Ownership Graphs and Reasoning in Corporate Economics

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Abstract
In corporate economics, the use of *company ownership graphs* has become instrumental in solving many critical problems for central banks, financial regulators, and national statistics agencies. In particular, National Central Banks (NCBs) treat and, sometimes, own company data for their key institutional goals in a variety of fields, e.g., *anti-money laundering*, or *economic and statistical research*. This paper aims at leveraging our experience with Automated Reasoning in Banca d'Italia, focusing on four real use cases typical in the financial domain: (i) *Integrated Ownership*, (ii) *Company Control*, (iii) *Ultimate Controller*, and (iv) *Close Links*. For each problem, we offer a formalization, providing practical and real-world examples based on Bank of Italy's company ownership graph. Finally, we express each problem in the form of compact and efficient deductive rules in the Vadalog language, allowing us to obtain a trade-off between computational time and expressive power compared to standard query languages.

1. Introduction

Company ownership graphs are critical items in corporate economics, with central banks, financial regulators, and national statistics agencies relying on them heavily. The essential notion in these graphs is ownership: edges are ownership links labelled with the proportion of shares a business or person x owns of a company y, while nodes are companies and people. Company graphs are employed in various contexts, including calculating a company's total ownership of another, (chains of) control relationships, collusion phenomena, collateral eligibility, etc. National Central Banks (NCBs) deal with company data in order to achieve key institutional goals in a variety of fields, including *banking supervision*, *credit-worthiness evaluation*, *anti-money laundering*, *insurance fraud detection*, *economic and statistical research*, and more. The Bank of Italy, as a supervisory authority, is intensely interested in studying and extracting valuable insights from the corporate ownership network. The Italian Central Bank owns the database of Italian companies, provided by the Italian Chambers of Commerce. It contains high-quality, fine-grained data of Italian *non-listed* companies, including information such as legal name, legal address, incorporation date, shareholders, the composition of the company board, historical data, and many others. Despite the database's vastness and depth, it has been shown [1] that many of the issues of interest are difficult to tackle with standard query languages. However, they can be succinctly expressed as reasoning rules.

Published in the Workshop Proceedings of the EDBT/ICDT 2022 Joint Conference (March 29-April 1, 2022), Edinburgh, UK
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Contribution and Overview[1]. In this paper, we illustrate four problems, i.e. *Integrated Ownership*, *Company Control*, *Ultimate Controller* and *Close Links*. These are recurrent problems in the financial domain of company ownership. For each such problem, we report the commonly accepted definition, and we present and describe a possible formalization, in the form of deductive rules in the Vadalog language, that allows both to have a compact encoding of the problem and to address an efficient solution to real and concrete problems and interests for our Institution. The remainder of the paper is organized as follows. In Section 2 we introduce the background of company ownership graph representations, as well as the Vadalog approach. In Section 3 we present the *Integrated Ownership* concept. In Section 4 we define and give rules for the *Company Control* problem. Section 5 describes the formalization for the *Ultimate Controller* problem, while in Section 6 we investigate the *Close Links* use case. Section 7 concludes the paper.

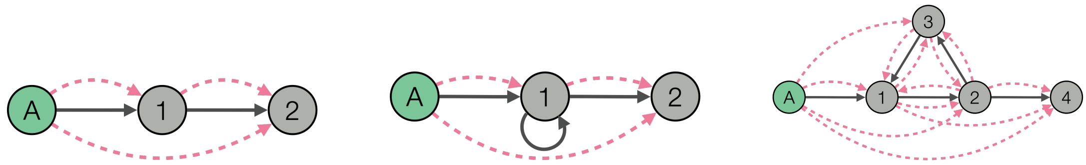
2. Preliminaries

To present the use cases of interest, let us introduce some general notions that will be used throughout the paper.

Definition 2.1 (Company Ownership Graph). A *Company Ownership Graph* $G(N, E, w)$ is a directed weighted graph, such that:

- $N = \{p_0, \ldots, p_n\}$ is a set of nodes;
- E a set of edges of the form (i, j), from node i to node j;
- $w : E \to \mathbb{R}$, $w \in (0, 1]$ is a total weight function for edges.

[1]The views and opinions expressed in this paper are those of the authors and do not necessarily reflect the official policy or position of Banca d'Italia.



(a) A simple indirect ownership.

(b) Indirect ownership with a self-loop.

(c) Indirect ownership with a strongly connected component.

