A FORMAL COMPOSITION OF MULTI-AGENT ORGANIZATION BASED ON CATEGORY THEORY

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ABSTRACT

The application of organizational multi-agent systems (MAS) provides the possibility of solving complex distributed problems such as, task grouping mechanisms, supply chain management, and air traffic control. The composition of MAS organizational models can be considered as an effective solution to group different organizational multi-agent systems into a single organizational multi-agent system. The main objective of this paper is to provide a MAS organizational model based on the composition of two organizational models, Agent Group Role (AGR), and Yet Another Multi Agent Model (YAMAM), with the aim of providing a new MAS model combining the concepts of the composed organizational models. Category theory represents the mathematical formalism for studying and modeling different organizations in a categorical way. This paper is mainly based on the idea of modeling the multi-agent organization AGR and YAMAM in a categorical way in order to obtain formal semantic models describing these organizations of MAS, then compose them using also the theory of categories which represents a very sophisticated mathematical toolbox based on composition.

KEYWORDS

Multi-agent systems, Organizational models, Category theory, composition.

1. INTRODUCTION

Multi-agent systems represent a set of agents that communicate with each other to meet a specific need, a goal or to accomplish a task (or a set of tasks) [1], the evolution of multi-agent systems and the cooperation between agents open the way to the emergence of the notion of organization for this type of complex systems, several models have been presented in the literature that take into consideration the notion of organization [2], such as Agent Group Role (AGR) [3], Yet Another Multi-Agent Model (YAMAM)[4] ,…

MAS organizational models can be defined as MAS mechanisms used in order to coordinate the agents' behaviors to accomplish complex tasks [5]. AGR organizational model [6] can be considered as one the most popular organizational mechanism used in the last years. This model is based on three different concepts, which are, Agent, Group, and Role used simultaneously to

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reflect the system behavior. In relation to complex problems [7], AGR was applied to the Pursuit-Evasion Game (PEG) [8] in order to provide a pursuit coalition formation allowing the grouping of the pursuers to capture the detected evaders.

In relation to AGR model, YAMAM is not based on the concept group, however, it is based on four concepts: Agent, Role, Task and Skills. The main principle of YAMAM can be resumed as follows: in order to play a specific role, an agent must have the appropriate skills in order to be able to improve the specific task. Recently, YAMAM was also applied to the PEG [9] with the aim of providing a pursuit groups access mechanism by the use of the concepts forming model.
To study an organizational multi-agent system, it is necessary to model these elements and the relationships between them, as well as these relationships with the environment in which it is located.

Category theory represents a multidisciplinary mathematical toolbox. It has been used in many fields of computer science. This theory offers a rich body of theory for reasoning about structures (objects and relationships between objects) [10]. In relation to existing formal methods, category theory provides the ability to organize and layer abstractions, as well as to find commonalities between different structures. Nowadays, the use of CT is not only reserved to the pure mathematicians. In other words, it was proved that CT represents a powerful tool in computer science, and industry [11].

Category theory is used to study and formalize organizations and collective phenomena in human societies with the aim of capturing their logics in categorical models. It is based on the idea of using category theory to develop organizational systems multi-agents by taking inspiration from collective phenomena and organizations in human societies in the work of [12]

Category theory is based on composition as in algebraic languages [13], it is at a very high level of abstraction, represented by a set of objects in the form of a category, morphisms between objects that represent the relationships between them, and functors between categories, these notions will be used for the modeling and the composition of organizational multi-agent systems.

The Category theory in its principle as indicated by its definition represents categories of objects and the links between objects as well as links between these categories of objects, (which can be sets or groups), this resemblance with the models of organizational multi-agent systems which are also groups of agents, links between agents and links between groups of the organization, , the agents play roles and perform tasks, these explicit links represent a support for the choice of the category theory for the modeling of organizational MAS

In other words, it is about transforming the Agent-Group-Role (AGR) organizational model in a categorical way in order to obtain a formal semantic model. This formal model allows the analysis, the verification and also the validation of the main concepts of an organization at a high level of abstraction.

The system of systems is a field that arose from the need to deal with specific types of problems where the fact that many capabilities and desired outcomes will be developed through the integration or composition of existing systems[14].

Organizational multi-agent systems are promising systems for managing the emergence of new systems, the main contribution of MAS as a simulation technique is its ability to represent the behavior of human actors, this representation through the organizational SMAs takes into consideration several important concepts in human society [15] such as the role, the group, the alliances... taking into account a heterogeneous and dynamic representation of the environment on which the system is located.

In this paper, we introduce a formal composition of AGR and YAMAM by the use of category theory principle. The main objective of this work is to provide a new organizational model that take into consideration the benefits of the concepts forming the composed models.

The paper is organized in the following way: in section 2, we detail the principles of category theory as well as the relations between YAMAM and AGR models. In section 3, we introduce the categorical representation of YAMAM and AGR organizational models. Section 4 is devoted to the categorical composition of the two studied organizational models. Finally, we conclude this paper in section 5 by providing a brief summary regarding the usefulness of category theory.

2. PROBLEM DESCRIPTION

This section is devoted to the description of the problem regarding MAS organizational models as well as category theory. The concept of the organization is very important in relation to multi-agent systems. The use of the organization in this field requires a formal framework to mathematically manage it, and validate interesting MAS properties.

Several models have been made to reflect the importance of organization in multi-agent systems, and to lead to effective solutions to complex problems, such as AGR and YAMAM, in the AGR model access to the Role is unconditional for any agent but on the other hand there is a control mechanism for access to the Roles in the YAMAM model, but there is not the notion of the group which exists in the AGR model, this notion of the group plays an important role in the organization,

The relation between AGR and YAMAM models is that they have common concepts Agents and Roles and to develop the relation between these concepts and take the benefits lake the access to roles by agents, the agents have to improve skills to take the role, and use the notion of group to simplify the accomplishment of system tasks, we will integrate them into a new model in a formal way, this new model which will contain the notion principles of the two models (AGR and YAMAM) and use it to resolve several complex problems.

Category theory allows to model AGR and YAMAM in a formal manner, category theory provides many mathematical aspects and concepts at a very abstract level. A categorical representation of the AGR multi-agent system was recently introduced through the use of category theory [16], which will allow us to represent or to transform the concepts related to YAMAM in a formal model, examine them in an abstract way, and formalizing the system as collections of objects (categories) and morphisms with the aim of reasoning about these objects and their relationships or interactions (morphisms).

