An ontology of organizational knowledge

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Abstract. *One of the main open problems in knowledge engineering is to understand the nature of organizational knowledge. By using a representation of directed graphs in terms of first-order logical structures, we defined organizational knowledge as integrated relevant information about relational structures. We provide an algorithm to measure the amount of organizational knowledge obtained via a research and exhibit empirical results about simulations of this algorithm. This preliminary analysis shows that the definition proposed is a fruitful ontological analysis of knowledge management.*

1. Introduction

According to [1], Knowledge management (KM) has produced a bunch of definitions that helps us to understand organizational knowledge, the kind of knowledge that we find in organizations. Nonetheless, there is no universal approach to the different kind of definitions available. We are in need of an ontological analysis of organizational knowledge that is capable to unify the different notion of knowledge relevant to bussiness.

Indeed, organizational knowledge has been thought according to four fundamental types [3, 4]. The first one we can call the *mental view of knowledge*. According to this standpoint, knowledge is a state of mind. In the mental view to manage knowledge involves to regulate the provision of information controls and to improve individuals capacity of applying such a knowledge. The second view is the *objectual view of knowledge*. Here knowledge is an object, something that we can store and manipulate. In the objectual approach manage knowledge becomes a process of stock managing, in which we could control the offers and the demands of individuals as parts of an integrated process inside a company. To take knowledge as a procedural phenomenon of information is the third approach, which we can call the *procedural view of knowledge*. In the procedural perspective knowledge becomes a process of applying expertise, so to manage means to manage the flows of information, such as creation process, conversion techniques, circulation processes and carrying out processes. The fourth perspective is the *credential view of knowledge*. In this approach knowledge is a credential for accessing information. In this case, KM focus on how you manage the credentials to access and what you expect to retrieve, granting the content as the result of a process.

The credential view of knowledge is the standard approach that has been applied in companies nowadays [5]. KM faces knowledge as the potential of influencing actions. By doing so companies consider KM as a process of granting the right competences to the chosen individuals. The focus is to provide the specific know-how to the realization of the processes and to grant that every processes has its correspond knowledge unit correlated.

In this paper we provide an logical method to quantify knowledge that can be used in all the four views of organizational knowledge and present computational results about them all. Quantitative indicators of knowledge can create benefits such as decreasing operational cost, product cycle time and production time while increasing productivity, market share, shareholder equity and patent income. They can drive decisions to invest on employees skills, quality strategies, and define better core business processes. Moreover, if applied to the customers, quantitative indicators can create an innovative communication platform, where the information of the clients can be quickly collected and processed into relevant decision indicators in specific terms such as abandoning one line of product, on the one hand, and investing, on the other [6, 7].

One way to unify this different approaches to KM is to outline a minimal ontology of business processes, in a Quinean sense. According to Quine, as it is well known, "to be is to be the value of a variable" [8]. In other words, ontology is the collection of entities admitted by a theory that is committed to their existence. In the present context, we call minimal ontology the ontology shared by every theory that successfully describes a processes as a organizational one. Our fundamental idea is to define organizational structures, using the general concept of first-order logical structure (Section 2). Thus, we propose a mathematical definition of information about organizational structures, based on the abstract notion of information introduced here for the first time (Section 3). The next step is to conceive organizational knowledge as justified relevant information about organizational structures (Section 4). From this approach we formulate an algorithm and simulate them (Section 5).

2. Organizational structures

We begin by some usual definitions in logic - more details can be found in [9]. The first one is associated to the syntax of organizational structures.

