CLD-Explorer: Toward a Tool for Causal Loop Diagrams Analytics

Anna Bernasconi[1], Stefano Ceri[1], Francesco Invernici[1], Chiara Leonardi[2] and Laura Daniela Maftei[1]

[1]*Department of Electronics, Information and Bioengineering – Politecnico di Milano, Italy*
[2]*Independent researcher, Italy*

Abstract

Causal Loop Diagrams (CLDs) document and visualize the dynamics of complex systems, describing their relevant factors, called variables, and causal relationships between them. The most interesting features for exploring CLDs are *causal loops*, i.e., circuits of causal relationships, which can be characterized as balancing or reinforcing; other interesting features of CLDs are *causal routes*, i.e., chains of relationships connecting any two pairs of nodes, recognized as increasing or decreasing. We hereby introduce *CLD-Explorer*, a prototype interactive system for inputting new CLD diagrams and analysing their features, reviewing their causal loops and routes. The system supports simple interfaces for systematically extracting and exploring loops and routes, which can be used by systemic designers in identifying the "areas of intervention" within a complex system, empowering organized reasoning on CLDs and improving the related decision-making processes.
Tool URL: **http://gmql.eu/cld-explorer.**

Keywords

Systemic Design, Causal Loop Diagrams, Modeling Tool, Data Analytics, Graph Databases

1. Introduction

Systemic Design is driven by the ambitious objective of addressing complex problems in terms of "relationship and global dynamics", rather than isolated components. An important instrument of systemic design is the description of complex systems' dynamics by means of Causal Loop Diagrams (CLDs, [1]). Nodes represent *variables* describing factors causing or affecting the problems; most variables express generic concepts. Directed edges between nodes emphasize their mutual influence; a positive polarity occurs when the growth of the source variable causes the growth of the destination variable, and a negative polarity occurs when the growth of the source variable determines the reduction of the destination variable.

In a companion paper [2], we showed that CLDs' analysis takes advantage of exploring causal *feedback loops*, i.e., cyclic paths looping from one variable back to the same variable, and *causal routes*, consisting of paths of edges connecting two nodes, denoted as source and destination. Loops are characterized as *balancing (B)* or *reinforcing (R)* - simply by counting edges with negative polarity along a loop, and denoting a loop as balancing if the count is odd, reinforcing if the count is even. Similarly, causal routes are associated with *increasing* and *decreasing* polarity - again by counting edges with negative polarity along a route, and denoting a route as increasing when the count is even, decreasing when the count is odd.

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anna.bernasconi@polimi.it (A. Bernasconi); stefano.ceri@polimi.it (S. Ceri); francesco.invernici@polimi.it (F. Invernici); chiara.leonardi@hotmail.com (C. Leonardi); lauradaniela.maftei@mail.polimi.it (L. D. Maftei)
0000-0001-8016-5750 (A. Bernasconi); 0000-0003-0671-2415 (S. Ceri); 0009-0002-5423-6978 (F. Invernici)

2. Overview

We designed and implemented a prototype of *Causal Loop Diagram Explorer*, a web-based application designed for the interactive construction and analysis of CLDs. Figure 1 illustrates the application's workflow diagram and sketches some of the pages of the web-based user interface.