CT is based on the mathematical composition as a whole of operation between objects, morphisms or functors, or even between categories, Composition: From the arrows :

It includes the following data [17]:

- Objects: A, B, C, etc.
- Morphisms: f, g, h, etc.
- Domain and Codomain: For each arrow f, we give objects: dom (f), cod (f) called domain and codomain of f. We write: $f: A \rightarrow B$ to indicate that $A = dom(f)$ and $B = cod(f)$.

- Composition: From the arrows f: A → B and g: B → C, that is to say with: cod (f) = dom (g), we have a given arrow: g ∘ f: A → C.
- Identity: For each object A there is a given arrow 1A: A → A, called identity arrow of A.

These components are required to comply with the following laws:

- Associativity: h ∘ (g ∘ f) = (h ∘ g) ∘ f, for all f: A → B, g: B → C, h: C → D.
- Unit: f ∘ 1A = f = 1B ∘ f, for all f: A → B.

f: A → B and g: B → C, that is to say with: cod (f) = dom (g), we have a given arrow:
g ∘ f: A → C.

a field called Systems of systems "SoS" is a term hugely used to describe systems composed of systems independent constituent acting to achieve a common goal. System of systems engineering (SOSE) is a field that emerged from the need to address the issues of SoS [18], this field has evolved through the results of the work of integrating existing or legacy systems, integrating one part of the system into another, or integrating the entire system, resulting in a system that provides the capability desired. Authors in [19], and as we said that CT is based on composition, we will compose AGR and YAMAM using CT to have a new model.

The objective of this work is to take advantage of the non-common concepts that make up the two models in order to see the emergence of a new more complete organizational model.

So in this work we are going to treat two essential points, to present YAMAM in a categorical way, the formal model obtained for YAMAM, as well as that of AGR form two categories which will allow us thereafter to compose them that take into consideration the benefits of the concepts forming the composed models in only one system categorically, by using comma category.

3. AGR AND YAMAM MODELING WITH CT

3.1. Categorical representation of the YAMAM model

In what follows, we present the categorical modeling of YAMAM, examine its structure, and represent the main concepts such as: skills, tasks, role and agents, and their relationships via category theory, and thereafter a return to the global system which is the set of these categories, which represent YAMAM using constructions from the Category Theory (CT).

But before we will detail the YAMAM model and its concepts then represent it in a categorical way.

3.1.1. Yet Another Multi-Agent Model (YAMAM)

Based on 4 concepts which are the pillars of this model, Agent, Role, skill and task.

The organization of YAMAM is described by its inherent structure, therefore the relations between the agents are paramount in relation to the agents and their behaviors. The organization is represented by a set of agents who have goals, tasks, skills and Roles, the goals of which the agent works to achieve them, performs a set of actions and plays one or more roles in order to achieve a desired goal. Agents may have new goals after a system update, which causes new actions to perform and roles to play.

Agents communicate with each other and cooperate to achieve the overall goal of the organization.

Agent: is defined as an autonomous entity in an environment equipped with sensors, able to communicate and use skills to complete tasks, these skills can be evolved over time.

Role: is defined as a function or form of agent identification or service. A role can be played or assigned to one or more agents in an environment, a set of tasks to be performed by agents. We consider that an agent can play a role only if he has the skills required to perform the tasks involved for this role.

Skill: is represented by a unit of knowledge necessary for the processing of given tasks. An agent can be aggregated several skills in order to perform the required set of tasks.

Task: it is the operation of a skill or an action that requires one or more skills to complete it.

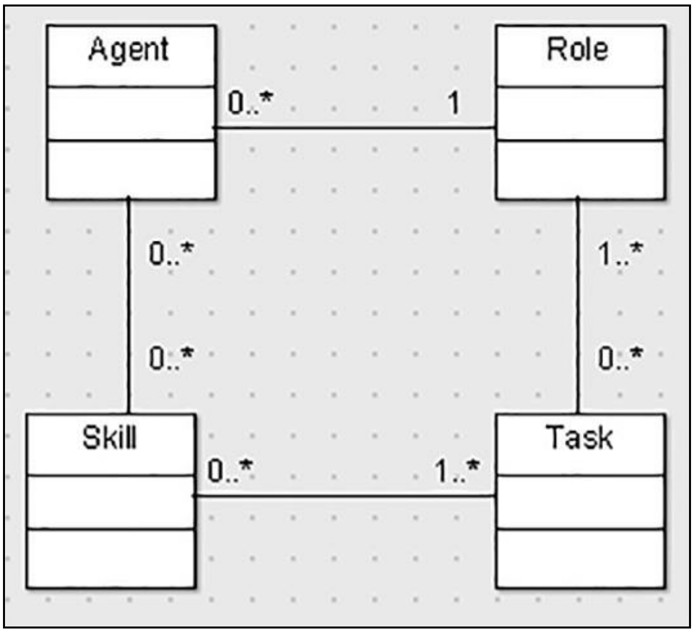

Figure 1. YAMAM meta-model

The following section contains definitions of: Skills, Actions, Tasks, Roles, Agents, and their relationships, which allows us to formalize the YAMAM organization in a categorical way.

3.1.2. Agent Category

The Agent category encompasses all agents of the YAMAM organizational model, represented by these objects, which can be autonomous objects in an environment capable of communicating and using skills to complete tasks. Morphisms are the identity morphisms of each object (agent).

