TOWARDS AN INFO-SYMBIOTIC DECISION SUPPORT SYSTEM FOR DISASTER RISK MANAGEMENT

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***Abstract*—This paper outlines a framework for an info-symbiotic modelling system using cyber-physical sensors to assist in decision-making. Using a dynamic data-driven simulation approach, this system can help with the identification of target areas and resource allocation in emergency situations. Using different natural disasters as exemplars, we will show how cyber-physical sensors can enhance ground level intelligence and aid in the creation of dynamic models to capture the state of human casualties. Using a virtual command & control centre communicating with sensors in the field, up-to-date information of the ground realities can be incorporated in a dynamic feedback loop. Using other information (e.g. weather models) a complex and rich model can be created. The framework adaptively manages the heterogeneous collection of data resources and uses agent-based models to create what-if scenarios in order to determine the best course of action.**

Keywords—disaster management; cyber physical systems; agent based models; dynamic data driven applications;

I. INTRODUCTION

In the field of humanitarian response and emergency risk management, modelling is an essential albeit complex process. One of the key elements for coordinating the relief efforts is to first understand and represent the actual damage and destruction. Before relief efforts can be planned, executed and humanitarian assets moved *optimally* to required regions, the change to the landscape needs to be modelled. Overlaid on this new representation of the disaster zone are the human movement models i.e. how have civilians within the zone moved to protect themselves. Based on these movements rescue efforts can be planned, modelled and deployed.

Research efforts in emergency planning and disaster management tend to either concentrate on pre-event risk identification or post-event intervention. The statistical and trend analysis of historic data is used to predict how events will unfold in the future. Within the realm of emergency response and management these sort of trend predictions are widely inaccurate as disasters are by their very nature outlier events. During disaster situations ground level intelligence is key to identifying hazards and critical zones. The emergence of cyber physical systems and sensors has created the availability of real-time data that helps to create more accurate models. However, the complexity of the problem and the requirement to capture human behaviour render pure data analytics inadequate to provide reliable decision support [2][3].

Simulations, incorporating Agent Based Models (ABM) are required to clearly assess all possible eventualities. Incorporating a data driven approach allows for any disaster management system to adaptively incorporate real-time data ensuring a resilient system in all eventualities.

This paper presents a holistic Dynamic Data Driven Application System (DDDAS) framework for disaster management from pre-event planning and mitigation strategies to post event adaptation and response. The framework aligns with the European Commission Report on Risk and Vulnerability Management [1] as a basis to outline the role of DDDAS, ABM's and Cyber Physical Sensors & Systems (CPS) before and after the occurrence of an emergency or disaster.

A summary of the EU Model for Risk and Vulnerability Management is covered in Section II. Other efforts in pre and post emergency management are discussed in Section III. The holistic info-symbiotic framework is presented in Section IV using exemplar disasters to create context.

Finally, section epitomises the challenges to realise such a framework.

II. EUROPEAN MODEL FOR RISK AND VULNERABILITY MANAGEMENT

The stages and required actions in the event of an emergency are outlined in a 2006 report by Atkinson et. al, commissioned by the EU (European Commission, Directorate-General Joint Research Centre, Institute for the Protection and Security of the Citizen, as part of the COMPASS Institutional Activity, Action no. 4335 - Vulnerability and Integrated Risk Assessment), [1]. This EU document entitled "Report on User Requirements supporting Risk and Vulnerability Management of Systemic and Industrial Risks" outlines the end-user requirements for systemic risk and vulnerability assessment and how these requirements relate to the decision-making process for improved system and human security. Keeping the user central, the report details the processes of identifying and understanding the amalgamation of users, processes, services, existing tools and the data required to firstly mitigate and secondly to manage a disaster within the European Union.

Key to the report is the Disaster Risk Management Life Cycle (shown in Figure 1). The life cycle is divided into two halves - before the disaster event and after the event. Before the event the risk management activities have two main stages. Firstly its ”Prevention and Mitigation”, where construction (or reconstruction from a previous disaster) takes place followed by risk assessment and planning. This involves primarily investigating infrastructure and resources in place and identifying any weaknesses. New infrastructure is built up with the aim of minimising risk and not disrupting existing mitigation strategies. By engaging with stakeholders and incorporating general policy based requirements on adaption and resilience, a risk identification processes needs to be undertaken. Critical infrastructure, irreplaceable assets, e.g., historic sites, and vulnerable members of society need to be identified along with the possible risks they face through different emergencies, e.g., flooding, earthquakes, epidemics and so on.

