used for "what if" analysis and validation cannot simply be about comparing computed behavior to "real" behavior, because there is no "real" system. Accordingly, face expert validation and sensitivity analysis often takes the place of quantitative or statistical validation techniques (Dooley, 2002; Louie & Carley, 2008). Validated results can then be used for strengthening the

'hard core' theory. Invalid results, however, should not be taken as falsification of the 'hard core' (Lakatos, 1978), but rather as a source for subsequent versions of the (simulation) model.

# 4. Initial Use of the Framework in Developing a Simulation Model

This section summarizes the steps followed until now in building a simulation model, according to the activities presented in the previous section.

## 4.1. Research Question

At an initial stage of research, a case study was done to confront the current understanding of coordination in crisis response with actual practices of coordination observed in crisis response exercises. The case was reported in (Gonzalez, 2008) showing that, by adopting an information-processing view of coordination (presented in the next subsection) standardization and mediation are favored as coordination approaches for crisis response, while mutual adaptation is given less prominence. Furthermore, emergent coordination is not adequately addressed or supported, although it does occur in practice.

The simulation process should thus contribute to answering the following research question:
*How do structured and emergent coordination mechanisms between crisis responders perform against each other in terms of effectiveness and efficiency and what are the conditions under which emergent coordination mechanisms perform better*?

## 4.2. Extant Theory

The theoretical framework for the simulation is the information-processing view of coordination, which constitutes the 'hard core' of the theory, while emergent coordination may extend this basic theory and is the focus of the experiments. In the information-processing view, coordination is understood as managing dependencies between activities (Malone & Crowston, 1994). For example, a dependency between shared resources can be managed by coordination processes such as priorities or budgets. In organizational design theory such processes or mechanisms are classified into: standardization (plans, procedures), mediation (hierarchy, boundary spanners, brokers) and mutual adjustment (feedback, adaptation) (March & Simon, 1958). In addition to those traditional mechanisms, we can simulate emergent coordination, which manifests itself at an aggregate level through the interaction of local behavior and feeds back on these local behavior as well. As a result we aim to (1) understand how emergent coordination fits within the information-processing view and (2) evaluate how it fares against the other three approaches.

## 4.3. Conceptualization

The next step is to select the simulation approach. Discrete-event simulation will be used because the variables of interest in the emergency scenario that determine the state of the system will change discretely over time. Animated objects and global control of the environment will be implemented in an object-oriented fashion. However, for the responders, more complexity and autonomy are desired. Software agents are thus appropriate for responders because distribution, autonomy, goal-based behavior, and mobility, among others, are considered to be characteristics of crisis responders and agents alike. In addition, agent-based approaches have been used before both to simulate and support crisis response, e.g. (Chen & Decker, 2005) and to simulate coordination issues, e.g. (Xu et al., 2006). Moreover, agent-based simulations have been

associated with theory development, insight and understanding, rather than prediction or optimization  (Macy & Willer, 2002), making agent-based simulation well-suited for the approach presented here.

A training scenario of an emergency was used for experimenting with coordination issues of crisis response. The scenario comes from an existing description of the way in which an emergency response should be carried out in the context of the Dutch GRIP (or crisis response coordination procedure) levels. The scenario starts with a crane on a road. The incident occurs when a truck carrying flammable liquid crashes onto it. This prompts the response of fire, police and ambulance services in what is initially a routine situation. Escalation of the incident occurs when the truck catches fire. The incident becomes larger than originally assessed, more response units are needed and a coordinated response is required from multiple disciplines.

*Standard* coordination mechanisms will follow FIPA agent interaction protocols (http://www.fipa.org/repository/ips.php3) that fit the information flows described in the GRIP levels; in addition, each agent is modeled as a finite state machine, where the states are derived from standard crisis response manuals. *Mediation* is reflected in the organizational structure of the response agents, based on the multidisciplinary hierarchical organization defined in the GRIP manuals. *Mutual adjustment* is modeled by providing the possibility of agent behavior to be used as feedback for coordinated action and by allowing agents to assign priority and trustworthiness to incoming messages (based, for example, on closeness to the incident or past message accuracy) independently of rank or standard interaction protocol. *Emergent* coordination can be modeled by specifying how agents interact with one another resulting in coordinated action. Emergence is arising of unexpected structures, patterns, properties, or processes in a self-organizing system, where the patterns of interaction usually persist despite continual turnover in its constituents and usually opposed to centralization (Dooley & Corman, 2002). For example, by default the fire chief is the operational leader of the response, but if the crisis scenario evolves into a primarily medical emergency, then the medical officer can become the operational leader, being in charge of operational decision-making at the multidisciplinary level. Although the resulting (emergent) coordination may result in a coordinated action that is equivalent to that obtained through standards or mediation, what the simulation contributes is a controlled way of examining how they differ from each other, how they can be used and how (or when) they should be supported during a real crisis.