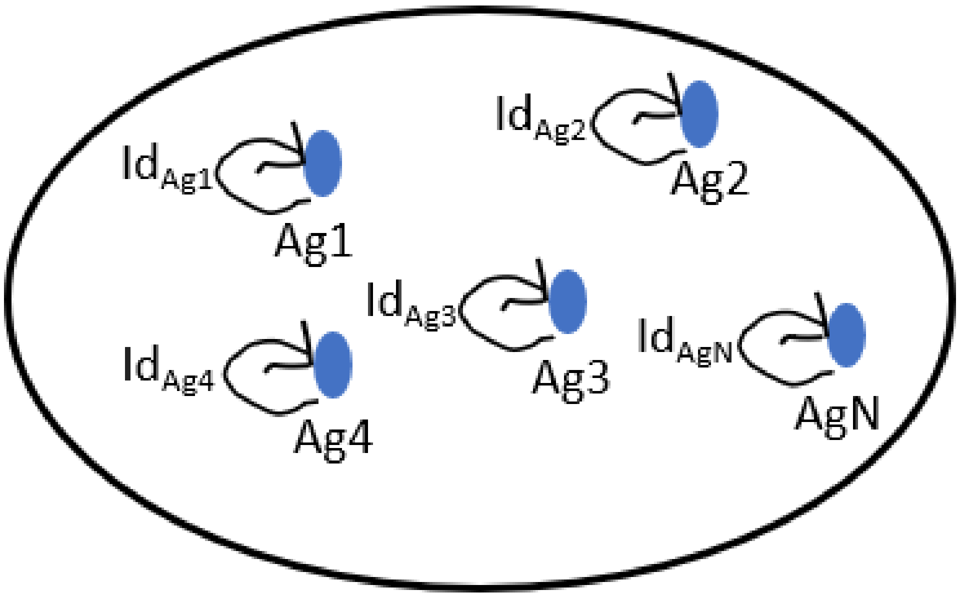

Figure 2. Category Agents

3.1.3. Role Category

In its definition, a role is a function or form of agent identification or a service, a role can be played or assigned to one or more agents in an environment, a set of tasks to be performed by agents. So to represent the role category, you have to define the task category.

3.1.4. Task Category

In the YAMAM model, the Task is the operation of a skill or action that requires one or more skills to complete. So the Task category is linked to the Skill category. An agent is able to complete a given task, if it has the necessary skills (the set of units of knowledge that represents the skill). To define the Task category, you must define the Skill category and then go up to the Role category

3.1.5. Skill Category

The skill category represented by one or more units of knowledge necessary for the processing of given tasks, an agent can be aggregate several skills in order to perform the set of required tasks. Objects and morphisms in this category are represented as follows

- Objects: are a set of knowledge units designated by CM1, CM2, etc.
- Morphisms: identity morphisms

CM objects are categories that encompass one or more knowledge units from the base category Knowledge Units. The knowledge unit is a discrete category, it contains only the identity morphisms and the objects which are the knowledge units.

The following figure presents the category that includes all the units of knowledge for the YAMAM model,

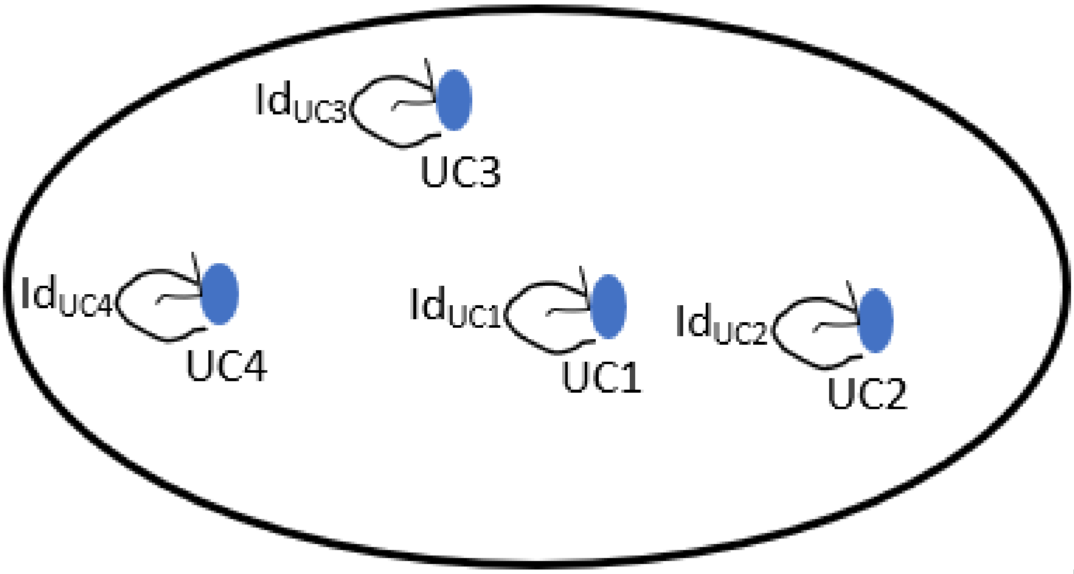

Figure 3. Knowledge units category

From the knowledge unit category, the Skill category is designed, a skill can have one or more knowledge units as shown in the following figure:

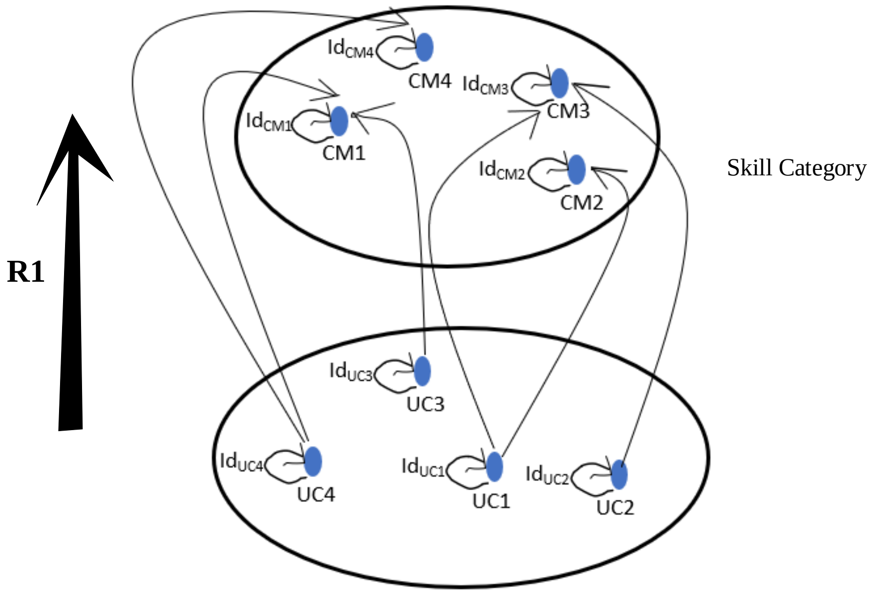

Figure 4. Skill Category creation

Functor R1:
Objects
R1(UC1) = Skill.CM2
R1(UC1) = Skill.CM3
R1(UC2) = Skill.CM3
R1(UC3) = Skill.CM1
R1(UC4) = Skill.CM1

Morphisms
$R1(Id_{UC1}) = Id_{R1(MC2)}$
$R1(Id_{UC1}) = Id_{R1(MC3)}$
$R1(Id_{UC2}) = Id_{R1(MC3)}$
$R1(Id_{UC3}) = Id_{R1(MC1)}$
$R1(Id_{UC4}) = Id_{R1(MC1)}$

Once we have designed the Skill category, we will create the Task category. As its definition indicates, a task is the operation of a skill requiring one or more skills to complete it.