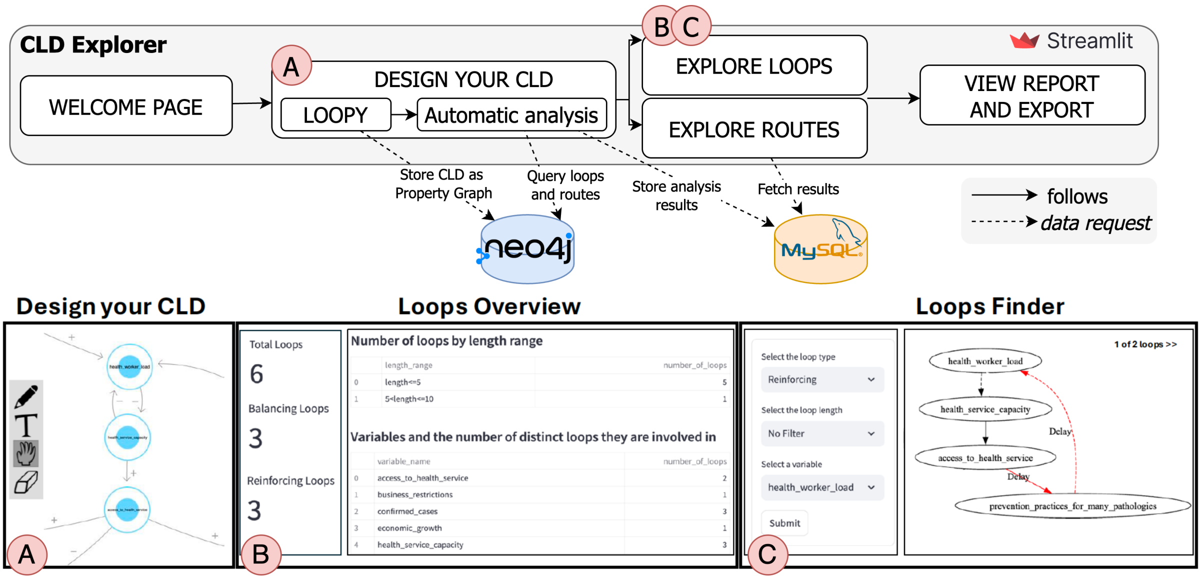

Figure 1: Workflow diagram (top) and user interface (bottom) of *CLD-Explorer*. Panel (A) shows a portion of a use case drawn in LOOPY. Panels (B) and (C) display the analysis of the FeedbackLoops of the use case. In Panel (C), a FeedbackLoop of the input CLD is extracted, matching the set filters. *CLD-Explorer* offers a similar interface for the CausalRoutes analysis.

The workflow consists of four phases, introduced by a welcome page, which can be progressively executed. Each phase is associated with a Web page; pages can be accessed from the sidebar of the interface. In the welcome page, a brief guide with all the main elements and characteristics of CLDs is presented to the user. The *Design your CLD* page (Figure 1A) embeds LOOPY [3], a simple open-source tool for CLD design. LOOPY lets users draw variables as nodes and model their interactions as positive or negative arrows between them.

After adding and editing all elements, it is necessary to export a LOOPY diagram and save it for reuse. The loading mechanism verifies that the diagram is a valid CLD and uploads the CLD to a Neo4j [4] graph database, used as an intermediate artifact for searching all interesting loops or routes - as querying for chains connecting pairs of nodes (or a node to itself) using graph databases is both very simple and efficient. All loops and routes extracted after executing this search are then stored in a MySQL [5] relational database for supporting further fast analytics.

In the *Explore Loops* (Figure 1B-C) and *Explore Routes* pages (not shown), users can browse, select, and visualize these CLD features using interactive forms. To help search, pages initially present statistics about the number of loops/routes existing in the CLD; loops are divided into balancing and reinforcing. The page also includes the list of all nodes of the CLD, and the total number of loops/routes in which the node is involved (see Figure 1B). Users can search for specific loops/routes by selecting, within a mask, the starting node, the polarity (balancing or reinforcing), the length (see Figure 1C), and choose to save them for inclusion in a final report. Loops/routes can also be paired for direct comparison.

At the end of the explorative process, users can find an exportable report of their activities in the *View Report and Export page*, which offers a visual summary of the features they have discovered in the process. Each report includes all the loops/routes that were saved during the current design session.

3. Implementation

The system combines a typical stack of web technologies with the Neo4j [4] property graph database, to automatically extract quantitative characteristics of CLDs. The user interface is implemented with Streamlit [6], a low-code Python web framework, and proposes a process organized in pages for constructing and exploring the CLDs, as shown in Figure 1.