Figure 1: Cases of integrated ownership. Nodes with letters are people, nodes with numbers are companies, solid edges are direct ownership relationships while dashed pink edges represent integrated ownership.

The weight $w(p_i, p_j)$ is the weight of edge (i, j); an edge (i, j) exists if and only if $w(p_i, p_j) \neq 0$; furthermore self-loops are allowed, i.e. $i = j$. In our context, nodes represent companies or people, edges (i, j) represent *ownership* with share $w(p_i, p_j)$. For ease of representation, we denote $w(p_i, p_j) = w(i, j)$.

In this paper, we formalize the *Integrated Ownership*, the *Company Control*, *Ultimate Controller* and *Close Links* problems by encoding them as sets of reasoning rules in the VADALOG language. VADALOG is based on the Warded Datalog$^{\pm}$ family that generalizes Datalog by allowing the existential quantification in the rule head while guaranteeing decidability and tractability in the presence of existential quantification and recursion. A *rule* is a first-order sentence of the form $\forall \bar{x} \forall \bar{y} (\varphi(\bar{x}, \bar{y}) \rightarrow \exists \bar{z}\, \psi(\bar{x}, \bar{z}))$, where φ (the *body*) and ψ (the *head*) are conjunctions of atoms. For brevity, we omit universal quantifiers and denote conjunction by comma. The semantics of a set of rules is defined by the well-known CHASE procedure.

In the reasoning rules, atoms can be either extensional (EDB) when they are immediately available in data stores (e.g. relational databases, graph databases, NoSQL stores, RDF stores, etc.) or intentional (IDB) when they are generated when needed as a consequence of a reasoning process. In the formalizations that will follow in this work, we adopt the convention of colouring extensional atoms in ***blue*** and intensional ones in ***red***.

3. Integrated Ownership

In the realm of complex global economic systems, it appears evident that companies could not be considered as stand-alone entities. The concept of *Integrated Ownership* helps quantify the ownership involvement of companies in complex economic structures such as networks and conglomerates. While the simple notion of ownership identifies the direct connection from a company x to a company y, the *Integrated Ownership* encompasses the accumulated ownership from a company x to a company y, considering all the current ownership along with all direct and indirect links. The *Integrated Ownership* problem has been extensively investigated in the literature, as in the work of [2], and various approaches can be found. As mentioned in a recent work [3], one could interpret *Integrated Ownership* as a notion of cumulative flow from one target company to another. Another way to see this problem is to think at the cash flow when dividends of a company y are distributed backwards and recursively to all its shareholders. The actual percentage of the dividends received by a shareholder x, part of the same ownership structure of y, is equal to the accumulated ownership from a company x to a company y.

Figure 1 shows three cases of ownership graphs. Figure 1a shows that company A receives dividends from company 1 proportionally to the owned shares. In turn, company 1 also receives dividends from the profit of company 2. Then, such last dividends are distributed again among all the shareholders of company 1, which in the example is only A. Therefore, A will eventually receive a percentage of company 2's dividends as well, and it is indicated as the dashed pink edge from A to 2. A more interesting case is shown 1b. The number of shares that firm 1 holds of itself (i.e., the self-loop in the ownership graph) are, de facto, removed from those available on the market. Therefore, the real percentage of shares of company 1 held by A is greater because the number of shares effectively available on the market is less than 100%. The example in Figure 1c is an even more complex scenario. In fact, the ownership relationships realize a strongly connected component, i.e., a cyclical structure, that behaves like self-loops do: it increases the actual amount of shares held by the companies involved in the cycle and, therefore, of all the accumulated ownership relationships (e.g., $A \rightarrow 2$, $A \rightarrow 3$, $A \rightarrow 4$) that flow through the cycle.