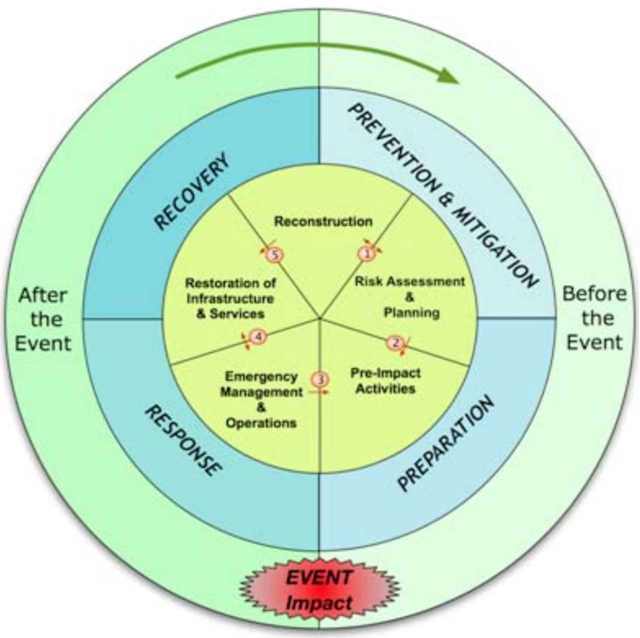

Fig. 1. European Commission Lifecycle for Disaster Risk Management Cycle [1]

The risk identification and planning process leads in to the ”Preparation” stage. Using the identified list of vulnerable areas and the adopted risk mitigation strategies the Pre-Impact activities concentrate on training, role identification, asset localisation, and awareness creation. These critical steps ensure that in the event of a disaster all parties and stakeholders in the impacted area are aware of key activities that need to be taken. Typically in disasters communication networks are initially unavailable and so it is of the utmost importance that rescue facilities and other stakeholders are trained beforehand. Within the zone they should know who/what is available to help, who/what needs immediate and critical attention, and finally what is required to be done before external help and coordination is established. Under the Pre-Impact activities control centres, scientists, and national, regional, and local authorities monitor sensor data to predict the next disaster.

Pre-event stages and activities can be classified as long term planning and management activities or predictive activities, while post-event activities are short term and prescriptive in nature.

Post event there are two new stages. The first is ”Response”. Figure 1 shows that primarily within Response is the Emergency Management and Operations activity. This includes identifying where people and infrastructure are in need, the nature of their requirements, and then mobilising rescue and repair assets. This becomes a scheduling and operations research problem. The key to success at this stage is the collection of reliable and actionable intelligence of ground realities. This will help in timely response from local resources and can estimate the requirements and distribution of assets being supplied from outside the disaster zone. To aide in collection of intelligence, the restoration of critical infrastructure (as defined by the Risk Assessment and Planning activity) is also an important part of the Response stage. While overall rebuilding will take place over a long term period, basic requirements like water supply, telecommunications and electric/gas supplies take precedence and operate in parallel to the emergency response.

After there is no further risk of loss of human life or damage to infrastructure, the final stage of the Disaster Risk Management Cycle begins - Recovery. Continuing from the restoration of critical infrastructure other aspects of society that can be fixed, repaired or restored are attended to. The final activity is reconstruction. This implies that infrastructure that was destroyed needs to be rebuilt. The rebuild process is either stand alone, because the object for reconstruction can not be relocated or adapted, or feeds into the preparation stage and is influenced by risk management strategies.

III. ROLE OF MODELING AND SIMULATION FOR PLANNING AND RESILIENCE

When planning for and recovering from a natural disaster, computer aided decision-support is essential for all aspects of effective management. There are two distinct themes within the decision support. The first is resource and infrastructure design, development, and deployment before the event. Predictive analysis and ”What-if” scenarios play an important role in ensuring that all construction and resource allocation is optimum in case of an emergency. Infrastructure can not be planned without factoring in roles and reactions of the civilian population in the event of a disaster and feed back from previous events can help ABMs in mapping these human factors and responses [4]. Consequently, Agent Based Models can form the central tool to evaluate what-if factors. Different hypothetical scenarios are played out and the responses are simulated to ensure long term resilience. Any vulnerabilities exposed by the simulations are either addressed, or in the event that they can not be corrected special measures are planned out.

