11TH ICCRTS
COALITION COMMAND AND CONTROL IN THE NETWORKED ERA

A Semantic Data Model for Simulating Information Flow in Edge Organizations[1]

Track Sessions:
C2 Concepts & Organization
C2 Modeling and Simulation
C2 Experimentation

Authors:
Marc S. Ramsey, *Stanford University*
Douglas J. MacKinnon*, *Stanford University*
Dr. Raymond E. Levitt, *Stanford University*

Point of Contact:
Marc S. Ramsey
Collaboratory for Research on Global Projects
Terman Engineering Center, MC 4020
380 Panama Mall
Stanford, California
94305-4020
(650)725-8970
mramsey@stanford.edu

[1] We wish to thank our colleague Ryan Orr for his helpful suggestions on this paper. The research described in this article is funded in part by the Command & Control Research Program, Center for Edge Power.

Abstract

Edge organizations emphasize the movement of decision-making power to individuals and teams who interface directly with fast-changing environments. Making decisions without timely access to relevant information leads to ad-hoc or delayed responses. A key determinant of effective Edge organizations is an optimized information infrastructure to collect, filter, store, and communicate data to those who need it. Computational modeling has been proven to be an effective tool for analyzing and optimizing project organizations. Existing project modeling tools do not, however, adequately represent the critical dynamic behaviors of workers in modern knowledge-based organizations. POW-ER is an extensible organization simulation platform, developed as an outgrowth of the Virtual Design Team (VDT) computational modeling research at Stanford University. This paper discusses the development of a new semantic data model for POW-ER. This enhanced data model provides the capability to simulate the behavior of personnel utilizing complex sensor and information systems in highly dynamic environments. Using POW-ER, researchers will be able to conduct emulation experiments on hypothetical Edge organization structures and information architectures to validate and calibrate the computational model. Ultimately, this will evolve into a tool that will aid in the systematic design and optimization of Edge and other organizational forms.

1.0 Introduction

Computational modeling is a powerful tool that has made significant contributions to organizational science and management practice. Stanford's Virtual Design Team (VDT), which has been developed and extensively validated over the past 17 years through field emulation experiments, has proven very effective at both developing theory and at helping managers to design more effective organizations. However, VDT is inadequate to model Edge organizations given their unique characteristics. VDT was developed to model routine project work. Consequently, it assumes a fixed organizational structure consisting of workers with static skills and application experience; all tasks can be predefined and sequenced without any changes; and all tasks have fixed assignments to workers that do not change. Unexpected exceptions merely add work to the predefined tasks to be carried out by the same workers.

We have developed a prototype of a new modeling tool for Edge organizations to address these limitations of VDT: Product, Organization, Workflow—Edge Research (POW-ER) (Ramsey & Levitt 2005). This paper discusses the development of a new semantic data model for POW-ER. This enhanced data model provides the capability to simulate the behavior of personnel utilizing complex sensor and information systems in highly dynamic environments.

1.1 Terminology

We begin by defining some key terms in the context of our research.

Data: factual values of variables used as a basis for reasoning, discussion, or calculation. These values may be static or dynamic in nature.

Information: is data selected through investigation, study, or instruction for use in a specific problem domain.

Knowledge: supports direct action and is applied to data to create information (Nissen and Levitt, 2003).

Edge Organizations: a new organizational form in which personnel in the field are given increased decision-making responsibility, allowing them to respond in a more agile and adaptive fashion to changes in their operational environment (Alberts & Hayes 2003). The concept leverages advances in information and communication technologies, which permit real time, high bandwidth access to relevant information from any location in the world. In essence, the concept is to move from the traditional deeply hierarchical, headquarters-centric organization, towards a flatter hierarchy made up of small network-centric distributed units. As with any new conceptual model, however, a significant amount of research is required on how best to go about implementing this type of organization. Laboratory and analytical methods are helpful, but suffer from weaknesses that make it difficult to apply the results to real-world situations. Field methods can be time consuming, costly, and suffer from poor experimental control.

Computational Modeling of Organizations: a complementary method which overcomes some of the limitations of both laboratory and field research. Agent-based computational modeling and simulation is a natural and intuitive method for developing predictive, multi-level social science theory. Mature, validated, micro-social science models of micro-behaviors can be embedded in computational organizational micro-agents (individuals or small groups) as sets of canonical micro-behaviors. Organizational researchers can then model the way in which these canonical agents behave and interact in their “virtual world”—which includes both other computational agents and relevant aspects of the task and/or environment—to generate predictive outcomes that can be validated against empirical data.

