Resilience Modeling

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Resilience modeling is an emerging topic in digital engineering (DE), model-based systems engineering (MBSE), and artificial intelligence/machine learning (AI/ML). Systems Engineers and developers need to identify, characterize, and accomplish trade-offs regarding cost, schedule, performance, and quality characteristics (including resilience) over the life cycle of a system. If system resilience could be accurately modeled, then quantitative (or at least qualitative) metrics could be used to evaluate a system’s resilience characteristics (e.g., via a digital twin). However, no single methodology is accepted for resilience modeling of simple, complicated, or complex systems. This section examines a few potential (and evolving) modeling techniques that practitioners of resilience engineering could use.

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Overview

A system resilience model represents a selective abstraction of a system to provide the required capability when facing adversity within the system and its environment. This definition of a resilience model is limited to human-made systems containing software, hardware, humans (e.g., socio-technical, organizational), infrastructures, concepts, and processes.

Modeling, Measuring, & Evaluating System Resilience

Formal Methods of Constructing Models for Systems Resilience—Resilience Contracts

Madni, Erwin, and Sievers (2020) proposed resilience contracts (RCs) as an upgrade to the widely used Contract-Based Design (CBD) approach. They observed that traditional methods like Büchi automatons and Linear Temporal Logic (LTL) work for systems that behave predictably. However, many modern systems do not always behave predictably. To handle this, an RC is a mathematical model that extends CBD to account for uncertainty and unpredictability.

An RC is a mixed model that uses fixed rules and flexible assertions and is represented as a Partially Observable Markov Decision Process (POMDP). A POMDP is a special form of a Markov decision process that deals with situations where some states and transitions are not directly observable.

RCs add flexibility to deterministic contracts for systems with random elements by repeatedly checking the environment and system status, choosing the best actions to achieve a goal, and executing those actions. After each action, the system’s environment and health are reassessed. The planning function then decides whether to continue with the current plan if the actions are effective or to make changes if they are not.

Application of System Dynamics

System dynamics is suitable for resilience modeling because it captures behavior over time, and resilience takes a behavior over time perspective, as shown in Figure 1 (from the System Resilience article, reproduced below). As with other types of modeling, one of the primary values of system dynamics modeling is that it can be used to build a shared understanding of the issues for all stakeholders.

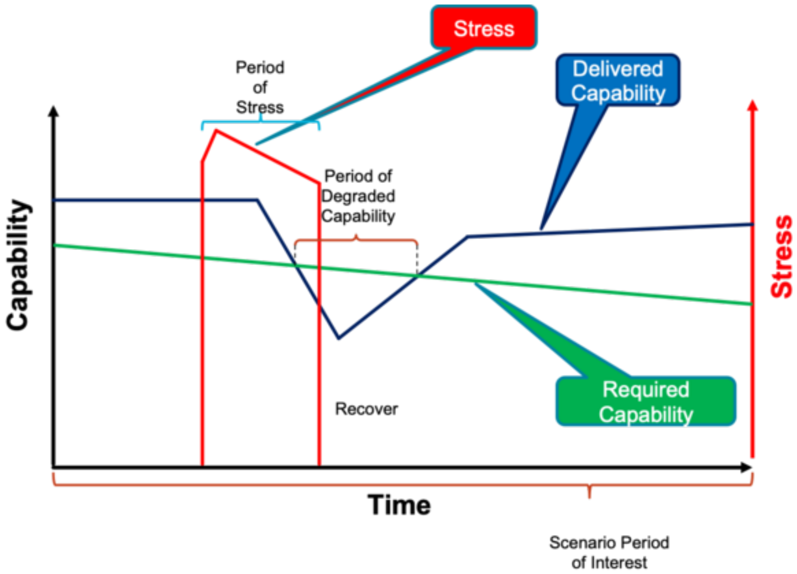

Figure 1. Time-Wise Values of Notional Resilience Scenarios Parameters. (Brtis et al. 2021, Used with Permission)

In this regard, system dynamics's long tradition of participatory model building can be uniquely valuable (Herrera and Kopainsky, 2020). These group model building activities produce causal loop diagrams, which demonstrate the feedback structure in a system in which a change in one component can ripple through the other connected components in the design and return to the original part in a reinforcing way that can lead to catastrophic failure or in a balanced way that can lead to stability and recovery from adversity.

Archetypes are another qualitative tool used in system dynamics modeling (Onyekachi, Onyeagoziri, and Ryan, 2021). In archetypes, a small set of models can examine many behavior types. In terms of resilience modeling, archetypes evaluate the feedback loops in the system that lead to both intended and unintended consequences in behavior where often the unintended consequences are not foreseen when the system is designed.

Quantitative system dynamics models have been applied to resilience modeling (Iturriza et al., 2017; Yabe et al., 2021). In this case, a highly interconnected system of first-order linear differential equations is solved using numerical methods (Radzicki and Taylor, 1997).

Software tools can be used to build interactive models applied to resilience modeling (Iturriza et al., 2017). Using interactive models, system engineers could experiment in a virtual environment to test procedures to improve the system’s Resilience under conditions that are not economical or even possible in real life.

The response of a system to adversity can be analyzed using quantitative system dynamics to determine the effectiveness of the resilience processes. This is effective in learning about the impact of natural disasters on critical infrastructure (Yabe et al., 2021).

Caveats Regarding Resilience Models

Misusing models can lead to problems. It is therefore essential to use a model only for its intended purpose. Modelers must ensure the model is suitable for this purpose, check that all assumptions are valid, and ensure that no constraints are violated.

Neches & Madni (2013) suggest that modeling tools and languages should align with their intended use. Sometimes, modelers have to use different tools or languages, which can cause compatibility issues. Because of this, multiple models need to be developed and made to work together, as models must cover various disciplines, aspects, and phenomena. Modelers must also create and manage different models, such as executable, depictional, and statistical models, and multiple categories, including device and environmental physics, communications, sensors, effectors, software, and systems.

Model Analysis with Consideration of Constraint Theory

Friedman & Phan (2017) point out that models face typical “well-posed” problems in mathematics. Modelers must check if complex models are internally consistent and if the requested calculations are mathematically allowable.

Complex models, especially those created by diverse teams, often have internal inconsistencies. Even if a model is consistent, many possible calculations might not be allowable due to over-constrained computational sets, where there are too many input values for the equations. On the other hand, under-constrained calculations, with too many equations and not enough values, can lead to unclear or undefined results.

Most models of complex systems include tight interaction loops called Basic Nodal Squares (BNS), which form the “kernel of intrinsic constraint.” These models often have more extensive, nested interaction loops important for emergent behavior and attributes of Resilience such as adaptability, flexibility, and handling disruptions.

When computational requests that are not allowed are made on models, it often leads to incorrect predictions.

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