

Work in Progress: Applying Model-Based Systems Engineering to Decentralised Earthquake Early Warning System Design

Sadjad Mirzaei <i>Massey University</i> Wellington, New Zealand Sadjad.Mirzaei.1@uni.massey.ac.nz	Raj Prasanna <i>Massey University</i> Wellington, New Zealand R.Prasanna@massey.ac.nz	Marion Lara Tan <i>Massey University</i> Wellington, New Zealand M.L.Tan@massey.ac.nz	Pasan Herath <i>Earth Sciences New Zealand</i> Lower Hutt, New Zealand Pasan.Herath@earthsciences.nz
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Abstract—Earthquake Early Warning (EEW) systems built on low-cost MEMS sensors and decentralised processing architectures represent a promising path toward affordable, large-scale seismic warning coverage. Yet despite considerable progress at the component level, the field lacks a formal engineering infrastructure capable of binding these components into a coherent, verifiable, and maintainable system. This paper presents work in progress toward filling that gap through the systematic application of Model-Based Systems Engineering (MBSE) to the design of a decentralised EEW framework. Grounded in Design Science Research Methodology (DSRM), the approach uses Systems Modelling Language (SysML) to produce a formal, traceable representation of system architecture and behaviour. We report on three completed stages: a systematic literature review that identified the core research gaps, a component analysis that produced a conceptual framework for the decentralised architecture, and the formalisation of node-level detection and alert logic. The ongoing SysML modelling activity and the path toward simulation-based validation are also described. The central argument is that MBSE is not merely a documentation exercise for EEW research; it is the missing engineering foundation that makes these systems verifiable, scalable, and transferable.

Index Terms—earthquake early warning, decentralised systems, model-based systems engineering, MEMS sensors, SysML, discrete event simulation

I. INTRODUCTION

Earthquake Early Warning (EEW) systems occupy a unique position in the landscape of disaster risk reduction. Unlike most natural hazard warnings, they do not predict an earthquake before it occurs; instead, they detect a rupture as it initiates and race the resulting seismic waves to deliver a warning to communities in the seconds before destructive shaking arrives [1]. Even a few seconds of warning is sufficient to trigger automated safety interventions (e.g. halting trains, isolating gas lines, opening emergency doors) or to give individuals time to Drop, Cover, and Hold On [2].

The practical deployment of these systems, however, has historically been constrained by cost. A national EEW network requires dense coverage, high-reliability sensors, and redundant centralised processing facilities, infrastructure that remains financially out of reach for most countries, including seismically active ones [2]. Two relatively recent technological developments have begun to change this picture. The

widespread availability of low-cost MEMS accelerometers, now common in consumer electronics and IoT devices, has made dense sensing networks economically viable [3]. Simultaneously, decentralised processing architectures, where detection and alert logic run at the sensor node rather than at a central server, offer a path to eliminating the costly computational bottleneck and the critical single point of failure that characterise traditional designs [4].

Research at the intersection of these two developments has accelerated considerably over the past decade. Several systems and algorithms have demonstrated the feasibility of the approach in small-scale deployments [2], [5]. Yet a critical gap persists: existing efforts tend to be component-centric, optimising individual detection algorithms or communication protocols in isolation, without a unifying engineering infrastructure to manage how these components interact, scale, and fail together. The result is a body of research where individual parts are maturing faster than the system as a whole.

This paper describes work in progress that aims to address this gap through the application of Model-Based Systems Engineering (MBSE) to the design of a decentralised EEW framework. The contribution is not a finished system but a methodology and a set of early artefacts (a conceptual framework, a formalised node-level behavioural model, and a prototype simulation environment) that together lay the engineering groundwork for a traceable, verifiable, and extensible system.

II. BACKGROUND AND RESEARCH GAP

A. The Case for Decentralised, Low-Cost EEW

The literature on low-cost EEW covers a broad spectrum of implementations, from fixed MEMS stations like the P-Alert network in Taiwan [6] and the community-engaged deployments of CRISiSLab in New Zealand [5], to smartphone-based crowdsourcing approaches like MyShake [7]. These systems have collectively demonstrated that low-cost sensors, despite their higher noise floors compared to professional instrumentation, can deliver actionable warnings when deployed in sufficient density with appropriate algorithms.