3.1. Definitions of Paths and Convergence

Integrated Ownership is at the basis of all the subsequent use cases that we will present in the remainder of the paper, such as company control. A possible approach for the *Integrated Ownership* computation is the one that aims at formalizing the definition of *directed paths* in the company ownership graph. This allows defining *Baldone ownership*, which we will also refer to as *Integrated*

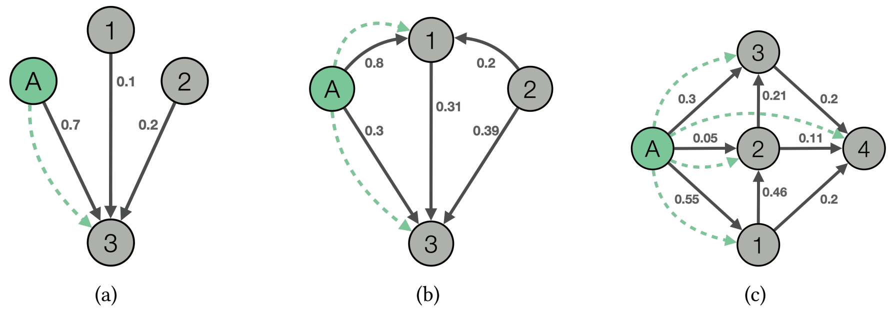


Figure 2: Sample ownership graphs where A, directly and indirectly,controls other nodes. Nodes are entities; solid edges are direct ownerships; dashed green edges are control relationships.

Ownership. First, let us define the *Directed Path*.

Definition 3.1 (Directed Path)**.** A *directed path* P is a finite or infinite sequence $[p_1, \dots, p_k]$ of nodes in N such that $(i, i+1) \in E$ for every $i = 1, \dots, n$. For a node $p_i \in N$, we call $\delta^+(i)$ the set of edges of E incoming into p_i and $\delta^-(i)$ the set of edges of E outgoing from p_i. We define the *weight* $w(P)$ of a path P as $w(P) = \Pi_{(p_i,p_j)\in P} w(p_i, p_j)$.

A second step is the definition of the set of directed paths whose weight is higher than a fixed ϵ threshold. This allows restricting the set of interests of all existing directed paths. To this purpose, we introduce the $\epsilon-$*Baldone path*.

Definition 3.2. An $\epsilon-$Baldone path P from s to t is a path $[s, p_1, \dots, p_k, t]$ such that $s \neq p_i$ for $i = 1, \dots, n$ and $w(P) > \epsilon$, with $\epsilon \in \mathbb{R}^+$ and $0 < \epsilon \leq 1$. Furthermore, we denote the weight of an $\epsilon-$Baldone path as $w_\epsilon(P)$.

We are now ready to define the ϵ-*Baldone ownership*, i.e., the summation of all the possibly infinite ϵ-Baldone paths from s to t.

Definition 3.3. The ϵ-*Baldone ownership* of a company s on a company t in a graph G is a function $\mathcal{O}^G_\epsilon(s,t)$: $(s,t) \to \mathbb{R}$ defined as $\sum_{P_i \in B_\epsilon} w_\epsilon(P_i)$, where B_ϵ is the set of all possible ϵ-Baldone paths from s to t.

Its generalization, the *Baldone ownership* is obtained by letting $\epsilon \to 0$ in the definition of ϵ-*Baldone ownership*. This latter is our *Integrated ownership*.

Definition 3.4. The *Baldone ownership* of a company s on a company t in a graph G is a function $\mathcal{O}^G(s,t)$: $(s,t) \to \mathbb{R}$ defined as $lim_{\epsilon\to 0}\mathcal{O}_\epsilon(s,t)$.

The convergence of *Baldone ownership* or, in the following, *Integrated Ownership* is essential its computation. We give two theorems that assure their convergence is guaranteed: (i) if it converges for G if $\mathcal{O}^G(s,t)$ converges for all $(s,t) \in E$, and (ii) if certain topological conditions are present that are peculiar to the company ownership graphs we dealt with.

Definition 3.5. The *Baldone ownership* $\mathcal{O}^G(s,t)$ of a company s on a company t *converges* if $\mathcal{O}^G(s,t) \leq 1$.

Theorem 3.1. For a given company ownership graph $G(N,E,w)$, the Baldone ownership $\mathcal{O}^G(i,j)$ converges for all $(i,j) \in E$ if and only if for each strongly connected component S of G, there exists at least one node $p_i \in S$ such that $\sum_{(j)\in\delta^+(p_i)} w(i,j) \leq 1$.

The proof of the theorem and further insights are beyond the scope of this paper.

