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Complex Systems Modeling for Humanitarian Action:
Methods and Opportunities

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Acknowledgements

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Executive Summary

The Global Humanitarian Overview 2021 estimates that 235 million people are in need of humanitarian assistance, with 160 million targeted for assistance in over 30 countries. These estimates are based on needs assessments that take place on a yearly basis to inform Humanitarian Needs Overviews and Humanitarian Response Plans in different crisis contexts.[1]

Although efforts are being made to include scenarios and risk projections in humanitarian planning, they largely remain static representations of humanitarian crises at a given moment in time. However, in many humanitarian contexts, the number of people in need of humanitarian assistance can fluctuate over short time scales as a result of sudden shocks (e.g., escalations in armed conflict) or seasonal environmental phenomena (e.g., floods), among other factors. Humanitarians need more robust methods for understanding and modeling these dynamics in order to more effectively address the needs of people affected by crises.

Complex systems modeling is a class of mathematical methods that predict the behavior of a system over time based on a set of assumptions on how components of the system interact. These techniques are suited to providing dynamic projections of how a humanitarian crisis will unfold and what effects different potential interventions could have in a given context.

Recognizing this potential, the Centre for Humanitarian Data (the Centre) conducted research on opportunities to apply complex systems modeling to humanitarian needs assessment as part of its 2021 Data Fellows Programme. This report summarizes the main findings from the Centre's research. The first section provides a definition of complex systems and an overview of the main modeling techniques relevant to humanitarian action. The second section explains why the use of complex systems modeling would be desirable in the humanitarian sector. The third section outlines feasibility, viability, and desirability criteria that can help assess whether specific problem spaces are suitable to complex systems modeling techniques. The fourth section proposes a general workflow for the development of the most suitable model for humanitarian settings.

The research yielded the following key findings:

- There is strong interest within the humanitarian community in the prospect of using complex systems modeling to improve the ability to understand, predict and respond to the needs of crisis-affected communities.
- To determine which problems are best suited to being modeled using complex systems techniques, humanitarians should consider the following criteria:
    - *Feasibility*: clear goals and output; clear target geographic area; existence of previous models and/or literature relevant to the problem space.
    - *Viability*: data availability; synergy with domain experts and humanitarian actors in the field.
    - *Desirability*: complexity of the problem space; ability to inform response activities; potential impact.

[1] See the Global Humanitarian Overview 2021 for more details: https://hum-insight.info/

- Out of the techniques considered (network/graph models, agent-based modeling and System Dynamics), System Dynamics is currently the most suitable for a pilot of complex systems modeling in the humanitarian sector. This is due to its potential to support response simulation even in contexts with limited data availability and due to availability of relevant expertise.

The main recommendations include:

- The Centre should coordinate initial pilots to better understand the potential impact of complex systems modeling techniques in the sector. One promising use case relates to infectious diseases modeling. The development of a Cholera Response Simulator (i.e, a model that would make it possible to simulate and evaluate the effectiveness of different possible cholera response strategies) has been identified as a suitable problem space for a pilot and an opportunity to concretely understand the potential impact of these techniques in the sector. More detailed information on this pilot and preliminary data exploration is available in this repository.
- The Centre should develop partnerships with actors from technical research environments and the development sector, where complex systems modeling is more widely in use.
- The Centre should create medium-term (6-12 months) research fellowships with academic institutions for students with relevant technical training in systems modeling or sponsor applied doctoral fellowships which would involve sustained collaborations with the Centre on systems modeling projects.
- The Centre should coordinate events and develop educational resources tailored to humanitarians to increase uptake of these techniques within the sector.
- To help bridge the technical gaps that constitute the main barrier to the adoption of predictive modeling techniques in the sector, the Centre should leverage its annual Data Fellows Programme to implement projects at the intersection of predictive analytics, data literacy, and data visualization.
- The Centre should continue its work in closing data gaps and consider how to improve and communicate model accuracy through collaboration between modelers and actors in the field.

