Resilient Community Recovery: Improving Recovery Through Comprehensive Modeling

by Stephanie E. Chang and Scott B. Miles

Research Objectives

The objective of this research is to develop an innovative, comprehensive model of urban recovery from earthquake disasters. The study aims to develop a robust conceptual model to frame future research and data reconnaissance, and to build user-friendly geographic information system tools for assisting community planning and preparation.

Understanding urban disaster recovery remains a significant challenge. No comprehensive framework or model of disaster recovery currently exists in the literature. Many studies touch upon facets of recovery, but none take it as their analytical focus. For example, in recent years, researchers have been paying increasing attention to modeling the direct and indirect economic impacts that earthquakes cause to communities (West and Lenze, 1994; Brookshire et al., 1997; Rose et al., 1997; Gordon et al., 1998; Okuyama et al., 2000; Cho et al., 2001; Chang et al., 2002). However, very little research has been conducted on how recovery proceeds over time, on the spatial dimensions of recovery, and on the interdependencies between sectors in the disaster recovery process. Moreover, a comprehensive model of recovery is needed in order to evaluate the potential consequences of decisions that affect disaster losses and recovery timepaths.

By addressing these issues, this study represents an initial attempt at developing a new generation of disaster loss models. This paper describes work completed to date on conceptual framework for disaster recovery, a prototype recovery model, and a test application for the 1995 Kobe earthquake, and associated sensitivity analysis. Further details on the study can be found in Chang and Miles (forthcoming).

This study is guided by numerous theoretical and empirical studies of how cities and their inhabitants recover from disasters. This literature suggests, for example, that marginal groups may not only be especially vulnerable to suffering losses as a result of earthquakes, but they are likely to have more difficulty in recovering from urban disasters (Hewitt, 1997; Blaikie et al., 1994). They may have lesser access to insurance, loans, relief aid, or government bureaucracies and decision-making, or face shortages

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Previous Summaries

***1999-2000**:*
Chang et al., http://mceer.buffalo.edu/publications/resaccom/9900/chapter1.pdf.
***1997-1999**:*
Tierney, et al., http://mceer.buffalo.edu/publications/resaccom/9799/ch2tiern.pdf.

Links to Current Research

This project builds on MCEER's research on loss estimation methodologies (M. Shinozuka, S. Chang, A. Rose) by extending them in the direction of modeling recovery processes. The project contributes to MCEER's goal of building user-friendly decision-support systems for improving community resilience to earthquake disasters.

in low-income housing (e.g., Bolin and Bolton, 1986; Bolin and Stanford, 1991; Bolin, 1993; Hirayama, 2000). Spatial effects have also been found to be important in disaster recovery. Decentralization of population and economic activity may be accelerated (Chang, 2001). Business losses are correlated with disaster severity in the neighborhood (Tierney and Dahlhamer, 1998). Retail and other locally-oriented businesses generally lag in recovery (Alesch and Holly, 1998; Kroll et al., 1991; Chang and Falit-Baiamonte, forthcoming).

Conceptual Model

The first step in addressing the need for a comprehensive community recovery model is the development of a rigorous and robust conceptual model. The conceptual model was built up by characterizing the attributes and behaviors of economic agents within a community, such as households and businesses, and describing relationships between agents themselves and relationships with their environment, such as buildings of residence and transportation networks (Figure 1). While the recovery model is designed to *measure* recovery at the community and neighborhood levels, it *models* recovery at the scale of the individual business and household.

The conceptual model focuses on the influence of agents' environments on their recovery processes. Specifically, it describes five principal types of recovery influences and processes that are useful in organizing and explaining the relationships expressed by the conceptual model. The five types are: (1) dynamic processes; (2) agent-attribute influences; (3) interaction effects; (4) spatial feedbacks; and (5) policy effects.