Post event the simulations created before the disaster tend to go out the window. It is not possible to model every possible eventuality in case of a disaster. Post event potential evacuation routes or core infrastructure maybe cut off or destroyed. The models themselves are not void but new rules and initial conditions need to be provided. A Dynamic Data-Driven Application Systems approach provides an adaptive framework that covers real time collection of data to set the new initial conditions [5]. As ground realities change streaming data from sensors and external simulations can be fed back to continuously refine the models and the simulations. This real time and adaptive framework can help managers coordinate resources and efforts effectively. As services are restored more data can be fed back further refining the models and ensuring maximum effectiveness. DDDAS's applications are wide ranging and have been successfully used in disaster rescue management [6].

Helping to drive the DDDAS approach is the use of Cyber Physical Sensors and Systems (CPS). CPS are distributed networks of collaborating elements that can be integrated to create federated control systems and provide feedback mechanisms to centralised systems [7]. In the case of a flood, it would be quite beneficial to incorporate data available from aquatic bodies in the affected regions. Data from cyber physical sensors can be incorporated to give a complete picture within models and simulations being carried out by emergency management services located outside the disaster zone [8]. Post event DDDAS simulations need to incorporate ABM's to ensure different options are evaluated before a decision is made. Agent-based models can benefit from streaming data through cyber physical systems and a framework is provided by [9].

As the adoption of Agent Based Models and Dynamic Data-Driven Application Systems approach has grown, considerable work has been done within the field of Emergency and Disaster Management. Different approaches at different stages have been proposed. Within these stages either different aspects of the management process are modelled, or when a complete model is created it is typically done at a micro level and does not fully encapsulate the disaster zone.

Keeping users and stakeholders central, the primary area of research involves modelling evacuation strategies. If Pre-Impact activities and post event Management and Operations are considered, moving civilian populations out of harms way is fundamental to the success of each activity. In the event of Cyclones or Hurricanes (like the one in New York, 2013 [10]) Pre-Impact activities involved vacating parts of the city, moving people out of harms way. Whereas *after* the earthquake in Japan, as part of the rescue operations, the population was moved out of the Fukushima area to protect human life.

Work done by Pel et. al model potential evacuation routes that people will adopt [11]. Further work by the authors, look at the sociological and psychological factors that govern adopted evacuation strategies [12]. While this work addresses the dynamic behaviour of road users and outlines the effect of potential external interventions the models are not adaptive. The application of Pel et. al models are effective Pre-Impact, post disaster the overall landscape and possible evacuation routes change. For effective Pre-Impact preparation there is a need to understand what would occur on the ground if key egresses are lost due to damage. Human frustration and desperation in the event of their known routes disappearing will also play a major role on the effectiveness of the evacuation. Post disaster dissemination infrastructure may also not be available, e.g., digital road signs, telecoms and so on. Work carried out by Dow and Cutter also looks at traffic modelling but doesn't take into account other factors that may influence evacuation strategies and loss of critical infrastructure [13]. Post disaster evacuation strategies are addressed by Chaturvedi et. al, and Wu et. al. Addressing the problem at a small scale Chaturvedi et. al, models evacuation strategies in the event of a fire at a Rhode Island night club. Using agents to model human movements the effectiveness of evacuation strategies are assessed [14]. The framework proposed is limited in it's use of a DDDAS approach as modelling before a fire the sensor information in the building will not be changing, thus losing dynamism and post fire the system does not feedback to evacuating people. Wu et. al, in their paper on Agent-based Discrete Event Simulation Modelling incorporate user evacuation processes and asset allocation to simulate disasters and mitigate future risks [15]. While all encompassing the approach presented lacks a dynamic component that can help in the changing environment post event.

On the macro scale work carried out by Saoud et. al, outlines an approach to evaluate large scale emergency rescue plans[16]. The authors clearly demonstrate how effective an agent-based approach is at modelling and simulating a complex socio-technical system. Their work includes models for the environment, victims, rescuers, along with the associated activities and interactions. Significantly, the influence of decision makers external to the target area are also incorporated. As part of the simulation performed different complex scenarios, involving differently affected groups with varying resources, are evaluated using criteria set by experts from the domain. The authors agree that prescribing any one rescue and response solution would not be possible, however their work can help decision makers identify vulnerabilities. What is critically required above the ABM is *what-if* support post event.