Definition 2.1. *A* signature *is a set of symbols $S = C \cup P \cup R$ such that $C = \{c_1, \dots, c_k\}$ is a set of* constants*, $P = \{P_1, \dots, P_m\}$ is a set of* property symbols*, $R = \{R_1, \dots, R_n\}$ is a set of* relation symbols*. A* formula *over S is recursively defined in the following way:*

1. *If $\tau, \sigma \in C$, $\rho \in P$, $\delta \in R$, then $\rho\tau$ and $\delta\tau\sigma$ are formulas, called* predicative formulas*;*
2. *If ϕ and ψ are formulas, then $\neg\phi$, $\phi \wedge \psi$, $\phi \vee \psi$, $\phi \rightarrow \psi$ and $\phi \leftrightarrow \psi$ are formulas, called* propositional formulas.

A theory *over S is just a set of formulas.*

Now we recall the general notion of first-order structure.

Definition 2.2. *Given a signature S, a* structure *A over S is compounded of:*

1. *A non-empty set $dom(A)$, called the* domain *of A;*
2. *For each constant τ in S, an element τ^A in $dom(A)$;*
3. *For each property symbol ρ in S, a subset ρ^A of $dom(A)$.*
4. *For each relation symbol δ in S, a binary relation δ^A on $dom(A)$.*

We write $A(\phi) = 1$ and $A(\phi) = 0$ to indicate, respectively, that the formula ϕ is true, false, in the structure A. Besides, we have the usual definitions of the logical operators $\neg\phi$, $\phi \wedge \psi$, $\phi \vee \psi$, $\phi \rightarrow \psi$ and $\phi \leftrightarrow \psi$ on a structure A. In particular, we say that a theory T is *correct* about A if $A(\phi) = 1$ for all $\phi \in T$.

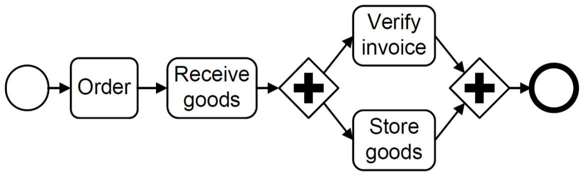

Figure 1. Bussiness process

Definition 2.3. *Given a signature S, an* organizational structure A^T *over S is compounded of a structure A over S, a theory T over S which is correct about A and expresses facts about a business process.*

The idea inside the definition of organizational structures is that they are just logical structures with a fundamental theory about how the processes works. In the proposition 2.1, we show that business processes are indeed special cases of organizational structures.

Proposition 2.1. *Business processes are organizational structures.*

Proof. According to [10], a business processes is a tuple (N, E, κ, λ), in which:

1. N is the set of nodes;
2. $E \subseteq N \times N$ is the set of edges;
3. $\kappa : N \to T$ is a function that maps nodes to types T;
4. $\lambda : N \to L$ is a function that maps nodes to labels L.

Let $L = \{l_1, \ldots, l_k\}$ be the set of labels and $T = \{T_1, \ldots, T_n\}$ be the set of types. Thus, we can define the organization structure A with domain $dom(A) = \{l_i : 1 \leq i \leq k\}$, subsets $T_1, \ldots, T_n$ of L and the relation E. □

In what follows, we write "α" $= \beta$ to mean that the symbol β is a formal representation of the expression α. Besides, X_β is the interpretation of β in the structure A, where X is a set over the domain of A. The elements of the domain $dom(A)$ of a structure A are indicated by bars above letters.

Example 2.1. *Let $S = C \cup P \cup R$ be the signature such that $C = \{i, f, o, r, s, v\}$, $P = \{E, A\}$ and $R = \{L\}$, in which "initial" $= i$, "final" $= f$, "order" $= o$, "receive goods" $= r$, "store goods" $= s$, "verify invoice" $= v$, "is event" $= E$, "is activity" $= A$ and "is linked to" $= L$. In this case, we can define the organizational structure A^T over S below, where $T = \oslash$:*

1. $dom(A) = \{\bar{i}, \bar{f}, \bar{o}, \bar{r}, \bar{s}, \bar{v}\}$;
2. $i^A = \bar{i}$, $f^A = \bar{f}$, $o^A = \bar{o}$, $r^A = \bar{r}$, $s^A = \bar{s}$, $v^A = \bar{v}$;
3. $E^A = \{\bar{i}, \bar{f}\}$ *and* $A^A = \{\bar{o}, \bar{r}, \bar{s}, \bar{v}\}$;
4. $L^A = \{(\bar{i}, \bar{o}), (\bar{o}, \bar{r}), (\bar{r}, \bar{s}), (\bar{r}, \bar{v}), (\bar{s}, \bar{f}), (\bar{v}, \bar{f})\}$.

