THE EFFECTS OF RELATIONAL COMPLEXITY ON GROUP PERFORMANCE

RESULTS FROM AN AGENT-BASED SIMULATION MODEL

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Abstract

The question of group performance is one of the most central in organization science. However until now the studies have been lacking theoretical clarity, formal demonstrations, and empirical tests. Focusing on technological interdependence, we will identify and define the fundamental types of systemic couplings: parallel, sequential and reciprocal (by feedback). Then we will precisely discuss and then simulate its characteristics and effects through an agent-based model. We measure and order the relational complexity, that is, the degree of complexity of each systemic coupling (technological interdependence between tasks). Group performance will be measured by means of two main indexes: effectiveness, which refers to the percentage of completed tasks respect to those potentially executable; and efficiency, which refers to the resources employed for getting the completed tasks. We analyze the variation of group performance depending on relational complexity.

The most general and important conclusions are that: i) listing in order of increasing degree of complexity, parallel is followed by sequential and then by reciprocal interdependence; ii) more complex interdependencies do require more complex norms. This latter conclusion is an exemplar confirmation of the law of requisite variety.

Keywords: agent-based models, complexity, coordination theory, group performance, law of requisite variety, organization science, theory of interdependence.

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1. Introduction

Organization sciences represent nowadays a field vast as that of economic sciences, and as that they concern normative and descriptive approaches, quantitative and qualitative methods, and many different research streams and fields of application. A central theme is certainly that of organization design that is of the rational criteria to build or change an organization structure, regardless if non-profit or for-profit ones. However, as in many fields of social sciences, the state of theoretical and empirical development is rather unsatisfactory because of a plenty of different theories, most of which never empirically tested and many of which lacking even logical consistency. Actually, this is largely due also to the tremendous cost of carrying methodologically sound and statistically significant empirical tests.

The construction of agent-based simulation models can help in both problems, because the necessity to create the model in the algorithmic form and to "run" it in a computer forces the researcher to solve possible logical inconsistencies. Otherwise, the model (the program) wouldn't run! Moreover, once built a model, it is easy to make changes so to explore new questions. Of course, all this happens into the virtual reality and not into the "real reality", but any theory, any model is always virtual and not real, by definition.

By means of an agent-based simulation model, our main goal is to study the effects of relational and structural complexity of a set of activities (tasks) on group performance. Thus, we are at a very micro-level of organization. This is an embryo of a complete and robust theory of organization design, which will include a theory of interdependence, a theory of coordination mechanisms (norms), and a theory of grouping activities and agents. In this paper we face principally with the basic definitions and questions of a theory of interdependence, and just marginally with the theory of coordination. Nothing will be said on the theory of grouping. Although incomplete, if seen in terms of the desirable theory of organization design, our model is robust, that is it is based on the principles of socio-cybernetics, and developed by an algorithmic structure. Even more interesting, it gives also confirmations of those principles.

This aspects is also rather fruitful, insofar socio-cybernetics (and cyberneticians in general) tend to pay too much attention to theoretical developments rather than to its empirical tests. The result is that there are many unproved statements, many Byzantine disputes lacking empirical applications and a plethora of approaches. The consequence –very dangerous for the future of a science- is that researchers and practitioners often don't see any concrete application or reference to reality. Currently, even into organization science, which is the most natural field of application of socio-cybernetics, many scholars don't know even the basic principles, like the law of requisite variety. On the other hand, we could say that, beyond very general examples made by the "fathers" of cybernetics, it is very difficult to find its concrete applications into the field of social sciences. It is almost impossible to find its operationalization and measurement out of the field of physics.

At the moment our model is rather simple, because it supposes that agents have the same competencies and motivations to work, that they don't learn, that they don't make mistakes, that there are no behavioral issues (personal conflicts, leadership problems, etc.), and that tasks differ just for their structure. Moreover, there are no scale economies and no other nonlinear phenomena. Hence, as can be seen, it is a very simple model. However, it is very helpful either because it is the ground on which building more complex and realistic models or because it already shows many interesting effects, which we are going to discuss in this paper.