Semantic data modeling: a conceptual tool that is used to model problem domains consisting of named objects and the relationships between them. In POW-ER, objects are used to represent agents, activities, systems, and other abstract concepts. Each object has a set of properties defining its characteristics. An object may also participate in a variety of relationships with other objects, these relationships may be one-to-one, one-to-many, many-to-many, etc.

1.2 Motivation

The VDT model is based on the information processing model of organizations, which was first proposed by March and Simon (1958), and elaborated for project organizations by Galbraith (1977). VDT assumed a project model of workflow in which all tasks are predefined and pre-assigned to specific workers in a fixed organization structure for execution. Uncertainty about the task and environment is limited to uncertainty about the amount of “hidden work” (coordination and supervision overhead) that will arise in executing the direct tasks in the task network and the resulting impact on duration and process quality, as key actors become backlogged and fail to supervise or coordinate. In modeling this kind of routine project work, VDT could abstract away almost all of the semantic content of tasks and treat them as simply a quantity of information to be processed — using the so-called “information processing” abstraction of work.

In contrast, Edge Organizations are deployed in contexts where both task and environmental uncertainty are very high. When conditions that trigger unplanned tasks arise, the organization must perceive, understand, and react to these triggering conditions by assigning agents from the available pool of resources with the appropriate skills and the capacity to carry out the needed tasks. A simulation model of organizations that operate at the level of uncertainty dealt with by Edge Organizations must model enough semantic content about their environments and repertoires of tasks to replicate Edge Organizations’ perception, interpretation, and task assignment behaviors.

Moreover, the VDT model assumes an implicit relationship between a process and the product it produces. A process can not begin until a designated set of prerequisite products are available, and on completion, will always produce exactly the same product. This is adequate for modeling routine projects, but does not provide the necessary flexibility to model the non-routine processes typical of Edge organizations.

The processes we are particularly interested in modeling involve observation, interpretation, learning, and adaptation. The products of these processes are information and knowledge. There may be more than one possible approach to obtaining the desired information, and workers may choose a particular approach based upon environmental factors, tacit knowledge, or through trial and error. This requires a richer model of the objects within the simulated environment - hence, the need for a richer semantic model. Through use of semantic data modeling techniques, we seek to make explicit the linkage between the environments, processes and products of Edge Organizations. By doing so, we can begin to examine the effectiveness of Edge organizations. We will also be able to examine the benefits of deploying newly developed systems and technologies within the context of these organizations.

2.0 The Virtual Design Team (VDT) Model

The Virtual Design Team (VDT) research group (Jin & Levitt 1996) was initiated at Stanford University in the late 1980s to help managers design organizations and work processes for executing fast-track development of complex products without incurring the large cost overruns and catastrophic quality failures that had frequently plagued such efforts. VDT was developed as an agent-based computational model of project teams and the work processes they were attempting to execute in a highly concurrent manner. It has been successfully used to model work tasks, communications, and exception handling within traditional organizations working on projects in areas such as construction, aerospace, consumer product development, and healthcare. VDT was commercialized as a single project simulator called ViteProject® starting in 1997, and then as a multi-project matrix organization simulator called SimVision® since 1999.

A VDT project model consists of a set of tasks to be performed, with appropriate sequencing constraints between them, and a project team made up of a set of actors organized into a supervisory hierarchy. We use the generic term *actor* to refer to simulated agents within a model, these may represent an individual or a team of people. Each *task* is assigned to a single actor, that actor may initiate work on the task when all of the relevant requirements (normally completion of the designated prerequisite tasks) have been fulfilled. Work is performed by the actor in increments which generally corresponds to a single working day. A *task* requires completion of a specified amount of direct work for it to be designated complete, when all of the tasks in the network are complete, the project itself is considered completed.

VDT differs from traditional project models employing critical path method (CPM) techniques, in that it also accounts for indirect forms of work. As each increment of work is performed on a task, there is a possibility that the actor will be requested to engage in communicating design and exception related information to other actors. In addition, exceptions often require decision-making effort by supervisory or technical personnel. These coordination activities take time, and are simulated and accounted for as part of the total effort required for completion of the task and the project as a whole.