The organizational structure A^T defined above represents the bussiness process in Figure 1.

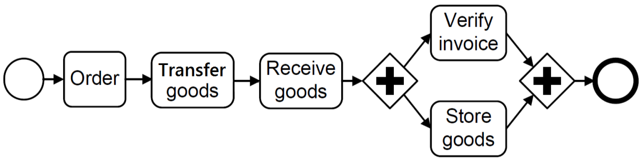

Figure 2. Extended bussiness process

3. Structural information

We turn now to the fundamental notion associated to knowledge, namely, information. The concept of information is polysemantic [11]. In this work we think of information in semantic terms. Since we are going to define a notion of information about organizational structures, we will call it *structural information*. Roughly speaking, the structural information of an organizational structure is the set of insertions and extractions that we need to perform in order to create this structure.

Definition 3.1. *Let A^T be an organizational structure over S. An* insertion *of the symbol ω into A^T is an organizational structure A_i^T such that A_i^T is an structure over $S' = S \cup \{\omega\}$ with the following properties:*

1. *$A_i^T(\tau) = A(\tau)$ for all $\tau \neq \omega$ such that $\tau \in S$;*
2. *If ω is a constant in S, then $dom(A_i^T) = dom(A)$ and $A_i^T(\omega) \neq A(\omega)$, but if ω is a constant not in S, then $dom(A_i^T) = dom(A) \cup \{a\}$ and $A_i^T(\omega) = a$;*
3. *If ω is a property symbol, then $dom(A_i^T) = dom(A) \cup \{a\}$ and $A_i^T(\omega) = A(\omega) \cup \{a\}$;*
4. *If ω is a relation symbol, then $dom(A_i^T) = dom(A) \cup \{a_1, a_2\}$ and $A_i^T(\omega) = A(\omega) \cup \{(a_1, a_2)\}$.*

Example 3.1. *Consider the organizational structure A^T over S from example 2.1. Define the signature $S' = C' \cup P' \cup R'$ equals to S except by the fact that $C' = C \cup \{t\}$, where "transfer goods" $= t$. Thus, the organizational structure A_i^T defined below is an insertion of t into A^T:*

1. *$dom(A_i) = dom(A) \cup \{\bar{t}\}$;*
2. *$t^A = \bar{t}$ and $\tau^{A_i} = \tau^A$ for $\tau \in C$;*
3. *$E^{A_i} = E^A$ and $A^{A_i} = A^A \cup \{\bar{t}\}$;*
4. *$L^{A_i} = L^A - \{(\bar{o}, \bar{r})\} \cup \{(\bar{o}, \bar{t}), (\bar{t}, \bar{r})\}$.*

The organizational structure A_i^T represents the business process in Figure 2.

Definition 3.2. *Let A be an S-structure. An element $a \in dom(A)$ is called* free *for the symbol $\omega \in S$ if there is no constant $\tau \in S$ with $A(\tau) = A(\omega)$ neither a property symbol α such that $a \in A(\alpha)$ and $a = A(\omega)$ nor a relation symbol β such that $(a_1, a_2) \in A(\beta)$ and $a_i = A(\omega)$ for $i \in \{1, 2\}$.*

If δ is a relation symbol, we write $A(\delta)_i$ to denote element a_i of $(a_1, a_2) \in A(\delta)$.