Madey et. al presents a complete decision support system based on a DDDAS framework. Called WIPER, the system incorporates Agent Based Models and Cyber Physical Sensors in the form of cell phone data [17]. The DDDAS within the WIPER system identifies the occurrence of disasters by detecting a change in movement and call patterns within a cellular network. Once a disaster has occurred the ABMs can identify where the problem is and predict potential choke points in civilian movement. Taking into account group dynamics WIPER identifies potential victim clustering and providers rescue workers with what-if scenarios for resource allocation that can be compared with real-time data.

The system is not holistic in that it has limited use before a disaster has occurred. Further, it concentrates on one facet of disaster Response - evacuation and victim location. Additionally it relies on one type of sensor network and does not incorporate any adaptability incase the network goes down. As was seen in the Nepal earthquake or the tsunami in Japan communication networks typically go down at the time of the event [18], [19].

Using DDDAS post event poses other interesting challenges. An effective DDDAS would need functioning networks of Cyber Physical Sensors and Systems. Aside from the obvious destruction of sensors, loss of connectivity and reliability of the streaming data can lead to inaccuracies within the DDDAS. There has been considerable work carried out regarding the reliability of CPS [20], [21]. Post event reliability

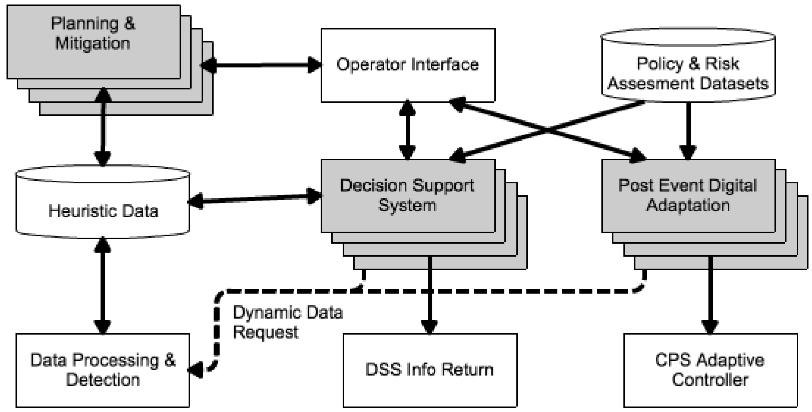

Fig. 2. Proposed Decision Support System and What-if Analysis interactions

and resilience needs to be either ensured or factored in through adaption methodologies [22]. Lin et. al, in a series of papers have outlined a framework for quantitative modelling of critical systems using CPS [23]. Their work covers the dependability of CPS and suggested adaption methodologies [24]. Key in their work is the inclusion of an ontologies-based system to integrate heterogeneous streams of data [25]. When modelling an urban environment every model needs to be able to handle heterogeneous streams of data and adapt or derive information

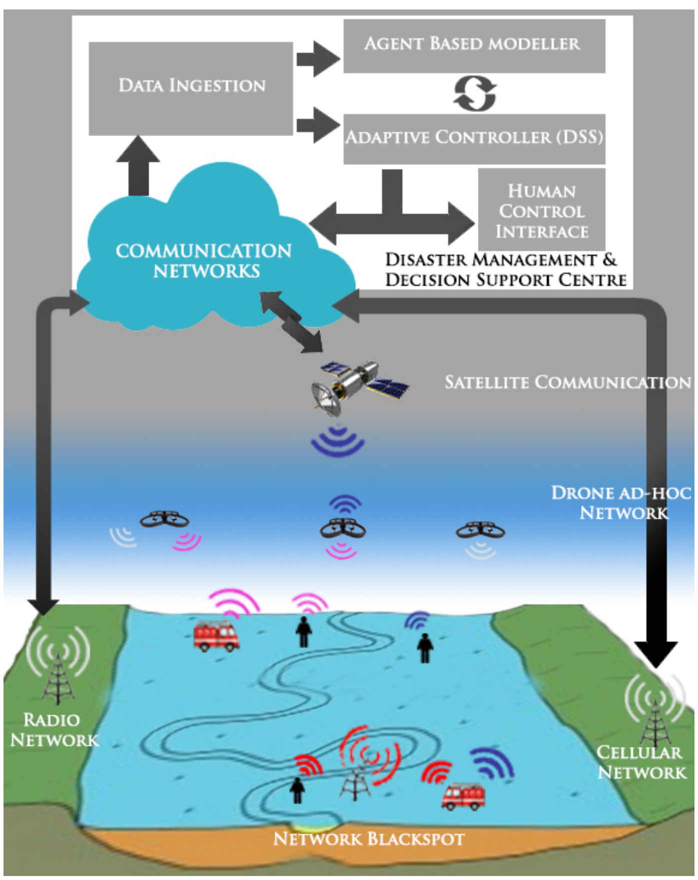

Fig. 3. The proposed system and its interactions with the real world

from other sources incase there is a break in communication. Lin et. al's work however does not cover dependability in the face of a disaster.