According to the metamodel discussed in [2], the Neo4j graph database represents the VARIABLES and CAUSALITYLINKS; each causality link is directed from a "tail" variable to a "head" variable, hence the Neo4j graph consists of uniquely identified nodes (with their names) and directed edges (with their polarity). We then use Cypher queries [7] to extract all FEEDBACKLOOPS (identified as a chain of nodes connecting an initial variable back to itself) and all CAUSALROUTES (as a chain connecting any two nodes); the output of the query is, in both cases, a list of intermediate node identifiers and binary attributes indicating either balancing/reinforcing for loops or increasing/decreasing for routes. This operation is almost instantaneous for CLDs of reasonable sizes, up to hundreds of nodes and thousands of edges.

The extracted characteristics are then uploaded to an instance of MySQL [5] to quickly enable the following exploratory pages of the analysis without recomputing them.

Limitations. The current version of the tool presents several limitations. First, integration with LOOPY is not seamless, as users must manually export and paste the diagram link to begin exploration. Additionally, starting a new session or exploring a different CLD requires the user to refresh or reopen the page, which disrupts the user-interaction workflow. Finally, while users can explore built-in diagrams, previewing custom CLDs before loading them into the system is not yet supported.

4. Evaluation on predefined use cases

The tool includes three predefined examples, whose CLDs can be loaded at any time. We consider the COVID-19 and the Fashion use cases presented in [2], and the complete CLD designed in [8], describing the adoption of renewable energy technology in Australian hotels, the largest, most documented CLD that we found in the literature. For these predefined cases, Table 1 reports the number of VARIABLES, CAUSALITYLINKS, FEEDBACKLOOPS, and CAUSALROUTES.

Use cases	VARIABLES	CAUSALITYLINKS	FEEDBACKLOOPS		CAUSALROUTES	
			num	max-length	num	max-length
(a)	18	27	6	6	337	10
(b)	31	68	442	20	89849	21
(c)	42	74	143	25	62171	29

Table 1
For each use case: **(a)** COVID-19 [2]; **(b)** Fast fashion [2]; and **(c)** RET adoption [8], we report the number of variables and causality links, and the number of loops and routes with their maximum length.

The CLD-Explorer can be used to support a case-based analysis for extracting quantitative insights that complement the visual modeling of CLDs. This proved particularly valuable in making explicit the structural properties of causal models that are often left implicit in qualitative practice. For example, in the case study on the environmental footprint of the fashion industry, the CLD was constructed with the aim of exploring the feedback structures surrounding the *fashion industry footprint* variable, which was found to participate in 359 feedback loops and initiate 875 distinct causal pathways. Interestingly, the variable *purchases of new clothes* appeared in an even greater number of loops—411 in total—underscoring its pervasive involvement across the system and highlighting the centrality of consumer behavior in shaping sustainability dynamics within the sector.

Figure 2 shows a comparison of alternative routes between *purchases of new clothes* and *consumers' desire to buy* (i.e., with reversed polarity). The first is increasing, simply going through *clothing*