The advantages of decentralised architectures over their centralised counterparts are well-established: enhanced fault tolerance, reduced communication latency, lower bandwidth requirements, and the elimination of the single point of failure [2], [4]. The SOSEWIN project [4] and, more recently, the CRISiSLab framework [5] have shown that meaningful decentralisation is achievable. However, both projects also highlight the limitations of ad-hoc development: without a formal systems engineering foundation, evaluation is difficult to replicate, scalability remains uncertain, and the path from research prototype to operational deployment is unclear.

B. The Missing Engineering Infrastructure

What distinguishes an engineered system from a collection of interacting components is the presence of explicitly defined interfaces, requirements, and lifecycle management practices. In the context of decentralised EEW, this engineering infrastructure is largely absent. Systems Engineering (SE) provides precisely the interdisciplinary framework needed to manage complexity of this kind, and its model-based variant, MBSE, extends this by making the system model, rather than a collection of documents, the primary artefact throughout the development lifecycle [8].

An MBSE model captures the relationships between stakeholder requirements, logical architecture, and physical components in a formal, computable representation. This “single source of truth” enables early validation of design decisions, supports unambiguous communication between research teams, and creates a durable foundation that future researchers can build upon. Despite these benefits, formal SE and MBSE methodologies have not been applied to decentralised EEW development in any systematic way, a gap that motivates the present work.

III. WORK COMPLETED TO DATE

A. Systematic Literature Review and Gap Identification

The foundational stage of this work was a structured literature review conducted following PRISMA guidelines across two academic databases, Scopus and EBSCO. The review was organised around two questions: what has been achieved in the use of low-cost sensors for seismic monitoring, and what architectural approaches have been taken to build decentralised EEW systems?

The review confirmed that low-cost MEMS-based sensing is a technically credible alternative to professional instrumentation at sufficient network density [3], [5], [6]. It also confirmed that decentralised architectures offer meaningful advantages over centralised designs in terms of fault tolerance, latency, and scalability [2], [4]. What the review did not find was an integrated framework that combines these two developments into a system that is simultaneously decentralised, scalable, and formally specified.

Two research gaps were identified. The first is the absence of a fully decentralised, scalable, and integrated EEW system framework built on low-cost sensors. The second is the absence of a formal systems engineering infrastructure to manage

the interdependencies between components in such a system. These two gaps define the scope of the present research.

B. Component Analysis and Conceptual Framework

Building on the literature review, the next stage involved a systematic analysis of the essential components of a decentralised EEW system. The goal was not to produce an abstract taxonomy but to identify the specific elements that must be present in any deployable system and to understand their dependencies.

Three functional layers were identified. The *sensing layer* handles ground motion acquisition and is responsible for continuous monitoring and threshold-based triggering. The *processing layer* carries out detection and alert logic autonomously at the node level, without relying on a central server. The *communication layer* governs peer-to-peer message exchange between nodes, enabling collaborative event confirmation across the network. A fourth cross-cutting concern, *energy management*, was identified as essential for ensuring that nodes remain operational during and immediately after the seismic event when grid power may be disrupted.

From this component analysis, a conceptual framework was developed to define the boundaries, roles, and interaction logic between layers. The framework establishes a clear operational mechanism: local detection triggers network-level communication, which enables distributed consensus, which in turn drives alert dissemination without any centralised coordination. This conceptual framework now serves as the primary input to the ongoing SysML modelling activity.

C. Formalised Node-Level Behavioural Logic

A concrete outcome of the component analysis and framework design was the formalisation of the detection and alert mechanism at the individual sensor node. This represents the most granular and arguably most critical piece of the system’s behaviour, since the correctness of the node logic determines whether the entire decentralised consensus mechanism functions as intended.

Each node in the proposed architecture responds to two types of trigger. The first is a local detection event, which occurs when the node’s own seismic detection algorithm reports that ground motion has exceeded a predefined threshold. The second is a detection message received from a neighbouring node, indicating that another nearby station has already triggered.