Dynamic processes refer here to changes over time. In true dynamic processes, a variable's current level depends upon its level in a previous period. What can be called pseudo-dynamic processes – changes over time that can proceed independently of variable levels in previous periods – also play an important role. Agent-attribute effects describe how the characteristics of a particular business or household may influence their respective recovery trajectory. For example, the demand for a business's product depends on attributes, such as whether it is in a locally-oriented or export-oriented sector and whether it is a large or small business. In particular, if locally-oriented, then the recovery of nearby households in the neighborhood and community matters, as these

Potential users of this research include lifeline organizations, emergency managers, urban planners, and local and federal government agencies concerned with facilitating disaster recovery. End users can use the tools developed as part of this research to explore and analyze strategies for reducing recovery time and any consequences related to failure of critical infrastructure within their community or organization.

are its customers. Interaction effects describe how the relationship between different agents or elements in the system influences their recovery timepath. For example, water availability is influenced by the survival of the electric power and transportation systems. Electric power may be needed to drive pumps that enable the water system to function; transportation disruption can impede the ability of the water utility to make repairs in a timely manner. Considering spatial feedbacks, households and businesses do not exist aspatially, but are affected by conditions in their specific neighborhoods, whether in terms of water availability, transportation conditions, or local consumer demand. Thus, the same type of household or business may recover differently depending upon which neighborhood it is located. Policy or decision effects are community-level decisions made either before the event, such as emergency planning and mitigation measures, or afterwards, such as recovery policy decisions.

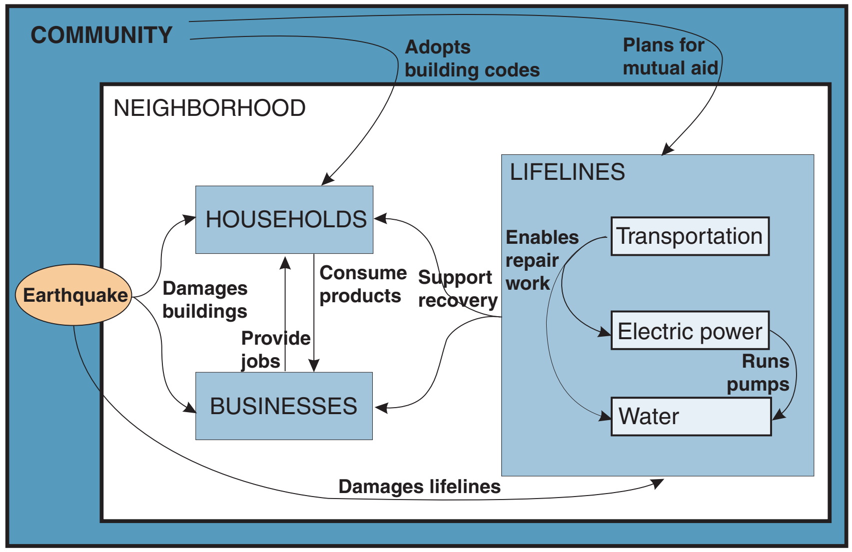


Figure 1. Overview of Disaster Recovery Conceptual Model

Computer Model

For the purposes of proof of concept and prototype development, a simple numerical framework was used in implementing the many relationships of the conceptual model. The prototype recovery model was implemented in the Matlab/Simulink software environment. The model framework takes the form of a series of simultaneous equations. Operationalizing the diverse relationships of the conceptual model was done by specifying each model variable as a relative index that varies between 0 and 1, rather than real world metrics, such as dollars. The approach taken is useful for integrating many metrics that would otherwise be difficult to mathematically combine. With each variable varying between 0 and 1, it was relatively simple to create basic first-order algebraic equations based on the relationships described by the conceptual model.

The subset of model variables referred to in this paper is listed in Table 1. Model variables can be of five different types: (1) driving variables, (2) agent attributes, (3) decision/policy variables, (4) intermediate variables, and (5) recovery indicators (output). Driving variables combine to serve as the temporal engine of a simulation by relating a particular variable (e.g., health recovery) to time with some restoration curve. For simplicity all restoration curves were assumed to be linear curves having some assumed or, potentially, calibrated slope. These slope values are modified within the model equations based on input variable values (e.g., for *MUT*, *CAP*, and *PRTY*). Driving variables are required as part of the implementation because none of the model inputs are explicit time series data.