The following figure shows the Task category

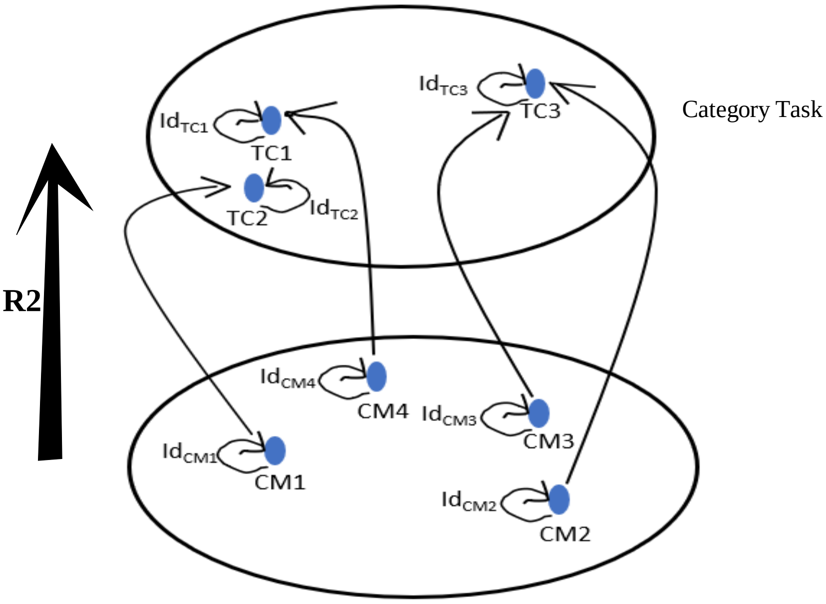

Figure 5. Task category creation

Functor R2:
objets
R2(CM1) = Task.TC2
R2(CM2) = Task.TC3
R2(CM3) = Task.TC3
R2(CM4) = Task.TC1
Morphisms
$R2(Id_{CM1}) = Id_{R2(TC2)}$
$R2(Id_{CM2}) = Id_{R2(TC3)}$
$R2(Id_{CM3}) = Id_{R2(TC3)}$
$R2(Id_{CM4}) = Id_{R2(TC1)}$

The Role category is represented by one or more sequences of tasks to be executed sequentially, in turn it will be designed from the Task category as follows:

Assuming that a RL1 (Role 1) is the sequence of the two tasks TC3 and TC2 represented by the morphism SC1, and RL2 is the execution of the Task TC1 as figure 6 shows.

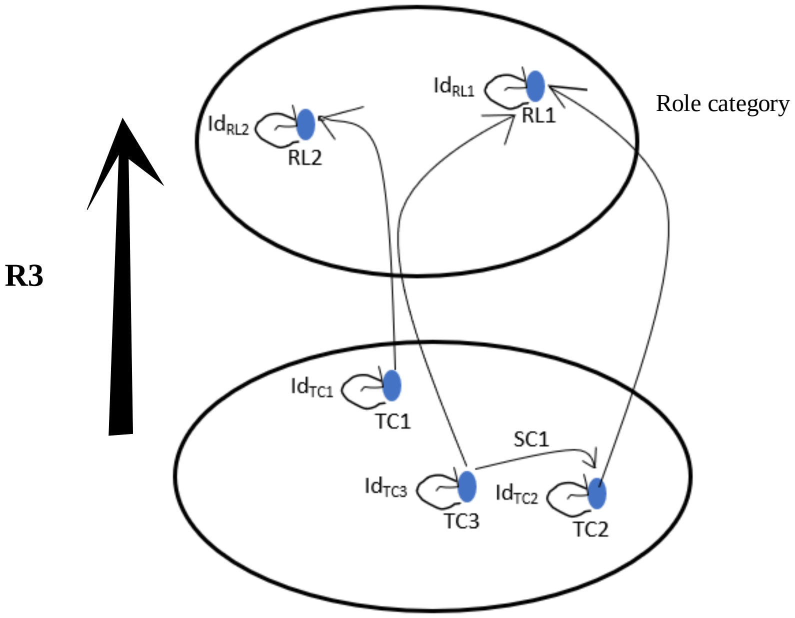

Figure 6. Role category creation

Functor R3 :
Objets
R3(TC1) = Rôle.RL2
R3(TC2) = Rôle.RL1
R3(TC3) = Rôle.RL1
Morphisms
Identity morphisms
R3(Id_{TC1}) = $Id_{R3(RL2)}$
R3(Id_{TC2}) = $Id_{R3(RL1)}$
R3(Id_{TC3}) = $Id_{R3(RL1)}$
Morphism SC1
R3(SC1) = $Id_{R3(RL1)}$

All the categories of the YAMAM organizational model have been presented in categorical form, the following diagram presents the YAMAM categorical model.