2.1 Extending VDT to Model Edge-like Organizations

A useful simulation of Edge-like organizations will model the processes of gathering information, reasoning about that information to produce a body of relevant knowledge, decision-making based on that knowledge, and executing the actions resulting from those decisions. It will model a set of actors (individuals or teams) who may be located in disparate geographic locations, have varying skill sets, levels of knowledge, and differing approaches to problem solving.

We would also like to place increased emphasis on modeling the abstract flow of information and knowledge, instead of just modeling quantities of information processing in the interdependent tasks that comprise work processes. Beyond innate knowledge gleaned from past experience, each actor's awareness of the simulated world is necessarily limited to that which the actor can observe (either directly, or through the use of a sensor system), that which has been communicated to it (by other actors, or through interaction with information systems), and information that it can reason about, given information and knowledge it already possesses.

VDT uses a fixed task network, with actors having fixed assignments to specific tasks. We would like to extend that concept such that each actor has a set of goals, which are achieved by actions that can be performed, given the availability of needed information. Goals are prioritized, either at pre-defined levels, or at levels established by the needs of the actor, or of other actors with which it communicates. A goal may be shared by multiple actors, efforts will be made to complete the goal by the first actor that has the relevant knowledge, and is available to process it. Goals have subgoals. The lowest level subgoals are enabled by one or more tasks.

The effectiveness of the simulated organization is directly related to its ability to respond to one or more specific events, by accomplishing associated goals and subgoals. There may be a number of criteria by which the effectiveness of the organization can be judged, including how likely it is that the relevant goals will be accomplished in response to the events, how quickly the organization can accomplish the goals, the correctness of the response(s), resources used, and costs incurred. Goals may also be in conflict, accomplishing some goals may have negative impact on other goals and hence on the overall outcome. It should also be possible to track changes in team performance with time and experience.

3.0 The POW-ER Model

POW-ER is an extensible organization simulation platform, developed as an outgrowth of the VDT computational modeling research at Stanford University. It is a meta-simulation framework, which provides facilities for describing entire classes of simulation models. At its heart is a stochastic simulation engine that evaluates a scenario to determine the likely outcome of simulated events. POW-ER adds several new kinds of representation and reasoning about tasks, actors and relationships to address the unique complexities of Power to the Edge Organizations.

A POW-ER model is a graph-based semantic structure consisting of a meta-model, which defines the contents of a model for a particular problem domain, and the model itself, which is a domain specific instance of the model describing a particular scenario. The primary role of the meta-model is to allow programmatic generation of a domain specific model editor and simulation engine. The typical end-user of POW-ER interacts only with the domain specific editor and simulator, simplifying the process of creating models of alternative scenarios within a particular domain.

3.1 Data Model

This section discusses the basic concepts used in POW-ER to model Edge-like organizations. These provide an abstract, simplified view of the world that we wish to represent for simulation purposes. The data model makes use of semantic data modeling techniques to allow for representation of complex extensible objects.

The data model is generic and intended to be applicable across a variety of domains with appropriate customization. Customization involves the creation of domain specific object classes with appropriate defaults. This reduces the level of detail required to create a model for a specific problem domain.

A *scenario* describes a self-contained simulated world as it evolves over the simulated time period. A scenario contains a set of objects representing people, places, resources, and behavior.

A *fact* describes a relevant attribute or property of an object. Any of the objects in the scenario may have facts associated with them. Facts may be numbers, identifiers, boolean values, etc, and may change value during the period of the simulation. A fact may be observable, either directly by an actor, or through use of specific types of simulated sensor systems.

A *belief* represents a perception of a fact, in essence, a single processed piece of information. A belief has a current level of confidence, expressed as a probability. Beliefs can be communicated from one actor to others, or stored for later use within an information system.

An *agent* is a human or non-human entity that can produce, hold, communicate, or use information. An agent has a set of behaviors that it can execute in response to changes in the simulated environment. An agent also possesses a set of beliefs, which constitute its perception of the state of the outside world, and determine which behaviors it chooses to engage in. An *actor* is a more specialized form of agent that represents an individual or team of people. We also provide the concept of a *system*, which is used to represent non-human agents such as information processing systems.