In next sections the key concepts and the theoretical architecture of the model will be presented. Then, the precise definitions of the three main types of interdependence will be given, followed by its implications in terms of relational complexity. In section three is shown the structure of the model, its methodology and the characteristics of agents behavior, while in section four the effects of relational complexity on group performance will be analyzed in terms of effectiveness and efficiency.

2. Key Concepts

Cybernetics is a very basic science because it offers principles and concepts applicable to many other sciences. This holds even for the issue of organizational interdependencies. They can be examines under three main dimensions:

- the technological one, referring to the way in which activities (tasks) can be connected each other;
- the behavioral one, referring to the types of human interactions in terms of psycho-sociological aspects;
- The informative one, referring to the knowledge exchange between cognitive agents.

In this paper we deal only with the first dimension, because we believe that it has a priority respect to the other two, at least in the short run. Indeed, if two workers do have personal conflict it is a serious problem, but it cannot modify the technology to produce a certain good. Of course, if there are technological alternatives not too disadvantageous, the behavioral dimension gives important indications to decision making, but if there are no technological alternatives then those people should be removed or their conflict faced with other managerial techniques. Something similar holds for the issue of the distribution of knowledge between workers. In any case, in the short run and lacking feasible alternatives, the technological dimension is prior to the other two.

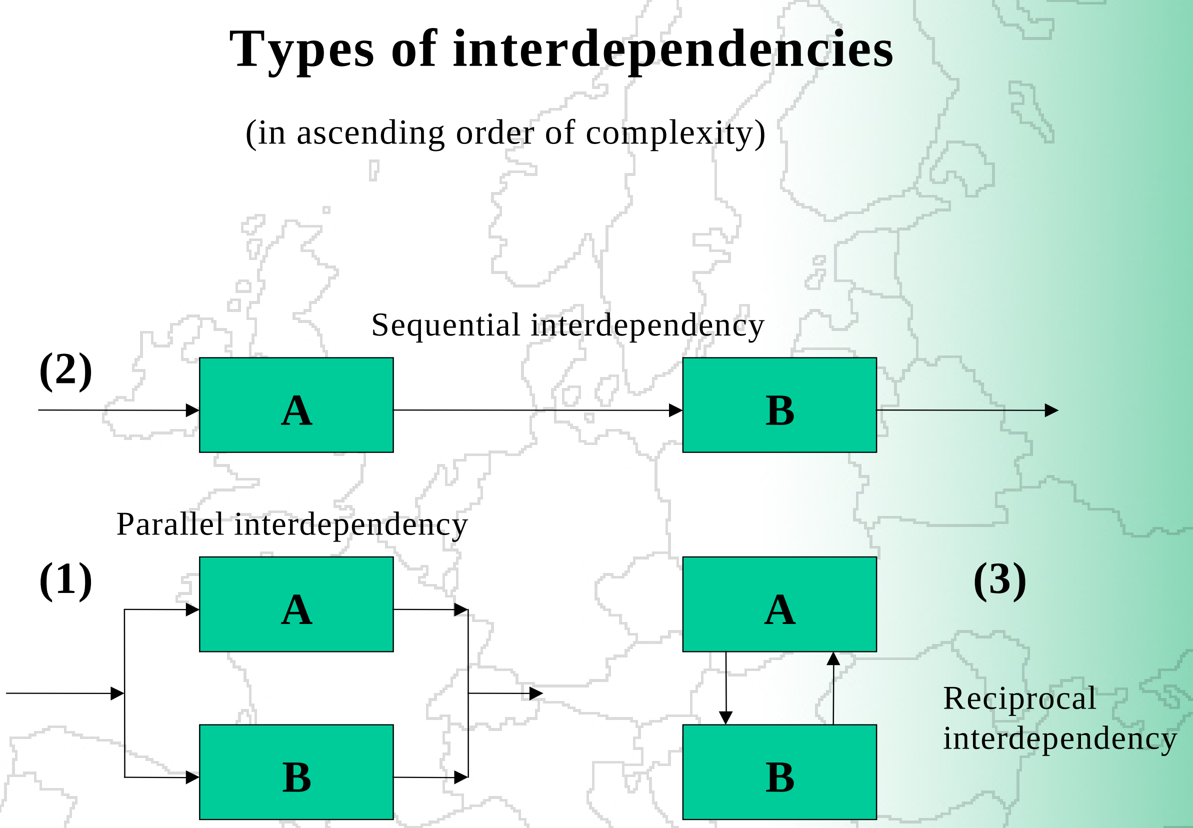
Under the technological dimension, two or more tasks can be connected by means of one of these three interdependencies or a combination of them (fig. 1):