I. What is a complex system?

Many social and natural phenomena can be described as complex systems. The climate is a notable example of a complex system: climate phenomena emerge from the interactions between multiple subsystems, including the atmosphere, oceans and terrestrial ecosystems, (which are themselves complex systems). The nervous system is another notable example: the biological and cognitive functions supported by the system cannot be explained in terms of the 'sum' of the activities of single neurons. The behavioral dynamics of both human and non-human social groups can also often be described as complex systems.

Complex systems are systems whose global behavior is *emergent*, *non-linear* and *adaptive*:

- **Emergent**: It cannot be explained from the behavior of individual components but is said to emerge from the interactions between individual components.
- **Non-linear**: Due to the ways in which interactions between the multiple components of the system accumulate, small changes in the behavior of individual components may result in disproportionate effects on the global state of the system.
- **Adaptive**: Individual components of the system can change their behavior to adapt to changes in the behavior of other components.

Given these properties of emergence, non-linearity and adaptiveness, the behavior of complex systems can only be predicted through techniques that explicitly factor in the dynamic interconnectedness between system components.

II. Why use complex systems modeling in the humanitarian sector?

Many humanitarian crises can be considered complex systems. Crises often come about as a result of interactions between multiple, mutually reinforcing political, social, and environmental factors, whose effects accumulate over time in non-linear ways. This makes these crises prone to sudden escalations and often resistant to humanitarian intervention.

In slow-onset and protracted crises, the effects of the interaction between multiple crisis drivers accumulate non-linearly *over long time scales*. This is the case, for example, for protracted food insecurity crises, where environmental, social, economic, and geopolitical factors reinforce each other in ways which make interventions targeting single crisis drivers often ineffective. Other crises are punctuated by sudden-onset seasonal shocks, such as floods or typhoons, whose effects propagate to the whole system *over very short time scales*.

To intervene in humanitarian contexts where needs can change dramatically over time, current needs assessment techniques need to be complemented by modeling techniques which factor in these complex systems characteristics. Complex systems modeling can support more effective and data-driven humanitarian response. Modeling techniques that factor in complexity help better predict how and why needs may change over the timeline of a crisis. They also support the development of tools that enable humanitarians to run more dynamic projections of possible scenarios, which can help identify leverage points for interventions to maximise the impact of humanitarian action.

Complex systems modeling can also help humanitarians understand the likely evolution of the situation at different time scales, enabling responders and policy makers to better understand the short and long-term impacts of planned response activities. In this way, it can provide insights on how to better coordinate humanitarian and development activities in order to address needs while also fostering the coping capacity of affected populations. These models could also help humanitarians understand the unintended consequences that immediate actions could have in the long run.

The potential applications of complex systems modeling in humanitarian action have pushed both practitioners and researchers to advocate for its introduction in the sector. Support has also been expressed by the technical experts and humanitarian actors interviewed as a part of this research. In addition, the high level of participation in the Complex Systems Modeling webinar organized by the Centre in June 2021 suggests a more general interest from within the humanitarian and academic communities in partnering to explore the possibilities offered by these new techniques for humanitarian action.

III. When is complex systems modeling feasible, viable and desirable in humanitarian settings?

Not all humanitarian issues are well suited to complex systems modeling. Some may be too vaguely defined to be modeled accurately (e.g., in terms of the target geographical area, the goals, or what factors should be included in the model). Others may require domain knowledge that is not available to the modeler or require data that cannot be collected. While modeling may be feasible in terms of clarity of target and data availability, responding to the model outputs may remain a challenge due to factors such as limited humanitarian access in the area or relevant interventions falling beyond the scope of the response.

Before embarking on the development of a complex systems model, humanitarians should evaluate whether the problem space meets a number of feasibility, viability, and desirability criteria outlined in Figure 1 and described in more detail below. These criteria are based on a review of modeling literature as well as the interviews conducted with modeling experts and humanitarians as part of this research.