To illustrate the algorithmic framework, which is comprised of 32 unique equations, the relationships used to calculate the recovery level (0, 0.25, 0.50, 0.75, or 1) of a particular household and the likelihood of the household moving to the next recovery level are expressed by Equations 1 and 2, respectively.

$$REC_b(t) = \begin{cases} 0.25((PT_b(t) \geq x) + RECH_b(t-1)), & REC_b(t-1) < 1 \\ 1, & REC_b(t-1) = 1 \end{cases} \quad (1)$$

$$PT_b(t) = \begin{cases} 0 & , if\ LEAV_b(t) = 1, REC_b(t-1) > 0 \\ 0.333\,(CRIT_c + HLTH_b + SHEL_c) & , if\ REC_b(t-1) = 0 \\ 0.2\sqrt{EMPL_c}\,(\sqrt{BL_b} + LL_c + CRIT_c + HLTH_b + SHEL_c) & , if\ REC_b(t-1) = 0.25 \\ 0.25 EMPL_c\,(BL_b + LL_c + HLTH_b + (1 - DEBT_b)) & , if\ REC_b(t-1) = 0.5 \\ 0.333 EMPL_b{}^2 (BL_b{}^2 + LL_c{}^2 + (1 - DEBT_b)^2 & , if\ REC_b(t-1) = 0.75 \\ 1 & , if\ REC_b(t-1) = 1.0 \end{cases} \quad (2)$$

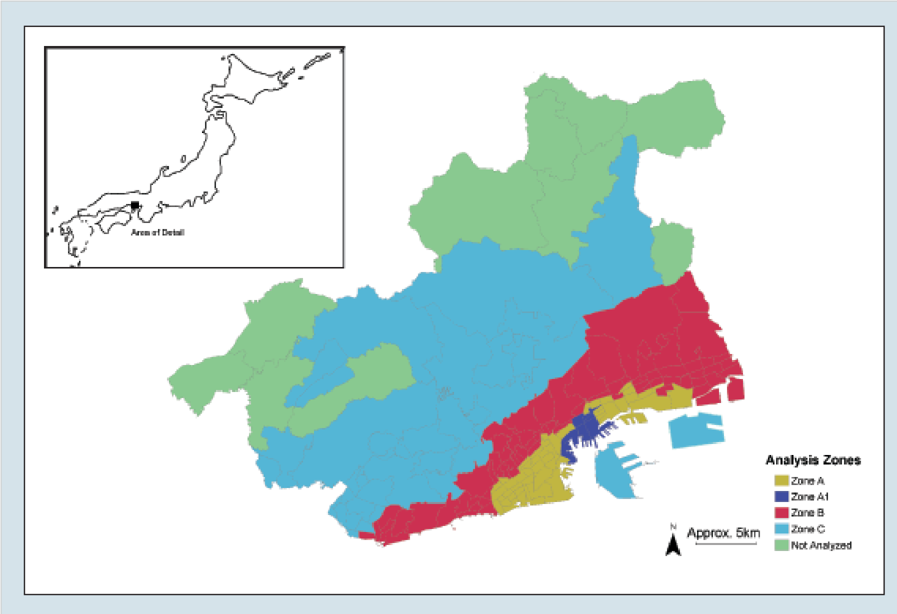
Table1. Selected Variable Definitions for Community Recovery Model

BLh	= availability of building for use, households
BMIT	= pre-earthquake structural mitigation
<u>CAP</u>	= recovery capacity of community (proxy for integration, consensus)
<u>CMIT</u>	= pre-earthquake mitigation to critical facilities
CRIT	= availability of critical facilities
DAID	= driving variable: aid availability status
DBLb	= driving variable: building repair status, businesses
DBLh	= driving variable: building repair status, households
DCRIT	= driving variable: critical facility availability
DEBT	= extent of indebtedness
DEL	= driving variable: electricity availability
DHLTH	= driving variable: health restoration curve
DINS	= driving variable: availability of insurance
DTRNS	= default transportation accessibility
DWAT	= default water availability
<u>EMIT</u>	= pre-earthquake mitigation to electric power system
EMPL	= availability of employment/income
INC	= income group of household
LEAV	= status of household leaving region
LL	= overall lifeline availability status
<u>MUT</u>	= provision for mutual aid in restoration plan
<u>PLAN</u>	= availability of restoration and recovery plan
<u>PRTY</u>	= restoration priority accorded to neighborhood
PT	= probability of transition to next higher recovery level
<u>RECh</u>	= household economic recovery level
SECT	= type of business sector
SHEL	= availability of temporary shelter
SIZE	= business size
<u>STH</u>	= reliance on short-term housing provision in recovery plan
<u>TMIT</u>	= pre-earthquake mitigation to transportation system
<u>WALT</u>	= provision for alternate water sources (water trucks) in plan
<u>WMIT</u>	= pre-earthquake mitigation to water system

Notes: Agent attributes in **bold**. Decision variables in **<u>bold underline</u>**. Driving variables in ***bold italics***. Recovery indicators in *<u>italic underline</u>*.