## 4.4. Model Construction

Construction of the model was based on performing analysis of the simulation using the Gaia agent-development methodology (Zambonelli, Jennings, & Wooldridge, 2003). Design was split into agent-based (continuing with Gaia) and discrete-event based using the D-SOL simulation suite (Jacobs, Lang, & Verbraeck, 2002). Detailed design and implementation of the agent-based system then followed the GAIA2JADE process (Moraitis & Spanoudakis, 2006) to allow implementing with the JADE agent environment (http://jade.tilab.com/). The high-level architecture of the model is shown below (see Figure 2).
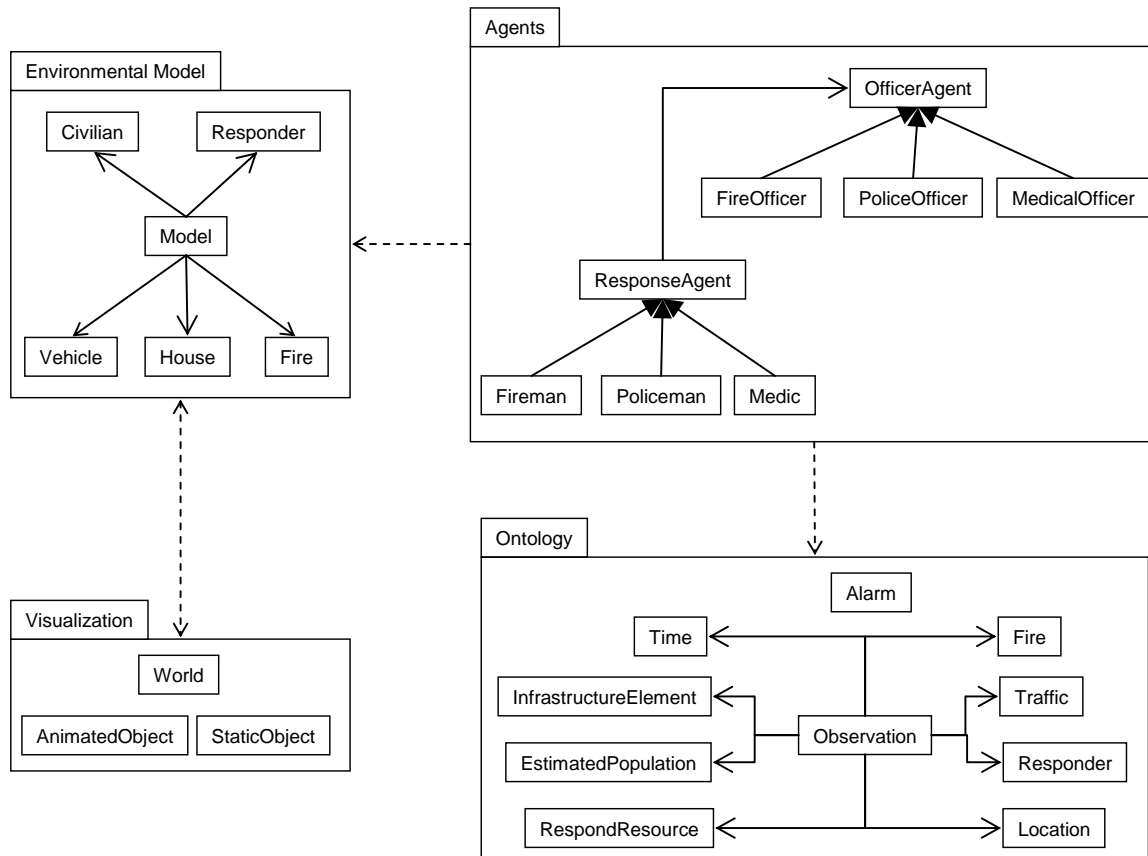
**Figure 2**: High-level architecture of the simulation model

In this architecture, the *Environmental Model* package and the *Visualization* package, represent the crisis scenario (the emergency-related entities are objects contained in these packages). These packages constitute the discrete-event based component of the simulation model. The *Agents* and *Ontology* packages constitute the agent-based component of the architecture. The *Agents* package contains the response agents and their behaviors. The *Ontology* package represents the knowledge objects with which the agents communicate and store their knowledge about the *Environmental Model*. The discrete-event and agent-based components remain loosely coupled so that the experimentation with the coordination mechanisms does not require changes in the crisis scenario. This also means that the same agents could also be applied to a different *Environmental Model*. A more detailed description can be found in (Gonzalez, 2009).

## 5. Discussion and Limitations

Simulation has been presented here as a method which needs to be contextualized into a broader framework for research which is outside the scope of this paper. In using simulation, several epistemological assumptions are implicit (Becker et al., 2005). It is imperative for the validity and reliability of the whole research that such statements are made explicitly and thus the use of simulation needs to be embedded within a wider research approach. This is particularly relevant under the difficulties of validation related to simulation in the domain of crisis response, where there is scarcity and inconsistencies in actual data for comparison (Robinson & Brown, 2005);

and where reference models or historical data may not be available, and interpreting the simulated data may not be straightforward (Jain & McLean, 2003). Validation should then start by making assumptions explicit with regards to epistemology, research approach, modeling approach, and domain of application. As a result, validity claims will be limited by such assumptions.

Current work is aimed at conducting experiments and validating the simulation model. This implies a use of screening and factorial design which fit the agent-based approach (Sanchez & Lucas, 2002), while at the same time considering further analytical tools in order to decompose or subtract the model when complexity is too large for successful statistical techniques to be employed (Fehler, Klügl, & Puppe, 2005). Several scenarios, each related to a particular coordination approach, will be tested under different configurations of input factors and evaluated in terms of performance of the response and the coordination effort.

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