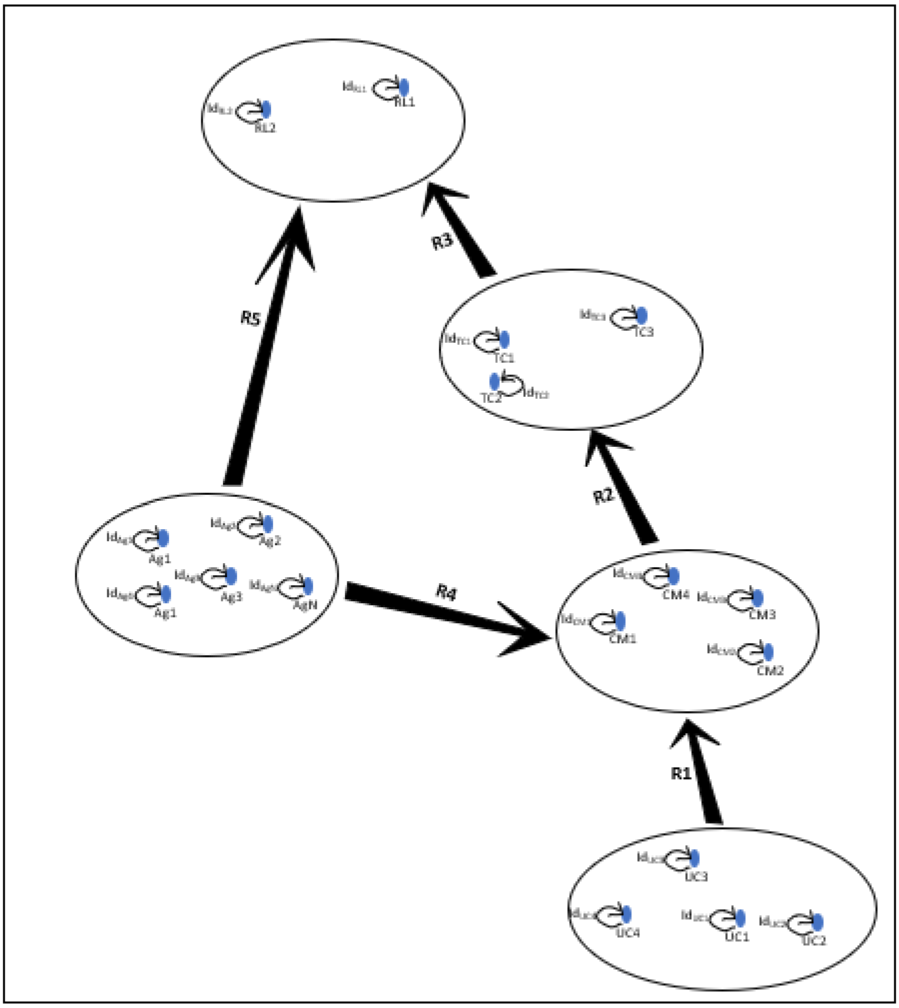

Figure 7. YAMAM Categorical Model

An agent can take the role if he has the skill (or skills) necessary for this role, through the functor R4 the agents point to the objects (skills) which have the abilities to use them to play the roles and complete the tasks. tasks related to them.

3.1.6. Play the roles by the Agents

In this part we will explain how agents take roles via categories.

Assuming that agent Ag1 has skills **CM1** and **CM2**, and agent **Ag2** has skills **CM2** and **CM3**, and agent **Ag3** has skill **CM4**

So the agent **Ag2** is able to complete **TC3**, Ag1 able to complete **TC2** and **Ag3** able to complete **TC1**

Consider the functor **R4**, **R4**: Agent Category → Skill Category.

Objets
R4 : **Ag1→CM1**, **et R4** : **Ag1→ CM2, so R4** : **Ag1→CM1**, **CM2**
This means that Agent Ag1 has skills CM1 and CM2

Morphismes

R4 : $\mathbf{Id_{Ag1} \rightarrow Id_{CM1}}$

R4 : $\mathbf{Id_{Ag1} \rightarrow Id_{CM2}}$

Agent objects Ag2 and Ag3:

R4 : **Ag2→CM2**, **et R4** : **Ag2→ CM3, so R4** : **Ag2→** (**CM2**, **CM3)**

R4: **Ag3 →CM4**

In order, Agent **Ag2** has skills **CM2** and **CM3**, Agent **Ag3** has **CM4** skills,
Now suppose we also have the functor **R2**,

Morphismes Agents Ag2 and Ag3 :

R4 : $\mathbf{Id_{Ag2} \rightarrow Id_{CM2}}$

R4 : $\mathbf{Id_{Ag2} \rightarrow Id_{CM3}}$

R4 : $\mathbf{Id_{Ag3} \rightarrow Id_{CM4}}$

R2: Skill Category →Task Category,

Objets

R2 : **CM1→TC2**,

This means that to accomplish the task TC2, the agent in charge of completing it must have the skill CM1.

Morphisms :

R2 : $\mathbf{Id_{CM1} \rightarrow Id_{TC2}}$

Objets

R2 : **CM2→TC3**, **R2** : **CM3→TC3**, so **R2** : (**CM2, CM3) →TC3**.

To complete the task **TC3** it is necessary to have skills **CM2** and **CM3**

Morphisms

R2 : $\mathbf{Id_{CM2} \rightarrow Id_{TC3}}$

R2 : $\mathbf{Id_{CM3} \rightarrow Id_{TC3}}$

Objets :

R2 : **CM4→TC1**,

The same for the **TC1** task, you must have the **CM4** skill in order to accomplish it,

Morphisms

R2 : $\mathbf{Id_{CM4} \rightarrow Id_{TC1}}$

Roles are defined as performing task(s), so

R3: Task Category → Role Category,

Objets

R3 : **TC1→RL2**,

Obtaining the Role **RL2** by an agent means that this Agent will execute the task **TC1**, and who has the skill(s) to complete it,

Morphisms

R3 : $\mathbf{Id_{TC1} \rightarrow Id_{RL2}}$

Objets

R3 : **TC2→RL1**, **R3** : **TC3→RL1**, donc **R3** : (**TC3, TC2) →RL1**,

Obtaining the Role RL1 by an agent means that this Agent will execute the task **TC3** and **TC2**, and who has the skills to complete it,

Morphisms

R3 : $\mathbf{Id_{TC2} \rightarrow Id_{RL1}}$

R3 : $\mathbf{Id_{TC3} \rightarrow Id_{RL1}}$

R3 : $\mathbf{SC1 \rightarrow Id_{RL1}}$

We are going to apply the composition function between functors as follows:

As an example we take the agent **Ag3** which will be linked to the skill **CM4** which is linked to the task **TC1**, the latter in turn is linked to the role **RL2** as shown in the following figure:

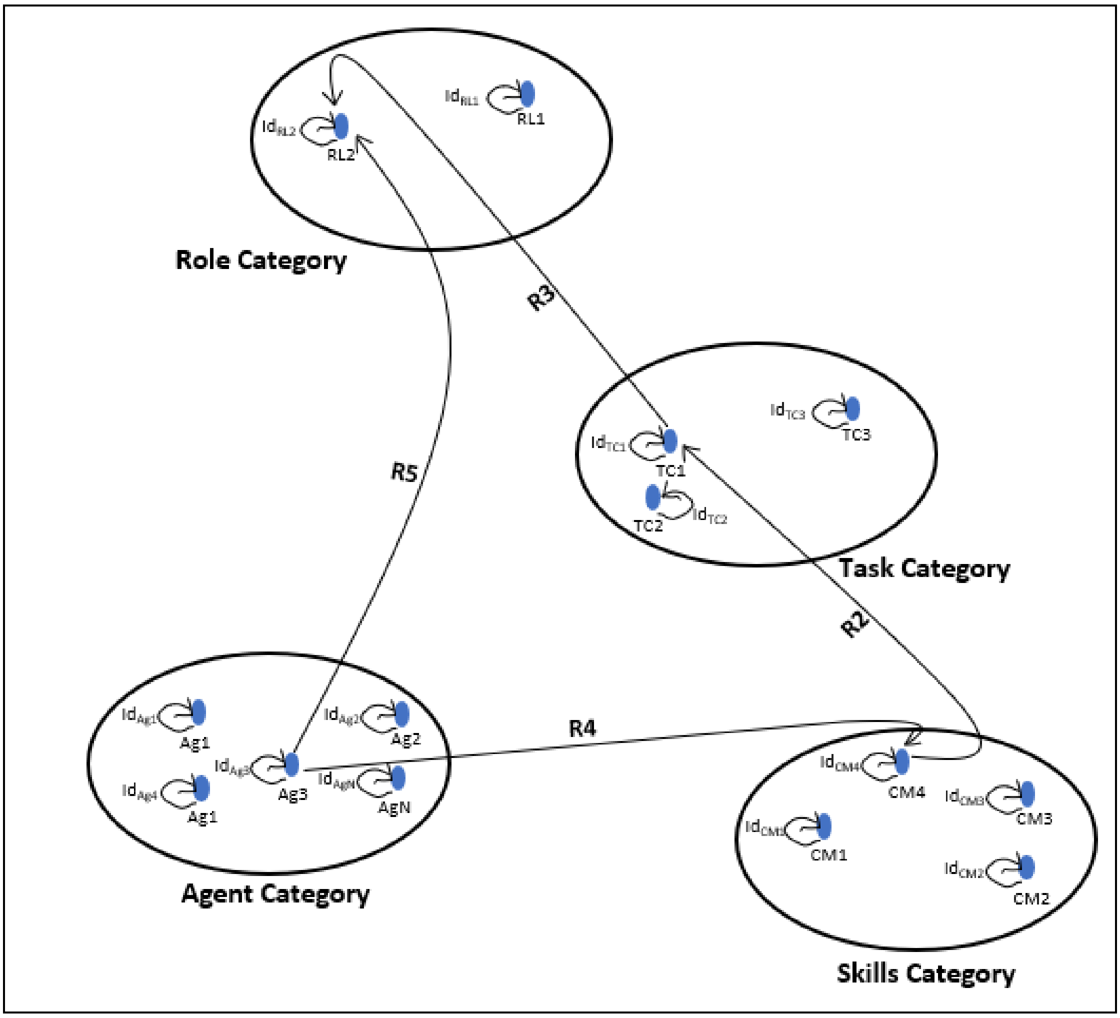

Figure 8. Role playing by an agent in the YAMAM categorical model.

From the previous figure we will obtain the following mathematical equations:

$$\begin{cases} \textbf{Ag3} \xrightarrow{\textbf{R4}} \textbf{CM4} \quad \textbf{(1)} \\ \textbf{Et} \\ \textbf{CM4} \xrightarrow{\textbf{R2}} \textbf{TC3} \xrightarrow{\textbf{R3}} \textbf{RL2} \quad \textbf{(2)} \end{cases}$$

From equation 2: **R3 ∘ R2 : CM4 → RL2** called the composite of R2 and R1, so the new equation is: R3 ∘ R2 : CM4 → RL2 **(3)**

Then we will dial 1 and 3: $\textbf{Ag3} \xrightarrow{\textbf{R4}} \textbf{CM4} \xrightarrow{\textbf{R3} \circ \textbf{R2}} \textbf{RL2}$

So: **(R3 ∘ R2) ∘ R4 : Ag3 → RL2**

This last composition is equal to **R5**:

(R3 ∘ R2) ∘ R4 = R5

Through these equations the role RL2 will be played by the Agent Ag3 who has the skill **CM4** that it is necessary for this role, and then Ag3 it will execute the task 3 (**TC3**), and to be able to play a role c' is the same for the other Agents in the Agents category.

4. COMPOSITION OF THE AGR AND YAMAM MODELS

Our organization is made up of agents equipped with environmental sensors to detect obstacles and the position of other agents, to see changes, to communicate with each other, etc. they can also act or react according to their objectives and their roles in the organization.

The environment in our study represented by a set of objects (categories) with certain properties and relationships between these objects.

Category theory is based on Composition, objects, categories and/or morphisms, it allows us to compose two categories to have a new category by ensuring any constraints or rules that may be presented in one of these categories composed, this powerful composition operation, will be used to compose two different organizational systems in a new system. The reformulation by the categories allows us to move on to the composition of the latter.

The categories represent a reformulation of the organizational SMAs, composing the functors between source categories (A, B) towards a target category (C) reflects the composition of a system A (AGR) with a system B (YAMAM) in a new system C , and the result is guaranteed to fit the target categories and satisfy the starting category paths.

In our case, we consider that a member system is represented by an organization of agents more particularly an organizational SMAs (source category A or B). So we are talking about a composition of organizations.

The first organizational system A is represented by the AGR organizational model that we have detailed in our work (Towards a formal multi-agent organizational modeling framework based on category theory).

The second organizational system B is represented by the YAMAM model, Which we modeled in the previous part.

