New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

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OPEN ACCESS

RECEIVED
15 March 2019

REVISED
26 May 2019

ACCEPTED FOR PUBLICATION
18 June 2019

PUBLISHED
8 July 2019

PAPER

Complexity analysis of sustainable peace: mathematical models and data science measurements

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Keywords: sustainable peace, complex systems, causal loop diagrams, ordinary differential equation models, databases, sentiment analysis

Abstract

Peace is not merely the absence of war and violence, rather 'positive peace' is the political, economic, and social systems that generate and sustain peaceful societies. Our international and multidisciplinary group is using physics inspired complex systems analysis methods to understand the factors and their interactions that together support and maintain peace. We developed causal loop diagrams and from them ordinary differential equation models of the system needed for sustainable peace. We then used that mathematical model to determine the attractors in the system, the dynamics of the approach to those attractors, and the factors and connections that play the most important role in determining the final state of the system. We used data science ('big data') methods to measure quantitative values of the peace factors from structured and unstructured (social media) data. We also developed a graphical user interface for the mathematical model so that social scientists or policy makers, can by themselves, explore the effects of changing the variables and parameters in these systems. These results demonstrate that complex systems analysis methods, previously developed and applied to physical and biological systems, can also be productively applied to analyze social systems such as those needed for sustainable peace.

1. Introduction

Achieving and sustaining peace among communities and nations is essential for people to lead safe, satisfying and fulfilling lives. However, most previous research studies have analyzed peace only in a negative way, considering it only as the absence of conflict, violence, or war. Recently, there has been a growing effort to understand 'positive peace', that is, the political, economic, and social systems that generate and sustain peaceful societies [1–5].

An international initiative lead by the Advanced Consortium on Cooperation, Conflict, and Complexity (AC4) at The Earth Institute at Columbia University has been analyzing sustainable peace as a dynamical system by using methods from the study of such complex systems that have proved valuable in understanding physical and biological systems. It is now in the third year of a projected ten year study to identify the factors that are most important in sustaining peace, determine how those factors interact with each other, and understand how these