Rather than issuing an alert on the basis of a single local detection, which would be unacceptably prone to false positives from ambient noise in residential deployments, the framework requires a two-event confirmation within a five-second window. When a node detects locally, it enters a *Detection* state and broadcasts a detection message to all nodes within approximately 30 km. An alert is issued only if a second qualifying event (either a further local trigger or an inbound detection message from a neighbour) arrives before the window closes. If no second event arrives, the node returns

to *Observation* state. The same confirmation logic applies in reverse when a detection message arrives first.

This design reflects a deliberate trade-off: the two-event requirement introduces a small additional latency but substantially reduces false alarm rates, which is essential for maintaining public trust in the system over time. The logic has been specified in pseudocode and is currently being formalised as a SysML state machine diagram.

D. Ongoing: SysML System Modelling

The MBSE activity is the current focus of the research. The system model is being constructed in SysML and is organised around four complementary viewpoints. The *requirements view* traces stakeholder needs (minimum warning time, geographic coverage, false positive rate) through to system-level functional requirements. The *structural view* uses block definition and internal block diagrams to decompose the system into its constituent components and define their interfaces. The *behavioural view* uses state machines and sequence diagrams to specify how nodes and the network as a whole respond to seismic events and communication messages. The *parametric view* establishes the quantitative relationships between design parameters and performance metrics, such as the relationship between sensor density and expected alert latency.

The node-level state machine, derived directly from the formalised behavioural logic described above, has been completed. Work is ongoing on the network-level sequence diagrams, which must capture the concurrent and asynchronous nature of message propagation during an event. A formal evaluation of the model for internal consistency and logical completeness is planned upon completion of the network-level views.

IV. CURRENT LIMITATIONS AND NEXT STEPS

The SysML model is currently incomplete at the network level. While the node-level state machine is well-developed, the interaction sequences between multiple nodes during a real event have not yet been captured in the formal model. Specifically, the asynchronous and concurrent propagation of detection messages across a network of dozens of nodes, each potentially in a different state when the seismic wave arrives, introduces a level of compositional complexity that the current model does not yet address. This is the primary open task.

A second limitation at this stage is that the formalised behavioural logic has not yet been validated against real seismic data. The node-level detection mechanism was designed to reduce false positives from ambient noise, but the specific parameter values (the confirmation window duration, the communication radius, the detection threshold) have been set based on prior literature rather than empirical tuning. These parameters will be evaluated and refined once the SysML model is translated into an executable simulation environment.

The immediate next steps are therefore: completing the network-level sequence diagrams in the SysML model; conducting the planned model consistency evaluation; and initiating the development of the Discrete Event Simulation

environment that will use the completed model as its direct specification input. The DES environment will then be validated against historical earthquake records from the GeoNet catalogue before the framework is prepared for pilot deployment on the existing sensor network in the Greater Wellington region.

V. EXPECTED CONTRIBUTIONS

This research is expected to produce two primary contributions. The first is a *design artefact*: a fully specified, MBSE-grounded architectural framework for a decentralised EEW system, expressed in SysML and traceable from stakeholder requirements through to sensor-level behaviour. This framework is intended to serve as a reusable blueprint that future researchers and emergency management agencies can adapt to different geographic and seismological contexts.

The second is a *methodological contribution*: a validated DES environment for pre-deployment evaluation of decentralised EEW architectures. The ability to rigorously test system performance (including fault tolerance, alert latency, and detection accuracy) in a controlled virtual environment before physical deployment addresses a significant practical gap. Systems that might cost significant public resources to deploy and fail can instead be refined in simulation, lowering the barrier to adoption in resource-constrained settings.

The research engages directly with the call from the EEW community for more integrated, systems-level perspectives on decentralised architectures [2], [5]. By bringing formal engineering methodology to bear on a domain that has largely operated through ad-hoc development, it aims to make decentralised EEW systems not just technically feasible but practically deployable.

VI. CONCLUSION

This paper has described ongoing work toward a Model-Based Systems Engineering framework for decentralised, low-cost EEW systems. The contribution is positioned at an early but substantive stage: the conceptual framework, the formalised node-level detection logic, and the prototype simulation environment are in place, and the SysML model is under active development. The immediate next steps are completing the network-level model and integrating real seismic waveforms into the simulator, which will set the stage for rigorous simulation-based validation, after which pilot deployment on field sensors will follow.

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