Figure 1. Criteria for determining the feasibility, viability and desirability of complex systems modeling in humanitarian settings

Feasibility	***Viability***	***Desirability***
Clear goals and output	Data availability	Complexity of the problem space
Clear target geographic area	Synergy with domain experts and humanitarian actors in the field	Ability to inform response activities
Existence of previous models and/or literature		Potential impact

Feasibility criteria
The following criteria help determine whether it is *feasible* to model a specific problem space using complex systems methods:

- **Clear goals and outputs:** The possibility to develop a model depends on clearly specified goals and outputs. This translates into defining: a) what the applications of the model should be; b) what exactly the model should predict/monitor dynamically; c) how confident one is that this/these variable(s) adequately reflect the type of humanitarian need one wants to address through intervention. Model development will be a challenge if any of these points is underspecified.
- **Clear target geographic area:** Successful model development requires the identification of a specific target geographical area (at least for initial iterations of model development). This criterion is specific to applications of complex systems modeling to humanitarian crises, where drivers may be highly specific from crisis to crisis, and domain knowledge on the context will be necessary to develop a plausible model of the crisis.

- **Existence of previous models and/or literature:** The existence of literature on systems modeling for the problem space of interest supports (but is not essential to) the feasibility of modeling. Existing work can provide a robust starting point for model development.

Viability criteria

The following criteria help determine whether model development is *viable* within the constraints posed by the specific target context(s):

- **Data availability:** A core aspect to consider is whether sufficient data are available to support validation and estimation of a model. Data availability (especially historical data) is often a challenge in countries with humanitarian operations. The lack of data can jeopardize the possibility to build reliable predictive tools[2,3]. Nevertheless, developing the conceptual component of a model may bring value by fostering trust and synergy between stakeholders, even when quantitative model estimation is not possible. Imperfect proxies or imputed data may also be sufficient in contexts when the focus is not on maximizing the accuracy of pointwise prediction of a certain variable at each time point (e.g., daily numbers of cases in an epidemic), but on projecting holistic scenarios and trends (e.g., when and whether the number of cases is expected to rise significantly).
- **Synergy with domain experts and actors in the field:** Receiving an explicit endorsement and establishing strong partnerships with domain experts and actors in the field is another key condition for model development to be viable. Although this is the case for many predictive modeling efforts, it is especially important for complex systems modeling. In order to identify direct and indirect drivers of humanitarian needs, formulate hypotheses on how these drivers interact, and best tailor the model to its intended applications, modelers need to rely on knowledge provided by domain experts, decision makers and actors close to operations.

Desirability criteria

The following criteria help assess whether it is *desirable* to model a specific problem space through complex systems modeling techniques:

- **Complexity of the problem space:** It is essential to consider whether the target problem space displays complex systems characteristics, which can only be captured through dynamic and causal modeling strategies, or whether traditional non-dynamic and non-causal predictive models may yield comparable insights. Preliminary data analyses may help clarify this point. This is a general criterion that applies to complex systems modeling beyond humanitarian settings.
- **Ability to inform response activities:** Complex systems models can be used to simply test hypotheses on the structure of causal drivers of a crisis, but their impact on humanitarian response may be significantly larger if they can *directly* provide decision makers with a tool to test and evaluate the potential consequences of different types of response activities. Considering whether a problem space affords

[2] See Bodanac, Nicholas, Predictive Analytics for Anticipatory Action: Challenges and Opportunities, p. 12. Available here: https://data.humdata.org/dataset/2048a947-5714-4220-905b-e662cbcd14c8/resource/89546fb6-b130-4189-9da9-c962053e729f/download/pa_2020_fellow_report_final.pdf.

[3] See Centre for Humanitarian Data: State of Open Humanitarian Data 2021, p. 21. Available here: https://centre.humdata.org/the-state-of-open-humanitarian-data-2021/

similar applications (and assessing whether decision makers in the target context are open to deploying such a tool) is key to understanding whether the practical benefits justify the time and resources required to develop and validate a complex systems model.

- **Potential impact:** It is important to consider whether the trade-off between resources required to develop a model and its overall impact on the context of focus is sustainable. Relatedly, it may be worth considering how likely it is that the model could be re-used for and adapted to other geographical areas, which could support impact beyond the initial context of focus.

IV. How is a complex systems model developed?

There are a number of modeling techniques that are designed to understand complex systems (see Figure 2 below for more detail). The goals and constraints of the specific problem of interest determine which modeling technique is most appropriate in a given context.