3.2. The Matrix Approach

The computation of the *Baldone ownership* of a company s over t can be obtained in closed-form by approximation over powers of adjacency matrix W. It is known that the r-power of W gives all the path of length r of the graph G; for example, in cell i,j of matrix A^2 we have the sum of the weight of path of length 2 and so on. If we sum all the matrices, we have the sum of the accumulated ownership of all the paths in each cell leading from node i to node j:

$$W + W^2 + W^3 + \ldots = \sum_{i=1}^{n-1} W^i \quad (1)$$

We have to exclude initial cycles; our *Baldone ownership* of company s over company t can be written as:

$$\mathcal{O}^G(s,t) = w(s,t) + \sum_{k\neq s} \hat{w}(s,k)w(k,t) \quad (2)$$

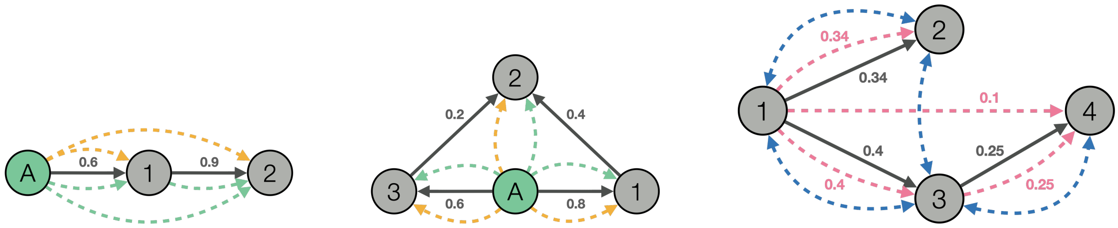
As in [2], Equation 2 can be manipulated into the following form:

$$\mathcal{O}^G = (I - diag(\mathcal{O}^G))W + \mathcal{O}^G W \quad (3)$$

that can be solved with respect to $\mathcal{O}^G$ as:

$$\mathcal{O}^G = (diag((I-W)^{-1})^{-1}(I-W)^{-1}W \quad (4)$$

More details can be found in [2].



(a) Ultimate Control in a control chain.

(b) Ultimate Control with two intermediary controlled company.

(c) Close Links scenario.

Figure 3: Sample ownership graphs with Ultimate Control and Close Link scenarios. Nodes are entities; solid edges are direct ownerships; dashed edges represent different types of relationships: green stands for control; yellow for ultimate control; pink for integrated ownership and blue for close links relationships.

3.3. The Reasoning Approach

Although the matrix approach provides a compact and elegant formulation for calculating the *Integrated Ownership*, it relies on matrix multiplication and inversion operations. These operations are known [4, 5] to become more and more computationally expensive as the matrix size increases. Ownership graphs collect information of many companies, typically at a national and even at an international level, so the matrix approach may be unsuitable in many cases. For this reason, we provide a more computationally efficient approach based on reasoning rules while keeping the problem formulation compact.

Definitions 3.1-3.4 can be formalized as reasoning rules in the VADALOG language, as follows:

$$\begin{aligned} \textit{\textbf{Own}}(x, y, w), w > \epsilon, v = \textit{sum}(w), \\ p = [x,y] \rightarrow \textit{\textbf{IOwn}}(x, y, v, p). \end{aligned} \quad (1)$$

$$\begin{aligned} \textit{\textbf{IOwn}}(x, z, w_1, p_1), \textit{\textbf{IOwn}}(z, y, w_2, p_2), \\ p = p_1|p_2, \textit{\textbf{BPath}}(p, v, \epsilon), v = \textit{sum}(w_1 \times w_2), \\ \rightarrow \textit{\textbf{IOwn}}(x, y, v, p). \end{aligned} \quad (2)$$

In Rule 1, whenever the amount of shares of company y held (through direct ownership) by x exceeds the threshold ϵ, then path p is a valid ϵ-Baldone path and v is the weight of the direct path p from x to y. Instead, in Rule 2, we can compose the integrated ownership from x to z and the one from z to y if for the entire path p (the symbol "|" denotes the path concatenation operator), from x to y, the Definition 3.3 holds. The integrated ownership is increased by the product of the two paths weights (i.e. $w_1 \times w_2$). The extensional atom *BPath* represents whether Definition 3.2 holds.

4. Company Control

Banks, financial intelligence units, financial intermediaries, regulatory and supervisory authorities, such as Central Banks, are all concerned with the company control problem. It entails determining who takes decisions in a vast corporate network, i.e., who has the majority of votes for each individual firm as, it is a generally accepted assumption [2] that, there exists a one-to-one correspondence between voting rights and company shares.

Control can be direct or indirect. A *direct control* occurs when x directly owns the majority of the shares of y (i.e., it is a shareholder of y). An *indirect control* occurs when x controls, directly or indirectly, a group of companies that collectively own the majority of the shares of y. This latter is a recursive definition of the company control and makes its computation by no means trivial.