A *task* represents a work process that may be performed by an actor or system. A task may require use of one or more resources, and may incur fixed or varying costs. The process of working on a task changes the state of variables associated with that task. It may also generate events which result in changes to the information held the by actor and/or system performing the work. A task is either assigned to a specific actor, or associated with a specific goal, and may reassigned to another actor at any time.

A *goal* represents a desired state of one or more simulated variables. When all of the specified pre-conditions are true simultaneously, the goal is marked as achieved, generating a corresponding event. One or more tasks may be associated with a goal, performing these tasks will fulfill some or all of the pre-conditions necessary to complete the goal.

An *event* causes a change in the state of the simulated world. The simulation is driven by a series of such discrete events. An event may be scheduled to happen at a specific time, may happen at a randomly generated time, and may happen repeatedly. When triggered, an event may change facts associated with various topics, and may cause the scheduling of additional events.

An *outcome* is an event that triggers the end of a simulation run. There may be a number of possible outcomes for a given model. An outcome may have an associated quality value, providing a means of measuring the overall quality of a series of simulation runs with differing outcomes.

3.2 Simulation Algorithm

The scenario contains an initial set of objects, which have been defined by the model. These objects include actors, systems, and observable state information. Associated with these objects are an initial set of facts. The simulation is started by changing the state of one or more of these facts. This will cause the posting of an initial set of events, and trigger processing by interested actors and systems.

A simulation is driven by a series of discrete events. An event may represent a change in the state of one or more facts in the scenario. Actors and systems respond to events, and may in response change the state of additional facts, resulting in the generation of further events. A simulation is terminated after a pre-determined simulated time period has elapsed, and/or at least one of the pre-determined goals has been completed.

At each event, an actor or system may continue processing an active event or task, select another task or event for processing, or remain idle if there is nothing available for processing. The selection of a task or event is determined by an attention rule (priority, FIFO, LIFO, random selection, etc.).

A task or event requires a certain amount of time and effort to process. At each clock tick, the amounts of time work performed on the active item are updated. Processing ends when a set of termination conditions are met, which results in changes to additional facts and beliefs associated with the item and the involved actors or/or systems

4.0 Applying POW-ER to the Traditional Project Domain

Our initial research effort uses POW-ER to implement a simulation environment for traditional VDT project models. This is done as a proof of concept, and as a means of validating POW-ER against our prior research results. We then extended the VDT model to address the character of command and control work processes and organizations.

VDT, ViteProject and SimVision all used a precedence diagram model of work flow, with two additional kinds of task interdependencies: reciprocal interdependency — where shared subgoals achieved by two tasks interact negatively; and failure interdependence — where a decision to perform rework on a given task triggers corresponding rework in a dependent task. Actors have fixed skill sets and organizational reporting relationships; and tasks are pre-assigned to actors and these task assignments do not change. Any coordination and rework overhead on direct work simply adds duration to the fixed tasks in the fixed task network, with fixed assignments to actors. This restricts the applicability of these models to relatively routine — albeit potentially very complex and severely time-pressured — projects like new product or facility development, software development, etc.

4.1 Modeling a Command & Control System

We will use as an example a model of watch-standing tasks on board a guided missile cruiser assigned drug interdiction operations in the Gulf of Mexico. As shown in Figure 1, the simulation agents (or watch organization team members) consist of the Commanding Officer, Tactical Action Officer (TAO), Officer of the Deck (OOD), and the CIC watch Officer and those subordinates who work for each of them. Each of these watchstanders is assigned tasks that include typical bridge and CIC (Combat Information Center) watchstanding duties required through safety of navigation, accomplished by bridge watchstanders, and typical local area surveillance, accomplished by CIC watchstanders.

We start the simulation under normal peace time conditions yet allow for the probabilistic sighting of a surface vessel suspected of carrying drugs. This sighting causes conditional tasks to be performed, such as: the vessel’s country flag to be identified, permission to board to be requested; boarding to be performed; and boarding to be completed. The simulation also allows for the watch to reach its completion while the conditional boarding mission remains active.

This model provides a simple yet realistic simulation of command and control elements in which we input realistic times and probabilities for watch and mission phenomena.

This method offers decision makers a way to enhance the usage of available manpower resources. This effort also communicates mission and watch organization structure, which provides a quick way for mission planners and team members to convey conceptions about how a mission will be designed, who will be responsible for different activities, and how changes in the mission-design and task assignments can have impacts on overall mission performance.