Prototype Simulation of Kobe Recovery

In order to begin to evaluate the usability, effectiveness, and behavior of the community recovery model, we chose to simulate the recovery of the city of Kobe after the catastrophic 1995 M = 6.9 earthquake disaster. For purposes of this analysis, Kobe was divided into four simulation zones (Figure 2): downtown (zone A1), the older urban core (A), the newer urban core (B), and suburban areas (C). These zones aggregated from census blocks and are defined on the



■ Figure 2. Analysis Zones Comprising Kobe, Japan, Study Area

"The holistic approach described in this paper demonstrates the complex impacts of mitigation, response, and recovery decisions."

basis of demographic, housing, and economic data (see Chang, 2001). In each zone, 100 households and 100 businesses are simulated, each of which can be interpreted as representing a group of similar individual agents.

To the extent possible, empirical data from the Kobe earthquake were used for simulation and calibration. The application required specifying three different groups of input variables: decision/policy variables, demographics (i.e., agent attributes), and the intensity of the earthquake's effects. The decision variables, such as pre-earthquake mitigation to the water supply system, are binary (yes/no) and apply to the entire city of Kobe. This constraint is an obvious simplification of reality. For example, some sections of a water pipeline may have been retrofitted, while other sections have not. The values determined for each of the nine decision variables are listed in Table 2.

Demographic variables are the attributes of each modeled household and business. For households, the demographic variables are relative income level (i.e., high, medium or low) and whether mitigation measures have been taken to improve the resiliency of their residence. For business agents, the demographic variables are relative business size (i.e., small or large), business sector (i.e., export-oriented or local business), and whether mitigation measures have been taken. Data for each of the 4 zones on the distribution of population and businesses according to these demographic groups were derived from census and other statistical publications by the

■ Table 2. Decision Variable Values for Kobe Application

MUT	CAP	PLAN	STH	
Yes	No	No	Yes	
WALT	**WMIT**	**TMIT**	**EMIT**	**CMIT**
Yes	No	No	No	No

City of Kobe. For both businesses and residences, buildings were classified into "mitigated" / "unmitigated" (better or worse performance) according to their construction vintage. The demographic data for households are shown in Table 3.

Ground motion input for each analysis zone was based on data on Japan Meteorological Association (JMA) intensity level and peak ground acceleration (PGA) (Bardet et al., 1995; EQE, 1995). In the prototype model, seismic intensity is represented by a single normalized value for each zone. This requires spatial aggregation over a wide range of earthquake intensities.

The Kobe earthquake simulation using the prototype model was intended as a first-order validation exercise. Simulation of the Kobe earthquake was performed for a time series of 260 weeks (5 years). Results, while less satisfactory than an earlier test application of the model that used a hypothetical input scenario (Chang and Miles, forthcoming), are instructive for future research directions. For example, one unexpected result was the prediction that no households would leave the region and no businesses would fail. This indicates the need to reexamine these elements of the model.

Figure 3 shows the overall simulated recovery of Kobe including city-wide recovery of households, businesses, buildings, and lifeline network. This figure was constructed by averaging the recovery value for each individual agent (i.e., household or business) across the entire simulation population for each time step. The figure shows that not all households and businesses reached a recovery level of one (i.e., complete recovery), even though no agents failed or left Kobe. The business and household recovery levels reached a plateau after a timeframe of about 55 and 140 weeks, respectively. Overall, lifeline recovery did reach a final value of one after 50 weeks. The general prediction that business and household recovery lags significantly behind lifeline recovery is reasonable. Building restoration was less realistic, only reaching a recovery level of 0.5 after 5 years.