IV. PROPOSED FRAMEWORK

The proposed framework is illustrated in Figures 2 and 3. Providing a holistic approach to emergency management the system can be used to model and simulate civilians, assets and fixed infrastructure before and after a disaster. Utilising DDDAS, ABM and CPS technologies the framework feeds into a semi-autonomous decision support system. Driving the simulations are a network of distributed high performance computers and low energy processing solutions [26]. A strong human-computer interface ensures transparency of the system and allows operators to override the system when necessary.

While all the mentioned technologies will be utilised pre and post disaster, their focus and the systems operational parameters will differ. Table I shows which technology predominantly operates during each stage. Broadly however, the systems focus or aim is as follows:

- **Pre-Event**
  - Influence urban planning and construction decisions;
  - Ingest sensor data and create "normal condition" models, profiling population and asset distribution at any given day and time;
  - Evaluate sensitive regions and the required interventions in case of emergency;
  - Model potential disaster and scenarios to evaluate response readiness;
  - Monitor sensors in order to find precursor signals that could intimate an upcoming event.
- **Post-Event**
  - Identify the disaster and quantify the disaster zone;
  - Adapt the initial condition of models to reflect the realities of the disaster zone;
  - Take measures to increase collection of ground level intelligence;
  - Reestablish communications within the affected zone;
  - Identify situation and if required deploy resources to sensitive regions using the best method possible;

- Predict population activities in response to the disaster and where needed intervene to streamline;
- Make best use of available resources and produce advisory information for external resources;
- Identify damage or bottlenecks in the response and recovery stages that were not encompassed in the pre-event simulations.

A. Pre-Event Functionality

During the Prevention and Mitigation stage of disaster management the system uses Agent Based Models coupled with scientific tools to identify potential problems with new construction or other infrastructural changes. Scientific tools may include weather modelling tools and earthquake simulators for example.

The preliminary task is to identify critical population, infrastructure or area to quantify its characteristics and risks. Using statistical analysis tools incorporated within the system, hazards and risks are identified based on historic frequency, scientific knowledge (in case of non-human disasters) and other intelligence reports (in case of human caused disasters). The additional reports and knowledge will help the predictive system qualify the type and quantify the potential intensity of the impending disaster. Agent based simulations can help then to predict where rescue workers would need to concentrate efforts and which regions will need additional pre-event resource allocations.

For effective disaster recovery and optimum resource allocation in case of an emergency during the Risk Assessment and Planning phases, policy makers and city managers need to prioritise their vulnerable assets. Loss needs to be quantified. Acceptable or tangible losses need to be separated from intangible losses. The later getting priority in case of a disaster. Those consequences that are considered acceptable losses form a post event first come first served to-do list.

Different Cyber Physical Sensors and Systems are integrated into the system to create the model of "*normal*". While the target area, its populations, associated infrastructure, environmental conditions and rescue resources form the model, the heuristic models created through sensor data provide the initial conditions. CPS include but are not limited to: road use sensors; temperature and wind sensors; water level and current sensors (from nearby water bodies); cell tower information; cellphone GPS data; and imagery through cameras, UAV and satellites. Social media information too forms a type of sensor that can be incorporated to identify movement of people (e.g. through check-ins) or early detection of a problem (e.g. identifying fires or feeling earthquakes [27]).

Normal however is not just one model. *Normal* is unique to the time of day, day of the week or time of the year. However, through deep learning and other pattern recognition systems, a complex model of *normal* can be created. Specifically in the event of human-caused emergencies, detection of deviation from the norm can factor as an early warning mechanism. In the case of a disaster (natural or otherwise) the normative model can give crucial start conditions in the event of an emergency. For example, in case of an earthquake in Manchester, UK on a Saturday night in October, the normative model will tell us that in all likelihood the population density around the Old Trafford or Bradford regions of the city will be high. This is due to the presence of the big football stadiums and historical evidence that on weekend nights in October people congregate in those areas. This can be further refined using actual human intelligence to suggest which stadium is actually being used on the given night. The system can then exclude historic data involving one or the other stadium.