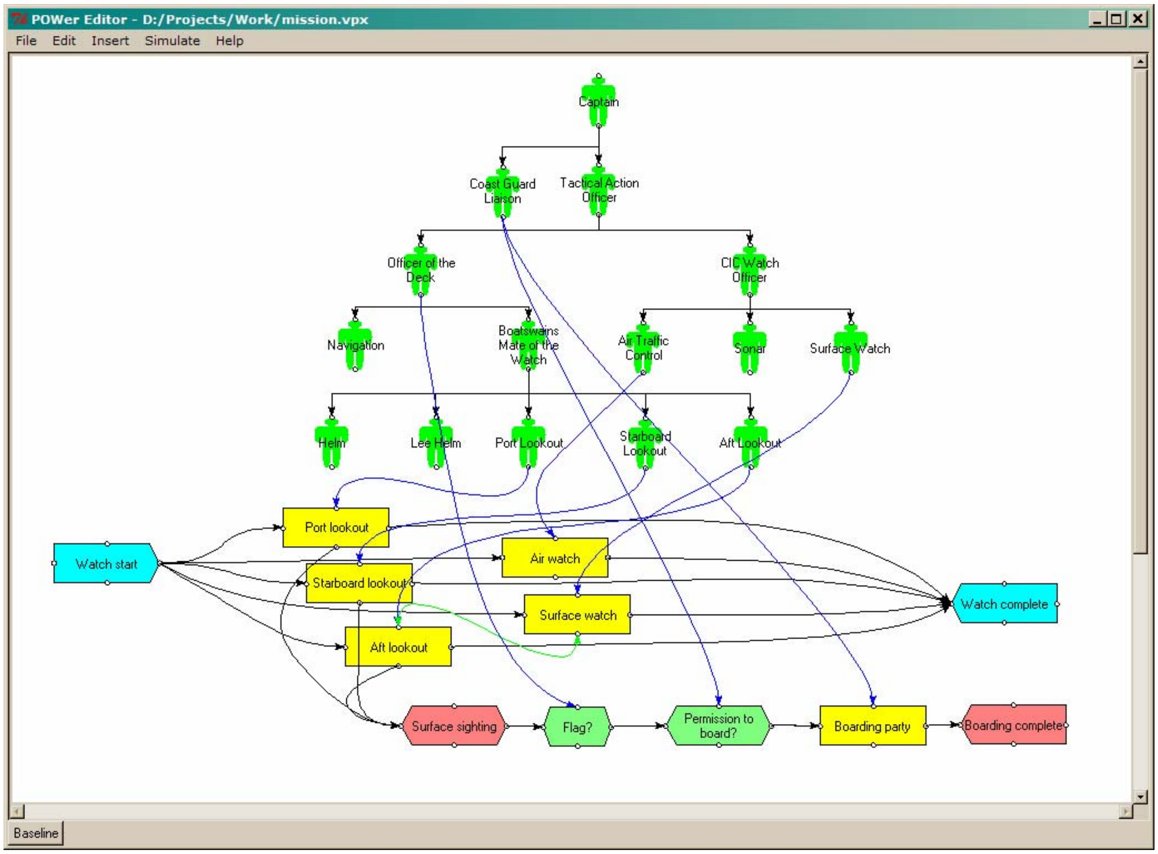

Figure 1 – The POW-ER "Watch-standing Model"

4.2 Modeling Specialist & Trans-Specialist Knowledge

To give another example, one of the first programs of computational experimentation conducted in the POW-ER modeling environment was to examine a dilemma that has been observed in the design of Edge-like, cross-functional teams that require both *specialist* and *inter-specialist* capabilities.

As background, in this paragraph we begin by describing the dilemma. Specialist capabilities, such as weapons, logistics, surveillance, and communications, are necessary to perform tasks efficiently. Inter-specialist capabilities, such as an understanding the goals and constraints of both weapons *and* logistics departments, or of surveillance *and* communications units, are necessary to coordinate and integrate specialized tasks towards the effective achievement of higher-level strategic objectives. But there is a dilemma in the design of these teams. On the one hand, if team-members are too specialized then they cannot coordinate effectively because they have different "thought worlds" or "interpretive schemes" (Dougherty 1992; Schein 1996). On the other hand, if team-members are not specialized enough then they cannot meaningfully contribute to efficient attainment of strategic objectives (Rulke & Galaskiewicz 2000).