Figure 4 summarizes household recovery across the four analysis zones. Generally speaking, the model is able to replicate the spatial disparities in recovery that were observed after the Kobe earthquake, wherein older neighborhoods lagged newer areas. This derives from both earthquake intensity and household and business demographics. The zones that recovered the slowest and to the lowest final levels of recovery are Zones A and A1, which both had a JMA intensity of 7. The zone that recovered most quickly and to the highest level of recovery was Zone C, which experienced the lowest earthquake intensity. The difference between Zones

■ Table 3. Household Demographic Data by Kobe Zone

Zone A1		Buildings		Zone B		Buildings	
		Unmitigated	Mitigated			Unmitigated	Mitigated
Income	Low	57%	0%	Income	Low	17%	0%
	Middle	8%	32%		Middle	40%	3%
	High	0%	3%		High	8%	32%
Zone A		**Buildings**		**Zone C**		**Buildings**	
		Unmitigated	Mitigated			Unmitigated	Mitigated
Income	Low	72%	0%	Income	Low	14%	0%
	Middle	13%	10%		Middle	36%	17%
	High	0%	5%		High	0%	33%

A1 and A can be partly explained by demographics. Zone A has 15% more low income households and 20% more households in old or unretrofitted buildings. Note, however, that these results also demonstrate a "plateau" effect. This derives from a shortcoming of the model, in which the driving variables themselves saturate after some amount of time and have no further influence on the simulation.

Sensitivity Analysis

Because of the large number of model variables and their interrelationships, the behavior of the model is complex. To explore this behavior, sensitivity analysis was conducted with reference to the Kobe simulation. The influence of decision and demographic variables was analyzed separately. In all cases, the basic approach consisted of analyzing each variable independently while holding the other variables constant. For example, to analyze the demographic variable *INC* (income) for households, the simulation was run once with all households assigned a relative income of "low" (a value of zero), with all other input variables retaining the baseline values, and again with all households being assigned a relative income of "high" (a value of 1). Similarly, to analyze the decision variables, the Kobe simulation (demographics) was first run once with all of the decision variables set to zero or "no" (i.e., zero capacity, no mutual aid agreement, no plan, etc.). The simulation was then run nine more times to look at the effect of changing each decision variable to one or "yes", with the other decision variables being set to zero (no). The opposite approach was also taken, where all variables were set to one and then the simulation run for each variable set to zero.

The numerous outputs from the sensitivity analysis do not facilitate concise presentation. To summa-