With initial conditions set, hazards and priorities identified, and risk quantified, different simulations can be carried out to influence development, training and policy. Geospatial hot-zones can be created for optimal placement of rescue assets (e.g. ambulances, firetrucks etc.). Complete Agent Based Models of evacuation scenarios can be created. Short to medium term aid can be quantified before an event so that bodies external to the disaster zone can have basic guidelines as to their response. For example if city A faces an earthquake of a certain magnitude, then X number of diggers and excavators will be required. However, if the river floods then depending on the location either beds/tents are required or a field medical hospital will need to be sourced. By collecting such disparate types of data and incorporating it through different functions, a city can prepare for almost any eventuality.

Finally before the disaster strikes, the ABMs, CPS and simulations using Scientific codes can help identify trends leading up to disasters (as discussed above in human movement). These system already exist as part of Early Warning Systems (EWS) deployed within urban centres [28]. Integration with existing EWS is important as every second is critical in getting rescue assets moving.

B. Post-Event Functionality

Upon the detection of a disaster, one of the critical steps that needs to be taken is to identify what has changed, how its changed and what objects now make up the working environment. In an earthquake, the collapse of a fire station with the tenders still inside means that those assets can not be factored into the rescue equation. In fact the fire station goes from being a source of relief assets to a sink. Potentially damage and not destruction at the fire station means that the priority list needs to be changed.

The DDDAS needs to make a two-pronged approach to dealing with the situation before actual relief efforts can be mobilised. In needs to identify the damage to the digital world. Therefore it needs to determine what regions of its sensor network are now inaccessible. Based on the list of damaged sensors the system needs to identify what readings it can do without in the short-term, by extrapolating data from other available sensors. This helps to streamline the reconnection activities. Regions that must be reconnected will be factored into the rescue stream of activities. The DDDAS component can reallocate resources (e.g. mobile cell towers or UAVs) to *dark* zones and either set up an ad-hoc network or connect to the existing infrastructure that may have only been cut-off.

The use of UAVs can also improve the resilience of communications. Mobile phones may stop working during a disaster due to loss of core infrastructure or lack of capacity, leading to a loss of communication for the vulnerable or those

TABLE I. DISASTER RISK MANAGEMENT LIFE CYCLE AND THE ROLE OF ICT BASED MODELLING AND SIMULATION.

Time frame	Stage	Activity	Technology
Before the Event	Prevention and Mitigation	Reconstruction	ABM, Scientific
		Risk Assessment and Planning	ABM, CPS
	Preparation	Risk Assessment and Planning	ABM, CPS
		Pre-Impact Activities	DDDAS, CPS, Scientific
		Early Warning Systems	ABM, CPS, Scientific
After the Event	Response	Emergency Management & Ops	ALL
		Restore Infrastructure & Services	DDDAS, CPS
	Recovery	Restore Infrastructure & Services	DDDAS, CPS
		Reconstruction	ABM

in need of help. First responders also need mechanisms to relay information back to the DDDAS. Under the proposed framework integration with tools and technologies such as Serval Mesh [29], Open Garden [30], Software Defined Radio (SDR) [31], allow smart-phones to communicate despite failure of the cellular networks and share available connectivity. The UAVs can also aid in user triangulation using Linear Technology LT5534 power signal detectors.

In parallel, the system must identify the damage to the human world. Using the priority list of assets and vulnerable locations, the DDDAS needs to reset all ABMs to reflect the ground realities. Changes in landscape and infrastructure need to be represented (detected through CPS or Geospatial comparisons). Using the agent-based models and the available sensor information the system needs to either send aid or alert the operator to ensure intangible losses are prevented.

Population response to the disaster can then be modelled, in light of changes to road/rail infrastructures making sure movements are optimised and aid is mobilized to the correct places.

After the short term response the system will quantify the damage and the affect of the response to learn. Policy makers and urban management can make changes to reflect any choke points that are identified. Changes that were made to infrastructure that were earlier quantified as acceptable can be reversed in case losses attributed to the changes prove to be intangible. The aim being to ensure no future reoccurrence of poor performance.