- *parallel connection*, when the tasks are connected only through its inputs and/or outputs. This case could be divided into three further situations, depending on the role of the time: sequential, simultaneous or with no any time constraint or specification;
- *sequential connection*, when the output of one task is the input of the following. The crucial difference between this type of interdependency and the parallel-sequential is that in the latter the tasks just follow each other but they don't use the respective outputs;

- *reciprocal connection*, when the output of a task is the input of the other and vice versa. Even this case could be divided into three further situations, depending on the role of the time: sequential, simultaneous or with no any time constraint or specification.

It's easy to see that this categorization coincides with those that, in various forms and languages, has been proposed by systems science, calling them systemic coupling. It's noteworthy to remind that they exhaust any type of coupling (connection, interdependency) and that, as underlined by cybernetics, only the third type of interdependency refers to cybernetic systems, because only in that case there is a feedback. Indeed, into the systems science the reciprocal connection is usually called structural coupling, while into the organization science is called mutual adjustment (Mintzberg, 1979, 1983).

Fig. 1



If we look carefully at the three types of interdependence we see that the word "interdependence" is fully appropriate only to the third case, the reciprocal connection, because only in reciprocity or in mutual adjustment two or more systems (activities, tasks, whatever type of concrete or abstract entity) are depending each other, as the word "interdependence" properly means. In the parallel connection there is joint dependence from another source in input or the reciprocal contribution to the same output without mutual- that is (inter)-dependence. In this latter case the output depends on the parallel connected systems, but they don't depend mutually each other: in fact, there is no feedback. In the case of sequential connection, there is still no feedback and inter-dependence, but rather dependence of the next from its preceding system.

Classical and recent authors (Crowston, 1997; Galbright, 1973, 1977; Grandori, 1995; Kiggundu, 1981; Lawrence & Lorsch, 1967; Malone, Crowston & Lee, 1994, 1999; March & Simon, Organizations; Mintzberg, 1979, 1983; Simon, 1962; Thompson, 1967; Van de Ven, Delbecq & Koenig, 1976) of organization and management sciences defined the types of interdependencies in a rather confused and incomplete way. Biggiero & Sevi (2005) review this literature showing inconsistencies, problems and defects, and bridging those definitions with systems science approach and with our definitions. Here and in next section we can give just some reference.

In sum we have indeed a case –parallel connection- of joint dependence from an external system, a case –sequential connection- of mono-directional dependence, and finally a case –reciprocal connection- of true interdependence. Hence, this field of research should be properly called the theory of systems connection, or coupling as is properly said in systems science. However, we chose to hold the label of "theory of interdependence" as used into the field of organization science, because indeed, notwithstanding this issue has been initially and effectively began and addressed by systems science, its development and improvement into the field of social sciences has been done by organization science. Moreover, the treatment received by systems science was indeed not so clear and complete as it is proposed here. For all this we believe that the "natural audience" for this field of study are social scientists, and among them especially socio-cyberneticians, organization and management scholars, economists and sociologists. Therefore, in order to facilitate the recognition of this topic, we decided to hold the same label "theory of interdependence".

3. The Architecture of the Model and the Methodology

3.1 The general structure.

Our model formalizes the three basic types of interdependency and analyzes the effects of relational and structural complexity on group performance[1]. The model has a hierarchical structure, which sees on the top two "objects": TaskCreator and WorkGroup. The former generates tasks while the latter manages agents' behavior. Through a frequency chosen by the model user, the former gives the quantity and quality of tasks to be executed. Thus, it operates as an input system for the group of workers, simulating another group belonging to the same organization or the external environment. It defines also the structural complexity by creating tasks with more or less components, depending on the goals of the model user (fig. 2).