A formulation of the company control problem that follows is a widely accepted model, and it has been already introduced in the logic and database literature [6] and also adopted in technical contexts [7].

Definition 4.1 (Company Control)**.** A person (or a company) x controls a company y, if: (i) x directly owns more than 50% of x; or, (ii) x controls a set of companies that jointly (i.e., summing their shares), and possibly together with x itself, own more than 50% of y.

In Figure 2a, a straightforward case of direct control is shown: node A directly owns more than the majority of the shares of company 3. In Figure 2b, through the direct possession of 30% of the share of company 3, A cannot exert control. However, A directly controls company 1, which owns 31% of company 3. Together with the direct share $A \rightarrow 3$, A therefore also controls 31% owned by company 1, totalling 61% of the share of company 3 controlled by A. The case shown in Figure 2c is even more complex. A controls company 1 by directly owning more than 50% of its total equity. With the contribution of the share that 1 owns of 2, A acquires indirect control over company 2. Also, A indirectly controls company 3 by contributing shares owned by 2. Finally, A controls 4 even though it does not own any direct share. In fact, the sum of the shares of 4 owned b 1,2 and 3 is greater than 50%. Since A controls the three intermediate companies, it has the majority of the decision-making power over 4.

Definition 4.1 can be formulated a set of compact VADALOG reasoning rules.

$$\textit{Company}(x) \rightarrow \textit{Control}(x, x) \tag{1}$$

$$\begin{aligned} &\textit{Control}(x, y), \textit{Own}(y, z, w), \\ &v = \textit{sum}(w, \langle y \rangle), v > 0.5 \\ &\rightarrow \textit{Control}(x, z) \end{aligned} \tag{2}$$

The given formulation is recursive. In the base case, we assume that every company has control on itself (Rule 1) [2]. Then, inductively, we define the control of x on z by summing the shares of z owned by companies y, over all companies y controlled by x (Rule 2).

The formalization of the company control problem as a VADALOG reasoning task has been tested for performance both on real data (i.e. the Italian company graph) and synthetic graphs [8].

5. Ultimate Controller

Since control over a firm can also be obtained indirectly, it is not always the case that a firm's parent is necessarily independent in exerting control over the firm. In the financial world, in fact, there exist situations (e.g., typically for business groups) of chains of control in which a single individual or firm resides on top of it. This subject is defined as the *Ultimate Controller* for all the companies of the chain. In fact, it is the only one who is able to push his or her own decisions independently across the underlying firms in the chain of control.

In the economic literature [9], the *Ultimate Controller* problem is formally defined as follows:

Definition 5.1 (Ultimate Controller)**.** Given a company y, an investor x (either a company or individual) is said to be the *ultimate controller* of y if: (i) x is the head of a chain of companies among which there is y; and, (ii) x directly or indirectly controls all the companies in the chain without being controlled by any other investor.

Two examples of the ultimate controller relationships are shown in Figures 3a and 3b. In both scenarios, individual A has direct or indirect control over all other firms. In Figure 3a, company 1 directly controls company 2 but is not its ultimate controller. In fact, company 1 is part of the chain of control (i.e., $A \rightarrow 1 \rightarrow 2$) but is not at the top of that chain. Therefore, the ultimate controller in this scenario is the shareholder A since any other company or person does not control it. In Figure 3b, A realizes control over company 2 through the shares held by companies 1 and 3 over which A exerts direct control. A is the head of the three simple control chains (i.e., $A \rightarrow 1$, $A \rightarrow 3$, $A \rightarrow 2$), so he also assumes the role of ultimate controller. In general, whenever an individual has control over a firm, it is also its ultimate controller. In fact, by definition, no natural person can be owned, in any percentage, by another entity in the graph and neither controlled.

The formalization of the ultimate controller problem can be given starting from the ***Control*** intensional relationships derived with the program shown in Section 4.

$$\textit{Control}(x, y) \rightarrow \textit{Controlled}(y) \tag{1}$$

$$\textit{Control}(x, y),\ \textit{not}\ \textit{Controlled}(x) \rightarrow \textit{UltC}(x, y) \tag{2}$$

We collected all companies y that appears as controlled company in any control relationships (Rule 1). Then, we define the ultimate controller x for the firm y as the one that has the control over y but, in turn, it is not controlled by any other company (Rule 2).