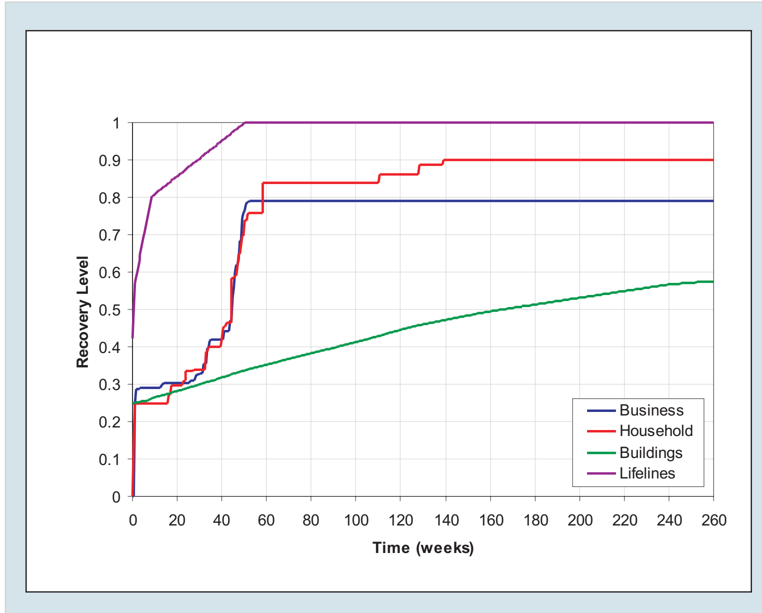


Figure 3. Overall Simulated Recovery of Kobe Using Prototype Model

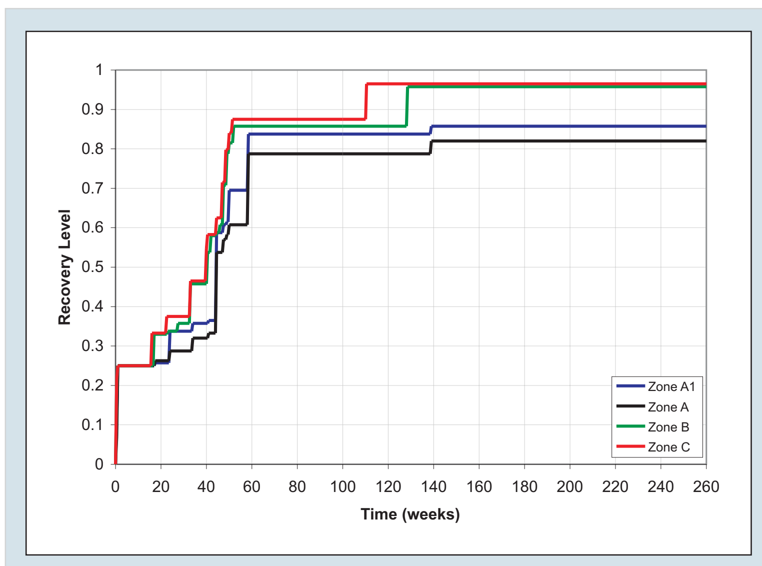


Figure 4. Simulated Recovery of Households by Zone for Kobe using Prototype Model

■ Table 4. Expectations of Simulation Behavior and Evaluation of Sensitivity Analysis

Business	Household	Expectations
X	✔	*A community with all new or retrofitted buildings (i.e., earthquake resistant) should recover more quickly than a community with all old buildings.
✔	✔	*A community with all high income households should recover more quickly than a community will all low income households.
✔	✔	*A community with all large businesses should recover more quickly than a community with all small businesses.
X	X	*A community with all export-oriented businesses should recover more quickly than a community with all local-oriented businesses.
X	X	All lifeline mitigations should hasten recovery times.
✔	✔	Mitigating transportation should hasten recovery more than mitigating other lifelines.
✔	✔	All planning and response measures should hasten recovery times.
✔	✔	Agents should be less likely to fail or leave as more mitigation and planning measures are taken.

* all else being equal; Note: ✔ = expectation met; X = expectation not met.

rize the results of the sensitivity analysis, Table 4 lists eight *a priori* expectations (i.e., design requirements) for the community recovery model. Listed with each is a general assessment of whether the particular expectation was met, with respect to simulated household and business recovery. For the most part, the sensitivity analysis demonstrated that the recovery model performs as expected, while highlighting several issues for refinement or modification.

Conclusions and Future Research

The work reported here represents the initial stages towards building a community recovery model and spatial decision support system. This effort is distinguished by its attempt to capture the complex interdependencies between sectors (households, businesses, and lifeline infrastructure), the relationships between geographic scales (agent, neighborhood, community), and recovery processes over time. This holistic approach demonstrates the complex impacts of mitigation, response, and recovery decisions. For example, it allows visualization of the disparities that may evolve across an urban area in the disaster recovery process. It illustrates how speeding up the restoration of lifeline systems has substantial recovery benefits across all sectors. It allows comparisons as to the relative effectiveness of various mitigation and preparedness activities for improving community resiliency.

As demonstrated in the prototype application and sensitivity analysis, further research is needed to improve the model itself and its usability for response and recovery decision-support. More detailed validation of the model in the Kobe context is needed. Refinements are needed to resolve data gaps between the types of data required by the model and the types that are available following an actual disaster. The input of stakeholders and potential end users, such as city planners and emergency managers, will be solicited. This will help to further evaluate the usability of the recovery model, identify additional decision variables, and determine requirements for a decision support system.

Model algorithms will also be refined. This effort is greatly facilitated by the implementation-independent conceptual model and modular computer model design, which permits modification of specific algorithms without requiring changes to the entire model. Specific changes to the algorithms will include rethinking the implementation of the driving variables to simplify their calibration and prevent the model from effectively stalling after a certain time. In addition, work will be continued to incorporate randomness within the model and make it more explicitly probabilistic. The recovery model will be improved to model household migration within the community (i.e., from neighborhood to neighborhood). The decision to migrate can be based on variables such as relative recovery levels of neighborhoods, location, access to financial resources, building damage, and reconstruction status. To facilitate incorporating migration, the community recovery model will be integrated within commercial geographic information systems (GIS) software. GIS integration will address the goal of building a spatial decision support system for improving community resilience to earthquakes.

Acknowledgments

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