V. FURTHER WORK & CONCLUSION

While many systems have been designed to a standard of TRL between 4-6, these systems focus on either pre-event scenario prediction or post-event actions. The approaches themselves are narrow in their remit and do not encompass all facets of disaster management. Any tools incorporated for planning and risk mitigation can not be utilised post-event to evaluate potential outcomes based on real scenarios. There is a real pressing need for a holistic approach to disaster management that is inline with public policy on the matter.

This paper has proposed a framework that utilizes advanced simulations, Agent Based Models, cyber physical sensors and systems, and a dynamic data-driven approach to attempt to fully encompass all facets of disaster management. The prototype system being developed incorporates the fact that no single aspect of humanitarian response can be considered in isolation. Human evacuation, infrastructure destruction and mobilization of rescue services are all interlinked and can have significant affect on each other. The proposed system also incorporates the concept of tangible and intangible loss, to help prioritise risks and corresponding response.

There are still several challenges in implementing this approach. Particularly, trust is a major hurdle to overcome. Urban planners will struggle with the importance of using a UAV for instance to bridge and reconnect a sensor network over using it to collect imagery. Additionally this is a complex system relying on a diverse set of historical and streaming data. Considerable effort is required to create ontologies to map out and create relationships between all the datasets. Utilising DDDAS in ABM-based social simulations where multiple ontologies and automated rule adaptation need tobe implemented is a particularly challenging endeavour [32]. From a simulation stand point modeling human factors is still a complex process and seamless integration with scientific code based simulations still need further evaluation.

Going forward, we plan to implement the proposed system as a prototype to monitor a vulnerable catchment area that is susceptible to flooding and has a high population density.

REFERENCES

[1] Martin Atkinson, Sara Bouchon, Anna-Mari Heikkila, and Jean-Pierre Nordvik. Report on user requirements supporting risk and vulnerability management of systemic and industrial risks, 2006.

[2] Peter J Haas, Paul P Maglio, Patricia G Selinger, and Wang Chiew Tan. Data is dead... without what-if models. *PVLDB*, 4(12):1486–1489, 2011.

[3] Peter J Haas. Model-data ecosystems: challenges, tools, and trends. In *Proceedings of the 33rd ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems*, pages 76–87. ACM, 2014.

[4] Peter Lee and Georgios Theodoropoulos. An open source simulation-based approach for neighbourhood spatial planning policy. In *Simulation Conference (WSC), Proceedings of the 2012 Winter*, pages 1–11. IEEE, 2012.

[5] Frederica Darema. Dynamic data driven applications systems: A new paradigm for application simulations and measurements. In *Computational Science-ICCS 2004*, pages 662–669. Springer, 2004.

[6] F Darema, C Douglas, and A Patra. The power of dynamic data driven applications systems. In *Multi-Agency Workshop on InfoSymbiotics/DDDAS*, 2010.

[7] Wayne Wolf. Cyber-physical systems. 2009.

[8] William Dees, Frank Phillips, Paul Bender, and Kay Kussmann. Aquatic-based cyber-physical systems in the calcasieu estuary. In *Proceedings of the Sixth ACM International Workshop on Underwater Networks*, page 19. ACM, 2011.

[9] Timothy W Schoenharl and Greg Madey. Evaluation of measurement techniques for the validation of agent-based simulations against streaming data. In *Computational Science–ICCS 2008*, pages 6–15. Springer, 2008.

[10] Eric S Blake, Todd B Kimberlain, Robert J Berg, JP Cangialosi, and John L Beven II. Tropical cyclone report: Hurricane sandy. *National Hurricane Center*, 12:1–10, 2013.

[11] Adam J Pel, Serge P Hoogendoorn, and Michiel CJ Bliemer. Evacuation modeling including traveler information and compliance behavior. *Procedia Engineering*, 3:101–111, 2010.

[12] Adam J Pel, Michiel CJ Bliemer, and Serge P Hoogendoorn. A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation*, 39(1):97–123, 2012.

[13] Kirstin Dow and Susan L Cutter. Emerging hurricane evacuation issues: hurricane floyd and south carolina. *Natural hazards review*, 3(1):12–18, 2002.

[14] Alok Chaturvedi, Angela Mellema, Sergei Filatyev, and Jay Gore. Dddas for fire and agent evacuation modeling of the rhode island nightclub fire. In *Computational Science–ICCS 2006*, pages 433–439. Springer, 2006.