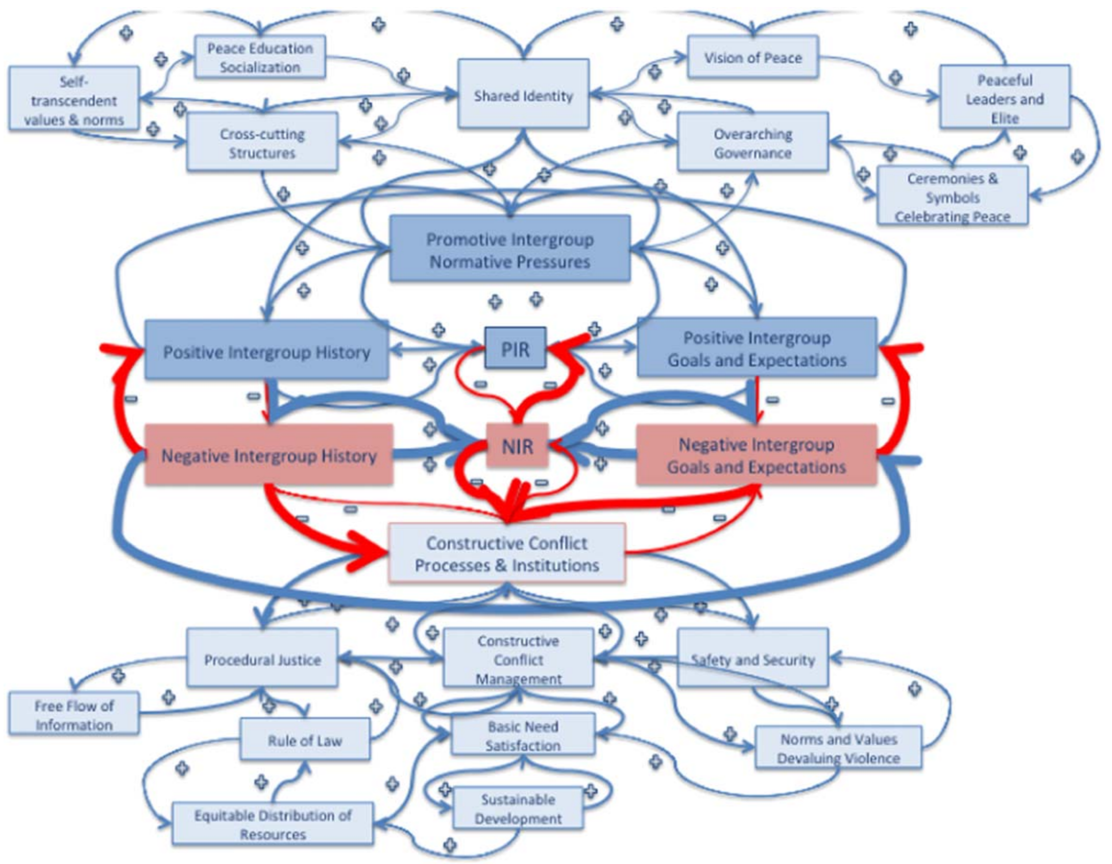

Figure 1. One Causal Loop Diagram (CLD) of the factors needed to sustain peace and their interactions. PIR is positive intergroup reciprocity and NIR is negative intergroup reciprocity. Positive factors and links are in blue and negative factors and links are in red. The strengths of the links are proportional o their thickness.

1.2. Mathematical model

A rigorous mathematical model, derived from the CLD, can further extend the value of the CLD by determining: (1) the quantitative values that result from the simultaneous interactions of all the peace factors, (2) the dependence of those values on the strengths and signs of the connections between the peace factors, (3) the dynamics, that is, the evolution in time of the values of the peace factors, and (4) the long term steady state values of the peace factors that define the dynamical 'attractors' of the system. It can also be the back end for an interactive interface for policy makers to study the consequences of different interventions in the system. Extending previous mathematical models of networked systems [11–15] to analyze a CLD, we determine the value x_i of each peace factor from:

$$\frac{\mathrm{d}x_i(t)}{\mathrm{d}t} = -|m_i|x_i(t) + b_i + \sum_{j=1}^{n}[c_{i,j}][\tanh(x_j(t))],$$

where the parameter m_i determines the memory time scale (set shorter for positive than negative peace factors because of the stronger and longer lasting effects of negative emotional encounters [16]), b_i is self-reinforcement or input from variables external to the system, $c_{i,j}$ is the strength of the influence from peace factor j to peace factor i. The hyperbolic tangent factor tanh() is used so that the effects from one peace factor to another are linear at small values but reach a limiting threshold at large values. In effect, this system is equivalent to a recurrent artificial neural network where the 'memories' defined by the attractors are determined *a priori* by the parameters, rather than by training the network. We integrate these coupled, nonlinear ordinary differential equations, forward in time using Euler integration requiring that all the values of peace factors $x_i \geqslant 0$ so that a negative peace factor acting through a negative link does not produce a positive effect.

1.3. Objectives

The current work of the project reported here is directed toward achieving four objectives:

I. Develop a user-friendly graphical user interface (GUI) to the mathematical model so that scholars, practitioners, and policy makers can see the consequences of changes that they make in the model.