Definition 3.3. *Let A_T be an organization structure over S. An* extraction *of the symbol ω from A^T is a database A_e^T such that A_e^T is an structure over $S' = S - \{\omega\}$ with the following properties:*

1. *$A_e^T(\tau) = A(\tau)$ for all $\tau \neq \omega$ such that $\tau \in S'$;*

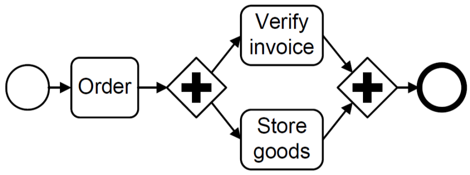

Figure 3. Contracted bussiness process

2. *If ω is a constant not in S, then $dom(A_e^T) = dom(A)$, but if ω is a constant in S, $dom(A_e^T) = dom(A) - \{A(\omega)\}$ in the case of $A(\omega)$ being free for ω, otherwise, $dom(A_e^T) = dom(A)$;*
3. *If ω is a property symbol not in S, then $dom(A_e^T) = dom(A)$, but if ω is a property symbol in S, then $dom(A_e^T) = dom(A) - \{A(\omega)\}$, where $A(\omega)$ is an element free for ω, and $A_e^T(\omega) = A(\omega) - \{A(\omega)\}$;*
4. *If ω is a relational symbol not in S, then $dom(A_e^T) = dom(A)$, but if ω is a relational symbol in S, then $dom(A_e^T) = dom(A) - \{A(\omega)_1, A(\omega)_2\}$, where $A(\omega)_i$ is an element free for ω, and $A_e^T(\omega) = A(\omega) - \{(A(\omega)_1, A(\omega)_2)\}$.*

Example 3.2. *Consider the organizational structure A^T over S from example 2.1. Define the signature $S'' = C'' \cup P'' \cup R''$ equals to S except by the fact that $C' = C - \{r\}$. Thus, the organizational structure A_e^T defined below is an extraction of r from A^T:*

1. *$dom(A_e) = dom(A) - \{\bar{r}\}$;*
2. *$\tau^{A_e} = \tau^A$ for $\tau \in C''$;*
3. *$E^{A_e} = E^A$ and $A^{A_e} = A^A - \{\bar{r}\}$;*
4. *$L^{A_e} = L^A - \{(\bar{o}, \bar{r})\} \cup \{(\bar{o}, \bar{s}), (\bar{o}, \bar{v})\}$.*

The organizational structure A_T^e represents the business process in Figure 3.

Strictly speaking, the organizational structure A_e^T in example 3.2 is *not* an extraction from A^T. For example, $L^{A^e} = L^A - \{(\bar{o}, \bar{r})\} \cup \{(\bar{o}, \bar{s}), (\bar{o}, \bar{v})\}$, which means that L^{A^e} was made of insertions in A_T as well. Since we are interested here in practical applications, we will not enter in such a subtle detail - we delegate that to a future mathematically oriented article. This point is important because it shows that to build new organizational structures from a given one is, in general, a process that use many steps. We explore this idea to define a notion of structural information.

Definition 3.4. *An* update *U^A of an organizational structure A^T over S is a finite sequence $U^A = (A_j^T : 0 \leq j \leq n)$ such that $A_0^T = A^T$ and each A_{j+1}^T is an insertion into or an extraction from A_j^T. An update $U^A = (A_j^T : 0 \leq j \leq n)$ is* satisfactory *for a formula ϕ if, and only if, either $A_n(\phi) = 1$ or $A_n(\phi) = 0$. In the case of a satisfactory update U^A for ϕ, we write $U^A(\phi) = 1$ to denote that $A_n(\phi) = 1$ and $U^A(\phi) = 0$ to designate that $A_n(\phi) = 0$. A* recipient *over in organizational structure A^T for a formula ϕ is a non-empty collection of updates $\mathcal{U}$ of A^T satisfactory for ϕ.*