6. Close Links

In the context of creditworthiness evaluation, the problem of collateral eligibility takes on particular relevance. It involves calculating the risk of granting a specific loan to a firm x that is backed by collateral issued by another company y. The Eurosystem provides credit only against adequate collateral, i.e., only if eligible [10]. European Central Bank regulations [11] for monetary policy define a set of criteria that National Central Banks must adopt to assess the eligibility of specific assets. For instance, for accessing the credit, National Central Banks of the Eurosystem do not allow a counter-party x to submit a collateral issued by a guarantor entity to which it is linked via a *close links* relationship. A *close links* situation is defined as follows:

Definition 6.1 (Close Links)**.** A counter-party x is in a *close link* relationship with its guarantor y if: (i) the total, either direct or indirect, ownership of y held by x is above 20% of the equity of x; or, the vice-versa, (ii) the total accumulated ownership of x held by y is above 20% of the equity of y; or finally, (iii) a common third party z owns, either directly or indirectly, 20% or more of the equity of both the counter-party x and the guarantor y.

The definition is based on the concept of total ownership that a company x owns both directly and indirectly of another one. That is the definition of *integrated ownership* that we introduced in Section 3.

A sample ownership graph for illustrating the *close links* scenario is shown in Figure 3c. We consider the

[2] This formalization of the base case is slightly different from the natural definition but commonly assumed in the literature as it is more compact and formally equivalent.

pair of firms 1 and 2. It exists an arc of direct ownership that shows the possession of shares of company 2 from part of company 1. Not being there other paths of ownership between these two companies, the amount of share directly owned by company 1 is equivalent to the total amount of share that it owns of company 2 (i.e. integrated ownership). Since the total quota exceeds the threshold of 20%, in agreement with the given definition, we can assert that companies 1 and 2 are in relation of close links. The same considerations apply for the pairs of companies 1-3 and 3-4. Companies 2 and 3 are also in a close link relationship because of the third point of the definition. In fact, a common third-party (i.e. company 1) owns, considering all the possible direct or indirect paths, more than 20% of the total shares of both the two companies. The Figure 3c also shows that close links relationships are undirected.

We formalize the *close links* problem as a set of deductive rules whose input (i.e. ***IOwn***) is directly taken from the reasoning rules in Section 3.

$$\textbf{\textit{IOwn}}(x,y,q), x \neq y, q \geq 0.2 \rightarrow \textbf{\textit{CLinks}}(x,y) \quad (1)$$

$$\textbf{\textit{IOwn}}(y,x,q), x \neq y, q \geq 0.2 \rightarrow \textbf{\textit{CLinks}}(x,y) \quad (2)$$

$$\begin{aligned} &\textbf{\textit{IOwn}}(z,x,q), \textbf{\textit{IOwn}}(z,y,w),\\ &\quad x \neq y, q \geq 0.2, w \geq 0.2\\ &\rightarrow \textbf{\textit{CLinks}}(x,y), \textbf{\textit{CLinks}}(y,x) \end{aligned} \quad (3)$$

There is a two-way correspondence between the reasoning rules shown above and the points in the Definition 6.1, hence the interpretation of the rules is quite straightforward. However, with Rule 1 we derive the existence of a close links relationship between x and y if the total (i.e. integrated) ownership of y held by x is equal or greater than 20%. The second rule is symmetrical to the first one and generates a close link relationship between x and y if the accumulated ownership of x held by y is more than 20%. Finally, Rule 3 considers the last described scenario in which a common third party z owns (either directly or indirectly) more than 20% of both x and y.

7. Conclusion

Company ownership graphs are helpful in many recurrent problems in the financial domain. One interesting problem is the *Integrated Ownership* problem, where the goal is to determine the accumulated ownership in complex economic entities. In the *Company Control* problem, the focus is on finding which entity controls a company of interest. An even more challenging problem is the *Ultimate Controller* problem, where it is requested to individuate the head of a chain of companies. The *Close Links* computation between two entities, the counter-party, and the guarantor, allows the evaluation of collateral eligibility. In this paper, we first described the background, the main definitions, and examples to provide an adequate overview of each of the above problems. Then, we formally characterized each problem, and we explained the efficient and compact encoding in the form of deductive rules in the VADALOG language. The approach based on reasoning rules showed great potential and ease of adoption in the financial domain.

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