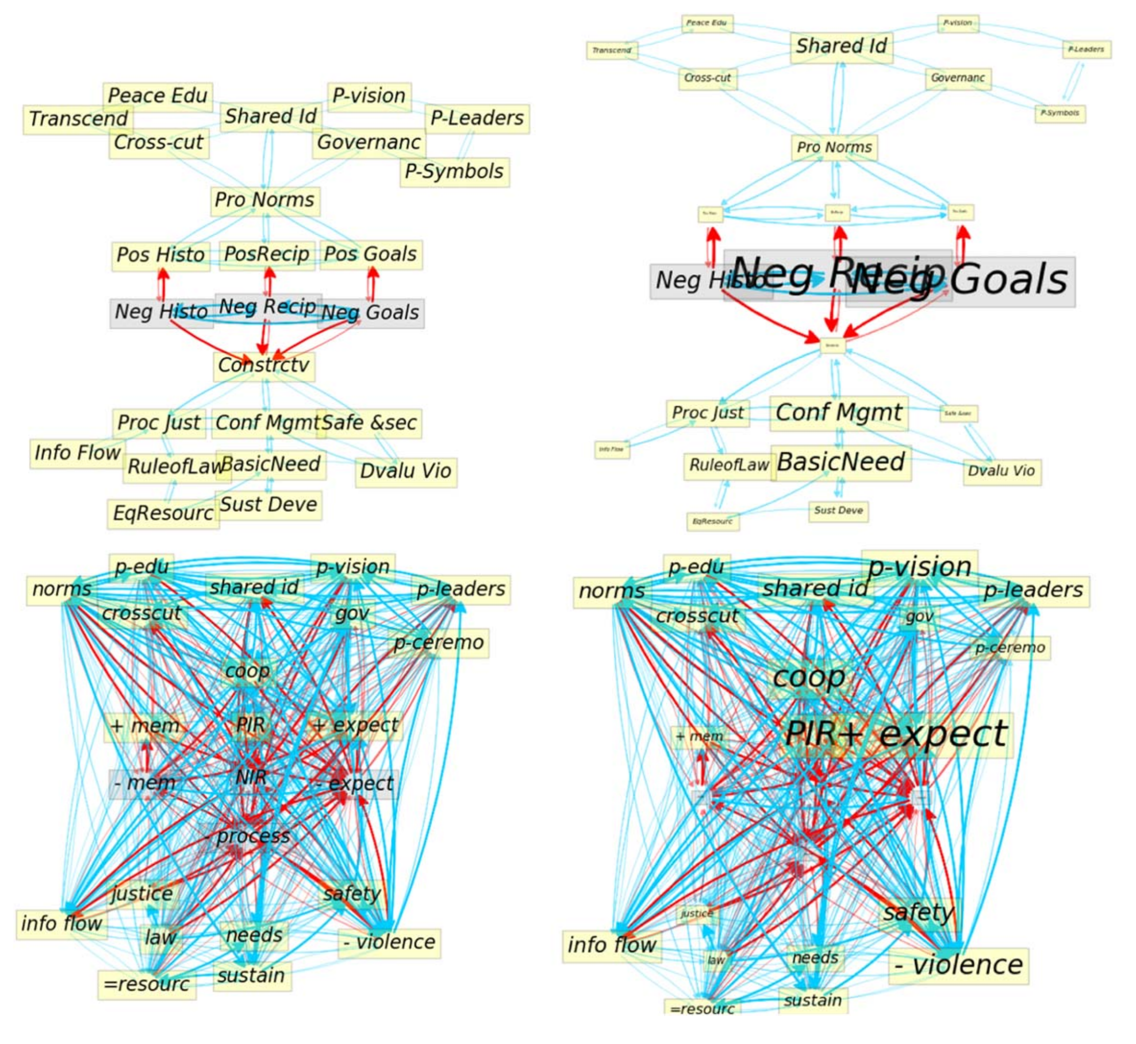

Figure 2. Initial conditions (left) and final steady state values (right) of the peace factors at their attractors. Top: sparse connection model. Bottom: dense connection model.

positive peace factors are made very large (10.0) and the the negative peace factors very small (0.10) does this system reach the 'Good' attractor.

- When we changed the connections strengths, additional attractors were created. For example, when we weakened the connections from the negative to the positive peace factors that split the system into separate independent communities with high values for both the positive and negative peace factors.
- To evaluate importance of individual peace factors in determining the system properties and understand the consequences of policy interventions, we fixed the value of one peace factor at a time and computed a global measure of the system, the average value of the positive minus the average value of the negative peace factors. This is equivalent to making that peace factor a source node. As shown in figure 3, as we varied that fixed value, some peace factors drove a sharp phase transition in the system, for example, switching Constructive Processes and Institutions from 0.622 69 to 0.622 70 flips the system from the 'Bad' to the 'Good' attractor. On the other hand, some nodes had little effect on the system properties.
- Because negative emotions have stronger and more long-lasting effects than positive emotions [16], those stronger interactions within the negative peace factors of the core engine self-reinforces those negative peace factors pushing the positive peace factors towards zero bringing the system to the 'Bad' attractor. We are able flip the system to the 'Good' attractor by increasing the connection strengths from the positive to the negative peace factors, by changing certain 'leverage' peace factors to sources, or by increasing the number of positive variables to overload the negative.
- Since both the topology of the network (as in the dense connection model) or the specific connection strengths (as can be done in the sparse connection model) can lead to sustainable peace, this suggests that thoughtful