The Centre's research determined that System Dynamics is likely to be the most suitable technique for a pilot of complex systems modeling in the humanitarian sector due to the potential of this technique to support response simulation even in contexts with limited data availability.[4] Our research also highlighted how humanitarian and development partners are already exploring the use of System Dynamics modeling (see Figure 3 for more concrete examples).

Figure 2. Selected methods for complex systems modeling

Complex systems modeling refers to any method that can be used to *represent* a system of interacting components and *predict* its behavior given a description of its components and a set of assumptions on the rules that define how the components behave. The following methods are among those most commonly used to model complex systems and with the highest potential relevance for use in the humanitarian sector.

Network/graph models: Components of the systems are represented as nodes in a network, and their relations (i.e., whether and how each node interacts with each other) are defined by edges connecting each node (which may include loops, i.e., edges that connect nodes with themselves). *Complex networks* are a specific class of networks which display special topological features. Small-world networks, for example, are networks where nodes tend to be grouped in tight clusters, but a few long-range connections between nodes make clusters communicate with each other. This is an example of a class of complex networks that is often found in real-world phenomena. In human social networks, for example, small-world properties motivate hypotheses postulating that all people are on average a few social connections away from each other (e.g., the six degrees of separation hypothesis). In addition to the complexity of the network structure itself, these models are also able to capture the evolution of dynamic processes in connected complex networks (e.g., an epidemic spreading in a society).

Agent-based modeling: Agent-based models are computational models that make it possible to simulate the behavior of a system based on a description of (i) the type of *agents* the system consists of and (ii) the *rules* on how these agents behave and interact. Agent-based models are a microscale modeling technique: the level of description is that of the individual agents, and the macroscale behavior of the system emerges (over the course of a computer simulation) as a function of the cumulative effects of agents' behaviors and their interactions over time. Agent-based models are often used to predict the dynamics of epidemic diseases as a function of assumptions on how individuals behave (e.g., the average number and duration of social contacts) and on epidemiological parameters (e.g., incubation time, recovery rate). Beyond epidemiology, agent-based modeling is widely used in a number of other fields (e.g., biology, computational social science, and economics). Agent-based models can be validated against real data to understand

[4] Note, however, that this is not a general recommendation for all humanitarian applications. If sufficient data are available and the problem space affords it, other techniques such as agent-based models or network approaches may yield higher predictive accuracy, and be more generalizable across problem spaces.

which set of assumptions best explains the emergence of behaviors observed in real life, or used to compare outcomes resulting from alternative sets of assumptions.

System Dynamics: System Dynamics is a technique initially developed for business and industrial applications where systems are represented at the macroscale in terms of *stocks* (system-level variables), *flows* (relations between stocks), *feedback loops*, and *time delays*. Development of a System Dynamics model involves first formulating hypotheses on which variables are relevant to defining the behavior of the system, and how they interact (i.e., formulating a causal loop diagram and a stock and flow diagram). Equations that *quantify* the flows are then defined in order to run dynamic simulations of how the system will evolve given a description of its initial state. These simulations can be used to clarify how a variety of mutually interacting factors give rise to specific dynamics in a system, and which component of the system someone could intervene on, in order to change the behavior of the system in the desired direction.

As described in Figure 2, a System Dynamics model is a way of representing a problem in terms of a graph of *variables* (“stocks”), *relations* between variables (“flows”), *time delays* (the time scale at which these relations take place), and *feedback loops*. System Dynamics models allow users not only to visualize the complex causal factors that are hypothesized to define the behavior of a system, but also to simulate--given these causal assumptions--how the system may evolve over time, and how external interventions on its components may change the way it evolves. This makes System Dynamics especially suitable to use cases where the aim is to simulate impacts and consequences of a humanitarian response plan and related interventions.

Developing a System Dynamics model in the humanitarian sector requires various types of expertise. Domain experts and actors directly involved in response operations in the geographical area of interest are needed to identify relevant variables and formulate hypotheses on how different factors influence each other. Technical experts should be in charge of developing, validating and estimating the model. Coordination actors are needed to develop and maintain synergies between parties involved, and to make sure that modeling efforts are tailored to the needs of the end users.