[15] Shengnan Wu, Larry Shuman, Bopaya Bidanda, Matthew Kelley, Ken Sochats, and Carey Balaban. Agentbased discrete event simulation modeling for disaster responses. In *Proceedings of the 2008 Industrial Engineering Research Conference*, 2008.

[16] Narjès Bellamine-Ben Saoud, Tarek Ben Mena, Julie Dugdale, Bernard Pavard, and Mohamed Ben Ahmed. Assessing large scale emergency rescue plans: an agent based approach. *The International Journal of Intelligent Control and Systems*, 11(4):260–271, 2006.

[17] Gregory R Madey, Albert-László Barabási, Nitesh V Chawla, Marta Gonzalez, David Hachen, Brett Lantz, Alec Pawling, Timothy Schoenharl, Gábor Szabó, Pu Wang, et al. Enhanced situational awareness: Application of dddas concepts to emergency and disaster management. In *Computational Science–ICCS 2007*, pages 1090–1097. Springer, 2007.

[18] Elizabeth Ferris and Mireya Sols. Earthquake, tsunami, meltdown - the triple disaster's impact on japan, impact on the world. *The Brookings Institution.*, may 2013.

[19] Netease. Nepal tibet communications disruption caused by the earthquake. *Netease Technology*, apr 2015.

[20] Manfred Broy. Engineering cyber-physical systems: Challenges and foundations. In *Complex Systems Design & Management*, pages 1–13. Springer, 2013.

[21] Mark-Oliver Stehr, Carolyn Talcott, John Rushby, Pat Lincoln, Minyoung Kim, Steven Cheung, and Andy Poggio. Fractionated software for networked cyber-physical systems: Research directions and long-term vision. In *Formal Modeling: Actors, Open Systems, Biological Systems*, pages 110–143. Springer, 2011.

[22] Mihaela Ulieru. Design for resilience of networked critical infrastructures. In *Digital EcoSystems and Technologies Conference, 2007. DEST'07. Inaugural IEEE-IES*, pages 540–545. IEEE, 2007.

[23] Jing Lin, Sahra Sedigh, and Ali R Hurson. An agent-based approach to reconciling data heterogeneity in cyber-physical systems. In *Parallel and Distributed Processing Workshops and Phd Forum (IPDPSW), 2011 IEEE International Symposium on*, pages 93–103. IEEE, 2011.

[24] Jing Lin, Sahra Sedigh, and Ann Miller. A general framework for quantitative modeling of dependability in cyber-physical systems: a proposal for doctoral research. In *Computer Software and Applications Conference, 2009. COMPSAC'09. 33rd Annual IEEE International*, volume 1, pages 668–671. IEEE, 2009.

[25] Jing Lin, Sahra Sedigh, and Ali R Hurson. Ontologies and decision support for failure mitigation in intelligent water distribution networks. In *System Science (HICSS), 2012 45th Hawaii International Conference on*, pages 1187–1196. IEEE, 2012.

[26] Georgios Theodoropoulos, Rob Minson, Roland Ewald, and Michael Lees. Simulation engines for multi-agent systems. *Multi-Agent Systems: Simulation and Applications, edited by Adelinde M. Uhrmacher and Danny Weyns (Editors), Publisher: Taylor and Fran-cis. ISBN*, 1779537239:77–108, 2009.

[27] Paul S Earle, Daniel C Bowden, and Michelle Guy. Twitter earthquake detection: earthquake monitoring in a social world. *Annals of Geophysics*, 54(6), 2012.

[28] Juan Carlos de León Villagran, Janos Bogardi, Stefanie Dannenmann, and Reid Basher. *Early warning systems in the context of disaster risk management*, Entwicklung and Landlicher Raum, Volume 2, page 23–25, 2006

[29] Paul Gardner-Stephen and Swapna Palaniswamy. Serval mesh software-wifi multi model management. In *Proceedings of the 1st International Conference on Wireless Technologies for Humanitarian Relief*, pages 71–77. ACM, 2011.

[30] Marcelo Nogueira Cortimiglia, Antonio Ghezzi, and Filippo Renga. Mobile applications and their delivery platforms. *IT Professional*, (5):51–56, 2011.

[31] Joseph Mitola III. *Software radio architecture: object-oriented approaches to wireless systems engineering*. John Wiley & Sons, 2004.

[32] Catriona Kennedy and Georgios Theodoropoulos. Intelligent management of data driven simulations to support model building in the social sciences. In *Computational Science–ICCS 2006*, pages 562–569. Springer, 2006.