Example 3.3. *Given the organizational structures A^T, A_i^T and A_e^T from the previous examples. The sequences (A^T, A_i^T) and (A^T, A_e^T) are updates of A^T that generates, respectively, the business processes in Figures 2 and 3.*

Definition 3.5. *Given a recipient $\mathcal{U}$ over a fixed organizational structure A^T, the* (structural) information *of a sentence ϕ is the set*

$$I_{\mathcal{U}}(\phi) = \{U^A \in \mathcal{U} : U^A(\phi) = 1\}.$$

Besides that, for a finite set of sentences $\Gamma = \{\phi_0, \phi_1, \ldots, \phi_n\}$*, the* (structural) information *of* Γ *is the set*

$$I_{\mathcal{U}}(\Gamma) = \bigcup_{i=0}^{n} I_{\mathcal{U}}(\phi_i).$$

Example 3.4. *Consider the recipient* $\mathcal{U} = \{(A^T, A_i^T), (A^T, A_2^T)\}$*. In this case, we have the following:*

1. $I_{\mathcal{U}}(Lrs \vee Lrv) = \{(A^T, A_i^T)\}$;
2. $I_{\mathcal{U}}(Lio) = \mathcal{U}$.

4. Organizational knowledge

Since we have a precise definition of information about organizational structures, we can now define mathematically what is organizational knowledge. The intuition behind our formal definition is that knowledge is information plus something else [12]. To be specific, we defined organizational knowledge as justified relevant information about organizational structures.

Definition 4.1. *Given an organizational structure* A^T *over* $S = C \cup P \cup R$ *such that* $C = \{c_1, \ldots, c_k\}$*,* $P = \{P_1, \ldots, P_m\}$*, and* $R = \{R_1, \ldots, R_n\}$*, the* organizational graph *associated to* A^T *is the multi-graph* $G_A = (V, \{E_l\}_{l<n})$ *such that:*

1. $V = \{(a, P_j^A) \in dom(A) \times \wp(dom(A)) : A(P_j(a)) = 1\}$ *for* $1 \leq j \leq m$;
2. $E_l = \{(b, d) \in V^2 : b = (a, P_j^A)) \in V, d = (c, P_k^A)) \in V, A(R_l(a, c)) = 1\}$ *for* $1 \leq l \leq n$.

Example 4.1. *Let* A^T *be the organizational structure from example 2.1. The organizational graph associated to* A^T *is graph* $G_A = (V, E)$ *such that:*

1. $V = \{(\bar{i}, E^A), (\bar{f}, E^A), (\bar{o}, A^A), (\bar{r}, E^A), (\bar{s}, E^A), (\bar{v}, E^A)\}$;
2. $E = \{((\bar{i}, E^A), (\bar{o}, A^A)), ((\bar{o}, A^A), (\bar{r}, E^A)), ((\bar{r}, E^A), (\bar{s}, E^A)), ((\bar{r}, E^A), (\bar{v}, E^A)), ((\bar{s}, E^A), (\bar{f}, E^A)), ((\bar{v}, E^A), (\bar{f}, E^A))\}$.

Definition 4.2. *Let* $\mathbb{R}^+$ *be set of non-negative real numbers. Given an organizational graph* $G = (V, \{E_i\}_{i<n})$ *associated to an organizational structure* A^T *over* S*, an* objectual relevancy *is a function* $d : V \rightarrow \mathbb{R}^+$ *and a* relational relevance *is a function* $D : \{E_i\}_{i<n} \rightarrow \mathbb{R}^+$ *such that*

$$d(a) \leq [d]$$

and

$$D(E_i) \leq [D],$$

for all $a \in V$ *and* $i < n$.

The functions d and D represent the relevancy associated, respectively, to the nodes and types of edges between nodes. Given that, we provide some axioms for functions that every measure of organizational knowledge must satisfy.