There are four key steps[5] in developing a System Dynamics model: 1) problem identification and system conceptualization; 2) model formulation and analysis; 3) model validation; and 4) policy analysis and implementation. These steps are explained in more detail below.

Step 1: Problem identification and system conceptualization

The problem should be narrowed down to a few concrete goals and outputs. Stakeholders should define which variables the model should predict, and what these predictions will be concretely used for. For example, if the target problem is modeling the unfolding of an epidemic, interviews with stakeholders and experts should be conducted to define whether the model should simply help to monitor the number of cases (e.g., to increase preparedness of the healthcare system) or rather understand how to intervene in order to minimize the number of deaths.

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[5] These steps are based on the Centre’s findings and existing literature on System Dynamics modeling process (See for instance ‘*Aguiar, A. The role of systematic reviews in the System Dynamics modelling process. Syst Res Behav Sci. 2020; 37: 892– 895. https://doi.org/10.1002/sres.2758*’).

If the model should allow simulation of the effect of a response plan, interviews with stakeholders should be conducted to identify a list of specific types of responses the model should be able to evaluate. Expanding on the example above, if the model is intended to help us understand how to minimize deaths due to cholera, interventions such as the distribution of rehydration kits, oral cholera vaccinations, or increased testing capacity may be relevant.

Note that this step is optional if the model is *not* primarily intended to test the effect of a response plan (but, for example, its goal is simply that of making it possible to explore hypotheses on causal drivers of a crisis).

Step 2: Model formulation and analysis
Factors that may directly or indirectly influence an output variable should be identified through interviews and/or workshops involving domain experts. Decisions should then be made on which factors to include based on relevance and practical considerations. Building on the previous example of an epidemic, even though conflict events may influence the number of deaths from a disease, modelers may decide not to include this variable if such events are sparse or not relevant to response plans in the target context.

Hypotheses on how different factors may influence each other (what causes what, and at which delay) should be developed. This step culminates in the formulation of a map or causal loop diagram of the causal structure of the problem. Literature review and input from domain experts and other stakeholders (in the form of bilateral interviews and workshops) are the key instruments to achieving this.

Technical actors should review available data sources to identify proxies for the qualitative variables of interest. If no proxy is available, data may be imputed.

Step 3: Model validation
The resulting causal loop diagram and the description of how relevant variables will be operationalized quantitatively (i.e., which proxy will be used for each variable, and from which datasets this information will be extracted) should be validated by a panel of independent experts. This step may lead to changes in the model. Whenever possible, this step should follow the guidelines of the Centre's *Peer Review Framework for Predictive Analytics in Humanitarian Response*.[6]

The model should then be validated against available data. If performance is not satisfactory, the model may be revised. Ideally, an independent dataset should be kept aside for the final validation of the model.

Step 4: Policy analysis and implementation
If the model is intended to be deployed as a predictive tool or a scenario exploration tool, user-friendly interfaces can be developed to make deployment easier and results more intuitive.

[6] Available here: https://data.humdata.org/dataset/2048a947-5714-4220-905b-e662cbcd14c8/resource/76e488d9-b69d-41bd-927c-116d633bac7b/download/peer-review-framework-2020.pdf

End users should be briefed on what use cases the model supports, and on the uncertainties and risks involved in its deployment. The level of detail and contents of these briefings will depend on whether end users will deploy the model with or without mediation from technical staff.

Finally, the model should be used to provide end users with insights according to the use case defined in step 1 (problem identification and system conceptualization), allowing them to test the impact of policies and experiment with different scenarios.

Figure 3. Examples of System Dynamics models

A few System Dynamics models have already been developed in the humanitarian and development sectors. A notable example is the model developed by the Internal Displacement Monitoring Centre at the Norwegian Refugee Council to simulate how displacement in the Horn of Africa is affected by a number of climate and human-induced factors[7].

While models and applications in the humanitarian sector are still sparse, System Dynamics is more widely used in the development sector. The Millennium Institute has supported the development of a number of models which make it possible to perform dynamic analyses and policy simulations concerning the achievement of the Sustainable Development Goals[8].