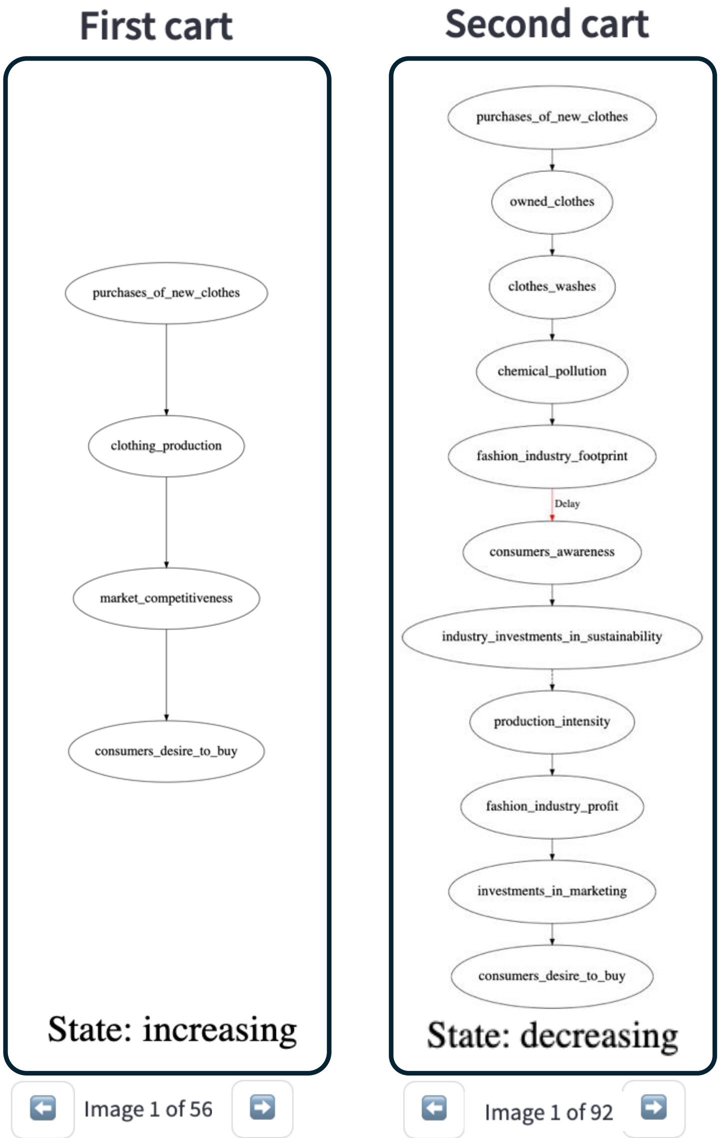

Figure 2: Comparison of alternative routes in Fast fashion CLD.

production and *market competitiveness*. The second, instead, is decreasing and takes a wider perspective, as the purchase of new clothes leads to increase of owned clothes and washes, resulting into chemical pollution and industry footprint; however –with some delay– this causes a raise in consumers awareness and consequent investments in sustainability, thereby decreasing (note the dashed arrow) production intensity. Here, profits diminish, decreasing marketing actions and consumers' desire to buy. The tool allows for placing pairs of loops/routes side by side (in carts) for visual comparison.

The application also enabled the comparison of structural positions of different actors. A clear asymmetry was observed between *consumer behavior* and *government policies*; while the former is connected to the footprint through several short/direct paths, the latter — despite being involved in many more distinct routes — tends to influence the system via longer chains involving ≥ 8 intermediate variables. This suggests a more mediated and potentially less immediate systemic effect of governmental action when compared to consumer-driven dynamics.

5. Conclusions

A parallel can be drawn between the CLDs formalism and the i^* framework [9, 10]. More precisely, the first is focused on system dynamics, feedback loops, and cause-effect relationships, whereas the second one targets goal-oriented modeling of stakeholders and their intentions. While the i^* community has produced artifacts and tools for modeling along the i^* model [11], CLDs so far are supported by basic tools such as LOOPY [3]. Our prototype is a first step towards the development of a platform for supporting systemic designers.

Preliminary workshops with expert systemic designers have been used to understand their needs for analytical support in their daily practice; our prototype supports their main requirements related to searching all loops and routes and characterizing their properties. We plan to extend the CLD-Explorer platform by turning it into a more user-friendly tool for supporting the design process, i.e,. various versions of the same CLD, thereby modeling the same system across different design stages and allowing the comparison of successive or alternative versions. Classical queries comparing versions will be used to monitor how models evolve—e.g., how the introduction of new variables or links leads to new feedback loops or reveals causal routes. The platform will support robustness analysis, help reveal structural vulnerabilities and redundancies, and foster interpretability by tightly linking visual representation and systemic logic. The design process will also be supported by a new UI for inputting CLDs.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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