Definition 4.3. *We write* $U_A(G)$ *to indicate an update* $U^A = (A_j^T : 0 \leq j \leq n)$ *such that* $A_0^T = A$ *and* $A_n^T = G$*. In special,* $\mathcal{U}_A(G)$ *denotes the set of all updates* $U_A(G)$*. In this way, we define that* $K : \mathcal{U}(G_b) \times \mathcal{U}(G_r) \rightarrow \mathbb{R}^+$ *is an* knowledge function *if, and only if:*

1. $K(U(G_b), U(G_r)) = K(U(G_r), U(G_b))$;
2. If $G_b = G_r$ then $K(U(G_b), U(G_r)) = 0$;
3. If $G_b \cap G_r = \oslash$ then $K(U(G_b), U(G_r)) = 1$;
4. If $G_b \subseteq G$ then $K(U(G_b), U(G_r)) \leq K(U(G), U(G_r))$;
5. If $G_r \subseteq G$ then $K(U(G_b), U(G_r)) \leq K(U(G_b), U(G))$.

The first axiom expresses the symmetry between the knowledge base and the research base. This is a consequence of the fact that insertions and extractions are dual operations and so it does not matter whether we consider the order of the structures. The second and third axioms are immediate and the forth and fifth represent the monotonicity of the structural information.

Definition 4.4. *Let A^T be an organizational structure and K a knowledge function over an organizational graph $G_b = (V_b, \{E_i\}_{i<n})$ associated to A^T, called* knowledge base*, and an organizational graph $G_r = (V_r, \{E_j\}_{j<n})$ associated to an organizational structure B^T, called* research base*. Thus, the* organizational knowledge *of B^T with respect to A^T and K is the number k such that*

$$\mathcal{K} = \min\{K(U_{G_b \cap G_r}(G_b), U_{G_b \cap G_r}(G_r)) :$$

$$U_{G_b \cap G_r} \in \mathcal{U}(G_b) \cup \mathcal{U}(G_r)\}.$$

5. Computational results

Our approach permits us to define the algorithm *Organizational knowledge* that calculates organizational knowledge. We could provide a mathematical proof that this algorithm computes an knowledge function, but we prefer to present empirical data about its execution - in a mathematical oriented article we will give all the details. The simulations provided in this section were implemented in a program wrote in Python.

The figure Fig. 4 is a graphic $K \times |V|$, where $|V|$ is the number of nodes of a graph $G = (V, \{E_j\}_{j<n})$, generated with a number of nodes from 1 to 100 with step of 5 nodes, 5 types of edges with 10 possible values, i.e., with $n = 5$ and $D : \{E_j\}_{j<n} \rightarrow \mathbb{R}^+$ with 10 possibles values. Each knowledge measure is a result of the mean of 10 trials. This graph shows that the variation in an research base with respect to nodes are irrelevant to knowledge. This is in accordance with axiom 3. As we randomly choose new organizational graphs bigger and bigger, the probability of finding completely different graphs increase, and so knowledge approaches to 1.

The figure Fig. 5 is a graphic $K \times |E|$, where $|E|$ is the number of edges of a graph $G = (V, \{E_i\}_{i<n})$, generated with a number of nodes from 1 to 100 with step of 5 nodes, 5 types of edges with 10 possible values. Each knowledge measure is a result of the mean of 10 trials. This graph shows that the variation in an research base with respect to edges is relevant to knowledge. This is a sigmoid function, a special case of learning curve [13]. Indeed, we have obtained the following function

$$K(x) = 1/(1 + 0.001010e^{-0.385636\sqrt{x}})^{1/0.000098}.$$

The square root $\sqrt{x}$ is just due to the factor of redundancy 2.19721208941247 generated by the fact that we have chosen the graphs randomly. This redundancy implies