To examine this dilemma, we conducted a series of computational experiments using the POW-ER modeling framework to simulate Edge-like, cross-functional teams and to test a series of 10 hypotheses concerning their optimal design. Independent variables included: specialist knowledge, trans-specialist knowledge, requirement complexity, solution complexity, labor cost, task concurrency and centralization. Dependent variables include simulated project duration, simulated project cost, functional risk and project risk. The experiments focused on the relative importance of specialist and trans-specialist capability in different organizational and environmental settings.

The series of computational experiments represents a first step towards applying the POW-ER computational model as a "virtual test-bench" – as a new method for analyzing the effects of micro-level organizational variables on macro-level organizational performance. In particular, the study sheds light on the circumstances under which it makes sense for members of Edge-like teams to develop common understanding, and, alternatively, the circumstances under which it makes sense to operate as "mutually ignorant" specialists. The study has been submitted to Organization Science for review and eventually for publication.

5.0 Future Research Directions

The POW-ER modeling framework holds promising potential to test the fitness of competing organizational forms—including those forms that have not actually been implemented in practice, such as agile new Edge forms—and to gauge organizational design parameters (i.e. matrix strength, centralization) and environmental factors (i.e. turbulence, complexity) that influence overall fitness levels.

We are just beginning to flesh out the modeling requirements for this domain through some early attempts to model Power-to-the-Edge organizations. We have built initial proof of concept models of individual knowledge acquisition and knowledge loss through learning and forgetting based on on-the-job training, mentoring and formal training; and task latency or task interruption; respectively. Results from these different examples are also being presented at the CCRTS and ICCRTS conferences (MacKinnon *et al*. 2006; Orr & Nissen 2006). During the summer of 2006, we plan to implement the occurrence of stochastic tasks (using multiple kinds of inter-arrival distributions) *vs.* the pre-defined project tasks that we can currently model in POW-ER.

Acknowledgements

This research was primarily funded by the Office of the Assistant Secretary of Defense for Networks and Information Integration (OASD/NII), through its Command & Control Research Program (CCRP), and coordinated by the Naval Postgraduate School's Center for Edge Power. Additional parts of this research were conducted under the auspices of the Stanford University Collaboratory for Research on Global Projects (CRGP).

References

Alberts, D.S. and Hayes, R.E. (2003), *Power to the Edge*, CCRP.

Dougherty, D. (1992). Interpretive barriers to successful product innovation in large firms. Organization Science 3 179-202.

Galbraith, J.R. (1977). *Organization Design*. Addison-Wesley, Reading, Massachusetts.

Jin, Y. and Levitt, R.E. (1996), "The Virtual Design Team: A Computational Model of Project Organizations," *Computational and Mathematical Organization Theory* 2:3 pp. 171-195.

Nissen, N.E. and Levitt, R.E. (2002), "Toward Simulation Models of Knowledge-Intensive Work Processes," WP #077, Center for Integrated Facility Engineering, Stanford University.

MacKinnon, D.J., Levitt, R.E., and Nissen, M.E. (2006), "Modeling Skill Growth and Decay in Edge Organizations: Near-Optimizing Knowledge & Power Flows (Phase Two)," presented at the 2006 Command and Control Research and Technology Symposium, San Diego, CA, June 2006.

March J.G. and Simon H.A. (1958). *Organizations*. New York: John Wiley and Sons.

Orr, R.J. and Nissen, M.E. (2006). "Hypothesis Testing of Edge Organizations: Simulating Performance under Industrial Era and 21st Century Conditions," to be presented at the 11th International Command and Control Research and Technology Symposium, Cambridge, UK, September 2006.

Ramsey, M.S. and Levitt, R.E. (2005). "A Computational Framework for Experimentation with Edge Organizations," presented in the proceedings of the 10th International Command and Control Research and Technology Symposium, McLean, VA, June 2005.

Rulke, D.L. and Galaskiewicz, J. (2000) Distribution of knowledge, group network structure, and group performance. Management Science 46 612-625.

Schein, E.H. (1996). The three cultures of management: implications for organizational learning. Sloan Management Review 38 9-20.