We will use comma category to perform the composition of the two AGR and YAMAM categorical models,

4.1. Composition using comma category

Commas categories [20] are categories where The basic idea is the elevation of morphisms of a category C to objects of other categories.

The complete generality for this category can be obtained by taking a subclass of morphisms - those whose source is in the image of a functor L: A→ C and whose target is in the image of another functor R: B→ C. Comma category (L; R) has as objects, triplets of the form (a; f: L (a) → R (b); b) where a is an object of A and b an object of B. A morphism in (L; R), from (a; f; b) to (a'; f'; b') is a pair of morphisms s: a→ a' and t: b→ b' such that the following square commutes :

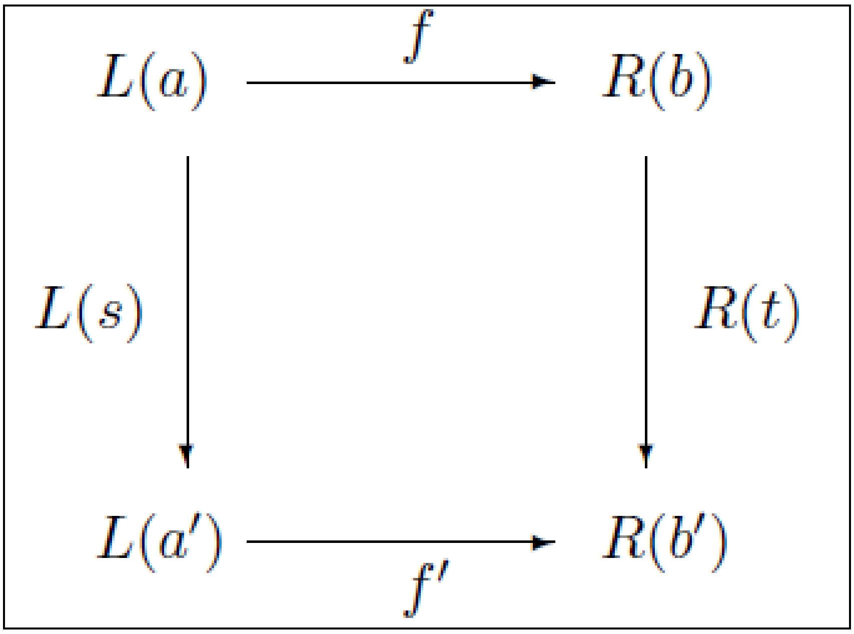

Figure 9. Composition of objects and morphisms in comma category

The composition is defined by component, (s , t) ◦ (s', t') = (s◦s', t◦t') and the identities are pairs of identities. The category commas are associated with two projection functors:

Left: (L, R) → A; right: (L, R) → B defined by: Left (a, f, b) = a
And Left(s, t) = s, And similarly for the right functor.

This category can serve us in the composition of systems, it does not modify the basic starting systems (source), and the new category uses the two source categories in its operation.

After modeling the two systems AGR and YAMAM categorically, in this part we will use the categorical models to compose them via Comma category

The following figure presents the two organizational models on the left AGR and on the right YAMAM,

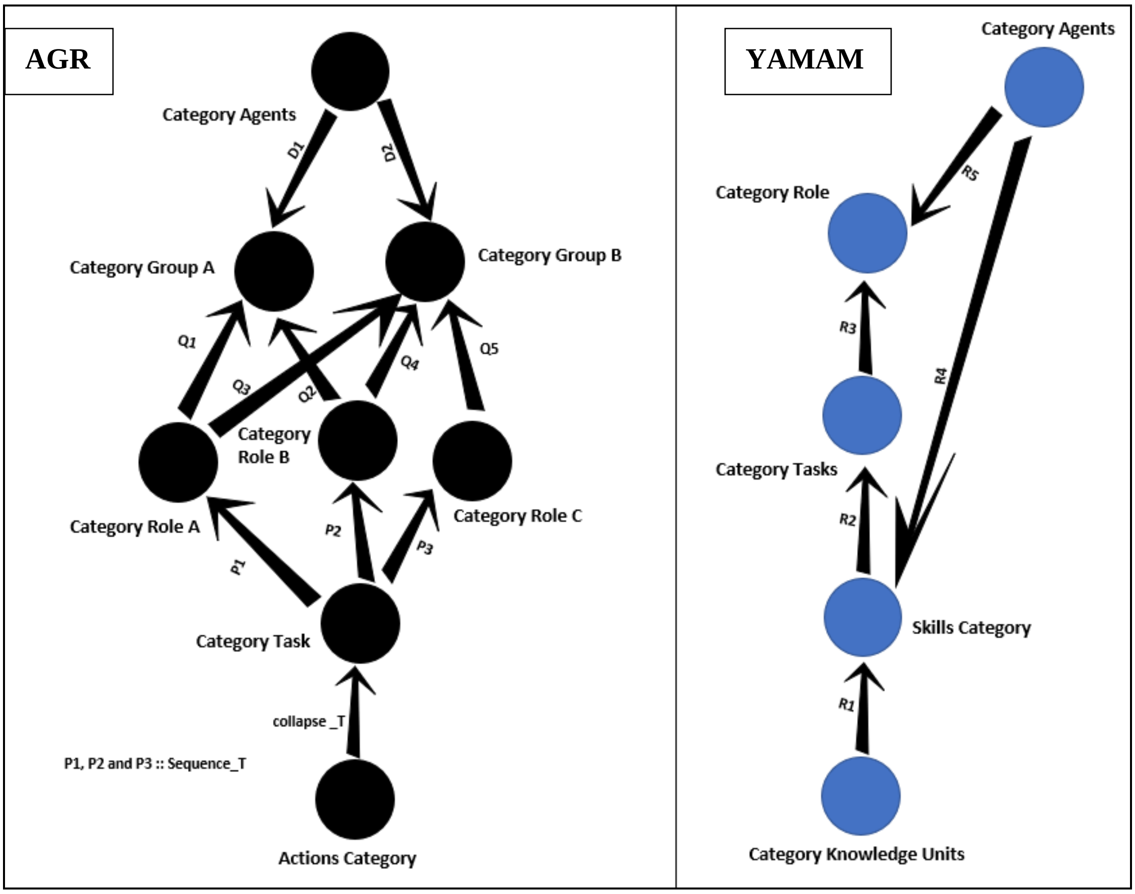

Figure 10. Simplified categorical representation of the two organizational models AGR and YAMAM.