Other examples relevant to the humanitarian sector are models such as World3 and Threshold21, which are inspired by Donella Meadows' seminal work on systems thinking. These models project scenarios on the dynamics of natural resource availability, climate, and socio-economic parameters over long time spans. These two models and related simulation interfaces are available online[9] .

[7] See Internal Displacement Monitoring Centre: Assessing Drought Displacement Risk for Kenyan and Ethiopian pastoralists, Available here: https://www.internal-displacement.org/publications/assessing-drought-displacement-risk-for-kenyan-ethiopian-and-somali-pastoralists
[8] See The Millenium Institute, The Integrated Sustainable Development Goals (iSDG). Available here: https://www.millennium-institute.org/isdg
[9] See Insight Maker, The World3 model. Available here: https://insightmaker.com/insight/1954/The-World3-Model-Classic-World-Simulation

V. What's next for complex systems modeling?

Complex systems modeling is a potentially powerful technique to help improve the effectiveness of humanitarian response. To realize this potential, humanitarians must address a number of challenges including: identifying suitable target problems; effectively coordinating the multiple actors involved; finding relevant data; and bridging the technical gaps that may cause resistance towards adopting these techniques in the context of decision making.

To better understand the potential impact of complex systems modeling techniques in the sector, the Centre should coordinate initial pilots for different types of humanitarian crises. Due to their highly dynamic nature and their impact on affected communities, epidemic disease modeling is a good use case for an initial pilot. More specifically, in line with the feasibility, viability and desirable criteria identified in this report, the development of a Cholera Response Simulator[10] could be a suitable opportunity to concretely understand the potential impact of these techniques in the sector. The Centre should further explore this opportunity according to the proposed roadmap for development.

To advance this work, the Centre should develop partnerships with actors from technical research environments and the development sector, where complex systems modeling is more widely in use. Institutions such as the Millennium Institute and consortia such as the Complex Systems Society[11] are examples of research partners that could help humanitarians to better understand the possibilities offered by complex systems modeling.

The impact of initial pilots and of potential subsequent work on complex system modeling conducted at the Centre would benefit from additional in-house expertise and longer-term collaborations with technical experts. **The Centre should create medium-term (6-12 months) research fellowships with academic institutions for students with relevant technical training in systems modeling or sponsor applied doctoral fellowships which would involve sustained collaborations with the Centre on systems modeling projects.**

Although complex systems modeling is gaining awareness in the sector, adoption of these techniques in humanitarian contexts is still relatively limited. This is due to the level of technical expertise required to understand how these methods work and how they can inform humanitarian decision making. To support uptake of these techniques within the sector (and ideally, in the longer term, their implementation as part of the humanitarian planning cycles or the anticipatory action plans)**, the Centre should coordinate events and develop educational resources tailored to humanitarians.**

The Centre should leverage its annual Data Fellows Programme to implement projects at the intersection of predictive analytics, data literacy, and data visualization. Projects

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[10] As part of this research, we developed a roadmap for the development of a Cholera Response Simulator based on System Dynamics techniques. We assessed the main data requirements and methodological challenges. This work has been done in collaboration with a student from the University of Bergen, Norway. More information is available in the GitHub repository linked above.

[11] The Complex Systems Society is already committed to exploring applications of systems modeling in sectors adjacent to the humanitarian sector. See: https://www.cnn.group.cam.ac.uk/news/CCS2021-Complex-Systems-for-the-most-vulnerable.

may be centered on developing educational resources that help humanitarians navigate existing methods and understanding how these methods map onto possible problem spaces and applications. In practice, this could be done by developing a predictive modeling cheat-sheet illustrated by examples, or a set of notebooks (e.g., as Jupyter books, or Observable notebooks) which introduces the reader to different techniques through toy models. The Centre could also supplement its catalogue of predictive models[12] with practical demonstrations of the main models.

Finally, limited data availability and poor data quality is one of the main barriers to the development of complex systems models. **The Centre should continue its work on closing data gaps and consider how to improve and communicate model accuracy through collaboration between modelers and actors in the field.**

[12] https://centre.humdata.org/catalogue-for-predictive-models-in-the-humanitarian-sector/

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