Algorithm 1 Organizational Knowledge

Require: $G_A = (V_A, \{E_k\}_{k<m}), G_B = (V_B, \{E_k\}_{k<n})$
Require: $d_A : V_A \to \mathbb{R}^+, d_B : V_B \to \mathbb{R}^+$
Require: $D_A : \{E_j\}_{j<m} \to \mathbb{R}^+, D_B : \{E_k\}_{k<n} \to \mathbb{R}^+$

$N := 0$
$N_A := 0$
$N_B := 0$
$R_A := 0$
$R_B := 0$
$K := 0$
for $(x, y) \in G_A$ or $(x, y) \in G_B$ **do**
  if $(x, y) \in G_A$ and $(x, y) \in G_B$ **then**
    $N := N + 1$
  else if $(x, y) \in G_A$ **then**
    for $(x, y) \in E_j$ **do**
      $N_A := N_A + 1$
      $R_A := R_A + \frac{D_A(E_i)}{[D_A]}(\frac{d_A(x)}{2[d_A]} + \frac{d_A(y)}{2[d_A]})$
    end for
  else
    for $(x, y) \in E_k$ **do**
      $N_B := N_B + 1$
      $R_B := R_B + \frac{D_B(E_i)}{[D_B]}(\frac{d_B(x)}{2[d_B]} + \frac{d_B(y)}{2[d_B]})$
    end for
  end if
end for
$K := 1 - \frac{N}{N + N_A R_A + N_B R_B}$
return K

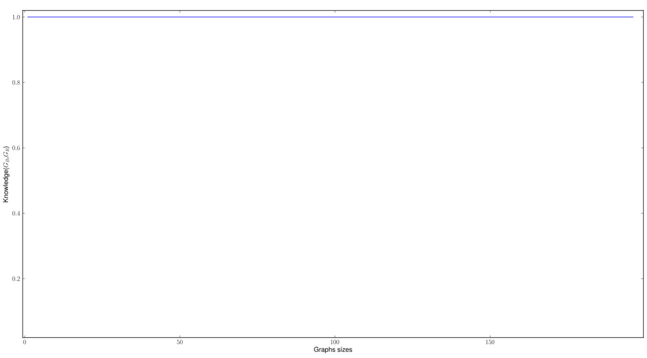

Figure 4. Knowledge between random graphs with variation of nodes

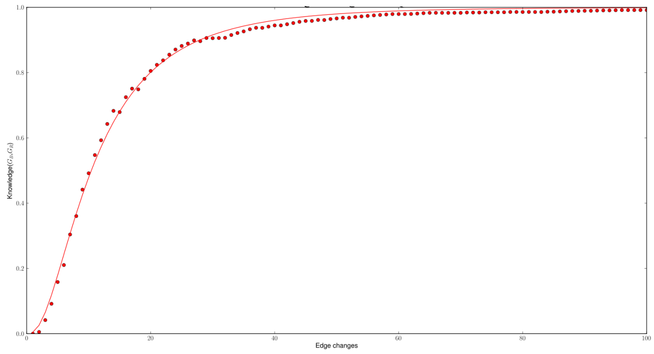

Figure 5. Knowledge between random graphs with variation of edges

a decreasing in the growing of knowledge. This is a very important result because, first, it shows a clear connection between our definition of knowledge and the usual empirical approaches to learning and, besides that, it is evidence that knowledge is indeed a relational property of organizational structures, as it have been sustained, for example, [5].

6. Conclusion

The main focus of the quantitative measure discussed in this paper is to use dynamic data taken from research methods about knowledge management. Our results shows that knowledge is a relational property of organizational structures. Nonetheless, much more should be done in order to understand the consequences of these results. At first, the organizational knowledge management techniques comprehend aspects of how to understand knowledge, using the right attitudes to the right environments. Once the knowledge meaning is defined, the knowledge sharing behaviour should be identified in order to apply quantitative measures and then driving the KM process toward a more certain path [14]. We also need to analyse how the measurement of knowledge given here can be used for these purposes. We relegate that to future works.

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