We have presented the categories in the form of objects to simplify the drawing of categories of the two AGR and YAMAM systems, these two models will be composed in a new category, in the middle as shown in the following figure:

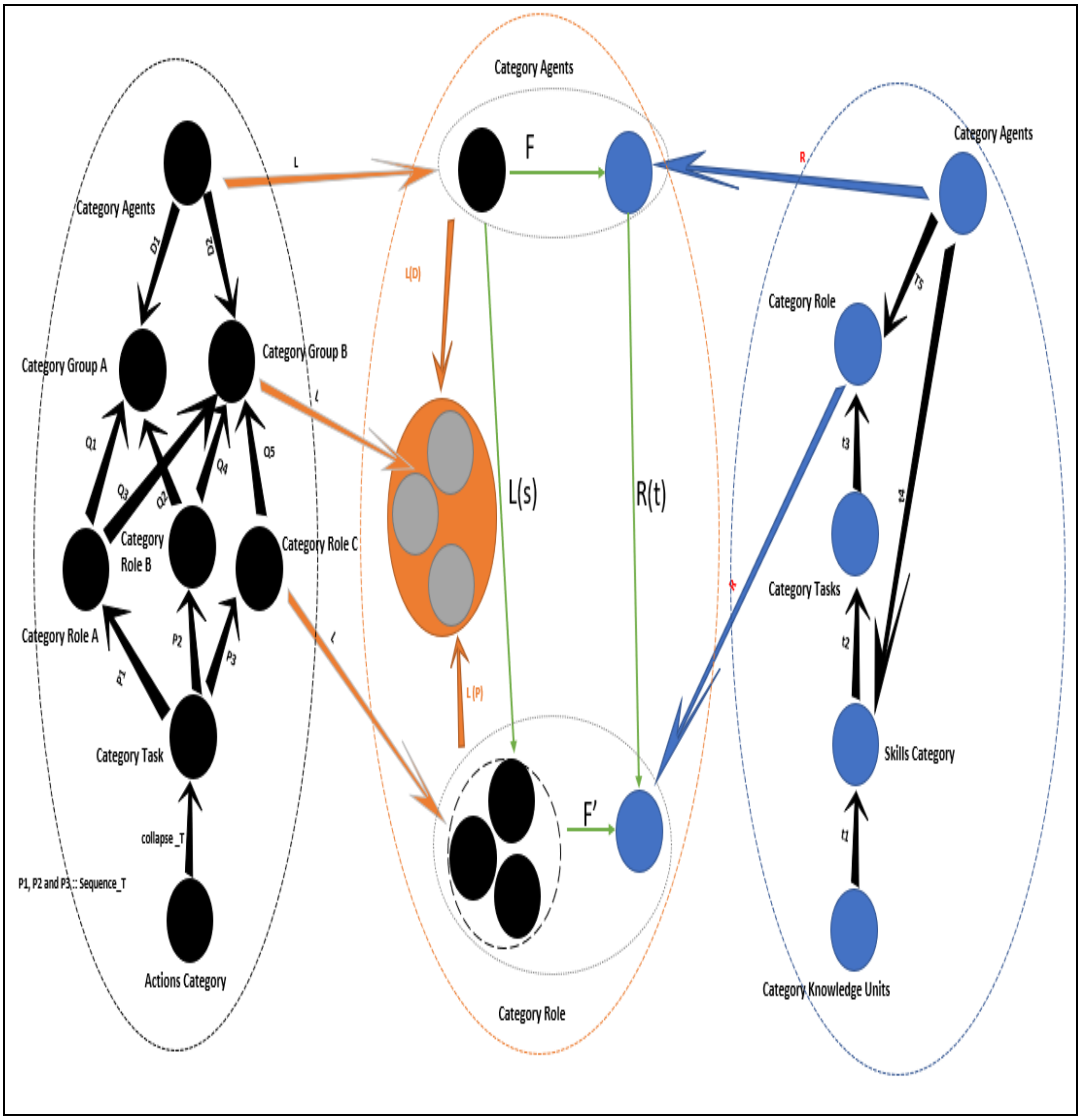

Figure 11. Composition of the two organizational models AGR and YAMAM with comma category

Explanation with comma category

The object (category agent) points to the object (CA) via L, and the object (Category Group B) points to the object (G), and the object (category agent) points to (category group B) which implies a morphism between the object (CA) and the object (G),
Object (category agent) points to object (CA) via R, and object (Category Group B) points to object (G), and object (category agent) points to (category group B) which implies a morphism between the object (CA) and the object (G),
The source is like a functor L: A→ C and whose target is like another functor R: B→ C. Comma category (L; R) has as objects, triplets of the form (a; f: L (a) → R (b); b) where a is an object of A and b an object of B. A morphism in (L; R), from (a; f; b) à (a'; f'; b') is an even pair of morphisms s: a→ a' and t: b→ b' such that the following square commutes:

5. CONCLUSIONS

In our study we are interested in the modeling of Organizational MASs and in these aspects, and compose tow Organizational MASs models (AGR and YAMAM), the complexity of this task requires a formalism that has a great power of expression, analysis and verification, category theory is better placed for this purpose, it is a very sophisticated toolbox for its graphical interpretation.

The advantages offered by category theory, first: visual formalism, mathematical support, modularity, hierarchical specification and easy description of systems, we can consider that it is the most suitable for modeling the dynamics of discrete systems, organizational aspects,

We will then focus on CT as a powerful graphical theory that allows the system to be easily understood and also allows the simulation of its activities,

This formalism is well suited to the formal verification of organizational MASs which contains both states and events represented by the interaction between the different Agents as well as between groups of agents and their roles in the organization.

Second: After the generation of the categorical model, the CT allows us to switch to several known modeling modes such as graphs or sets. This very important link represented by a functor (F) allows us to switch between the mathematical representation, which give us the possibility to reformulate the studied problem via graphs, sets, topos, and this allows us to use the characteristics and properties of each domain to solve the starting problem.

The use of CT in the composition of systems in general, and more specifically multi-agent organizational systems, as a new way of modeling them, opens the way perhaps to solving very complex problems in the future, by mastering the mathematical tools it offers.

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