A task is constituted by components, which are made by phases, each of them represents (absorbs) one step of simulation that is one interval (piece of time). What characterizes a task as parallel, sequential or reciprocal is the type of interdependency holding between its components. Here we make the simple assumptions that in one single task there is only one type of interdependency and that between the tasks, whatever is its interdependency, there is only parallel interdependency[2]. This means that the type of interdependency refers to the connections between the components of a single task, and so that relational complexity marks each single task and not its relationships, which is supposed to be always of the parallel type. This holds also in the case of mixed-interdependency groups, where the mix refers to the presence of tasks characterized (marked) by different types of interdependencies.

The phases of each single component, regardless of its number, are always connected by a sequential interdependency.

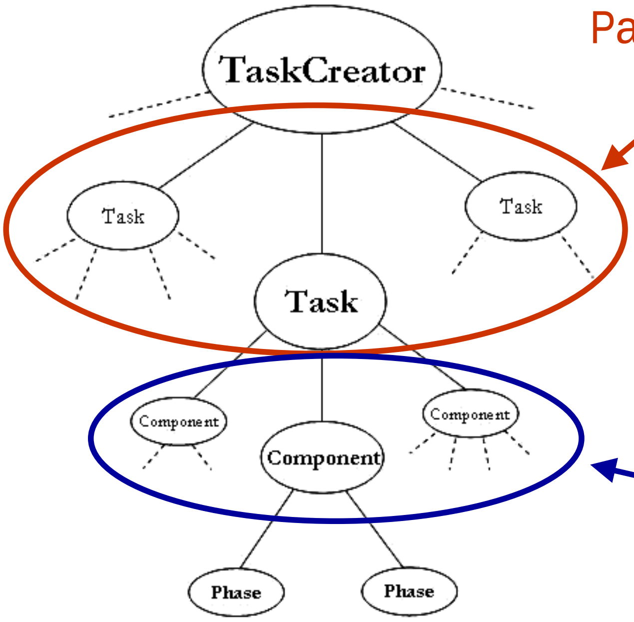
Fig. 2

[1] The program running the model is available on the URL of Knownetlab, the research center where the authors work: www.knownetlab.it. To run the program is needed the platform and language LSD (Laboratory on Simulation Development), available at www.business.auc.dk/lsd. With the program even some indications on its concrete handling are given. Anyway, the authors are available to give any support to use it and to questions concerning the topics here addressed.

[2] Here we chose the simplest type of parallel interdependency, that one without any time constraint.

The model

Parallel free interdependency



Interdependency
- Parallel
- Sequential
- Reciprocal

3.2 Agents' behavior

At any interval each agent can do one of three things (tab. 1): search, that is looking for a phase (of a component) to work on; working in the phase where s/he is currently eventually engaged; inactivity, because he cannot do any of the previous two things. In the basic version of the model we suppose that all agents are motivated to work, that they have all the same competencies, and finally that they choose randomly which phase to execute. In this paper, while the former two assumptions remains invariant, the latter will be modified by the introduction of norms, which force agents to follow a specific behavior. These norms are coordination mechanisms and have been set up in a way to be further constraining agents' behavior, so to increase group performance.

Tab. 1 **Agents' behaviors**

Behaviors	Descriptions
Search	Looking and engaging for a phase (of a component of a task)
Execution	Working on that phase
Inactivity	She doesn't find anything to do

The first behavior –the search- is followed by an agent who is not already engaged, and therefore she looks for a (phase of a component of a) task. Such a search consists in checking all phases of all components of all tasks existing in that specific interval in TaskCreator, and then in choosing one randomly. If she finds a task, then she engages in that same interval, and in the following interval she works it out. So, it is clear that for each time spent working there is a time spent searching and engaging. If she doesn't find any free task, then she waits for the next step to start a new search. Of course, when an agent engages the others cannot engage into the same phase, and so doing she automatically reduces others' alternatives of engagement. In order to avoid that some agent had a smaller set of choices, the model changes their priority of choice every time.
Agents working in a certain phase will end the corresponding component, thus, moving to the next phase until the whole component is completely executed. In this case, while moving from a phase to the next one into the same component there are no intervals spent for searching. Once ended up the last phase of the component, the agent will be free to search a new phase in a new component of the same task or of another task.
The third possible behavior is the inactivity. It means that, temporarily or definitely, she cannot work out the phase she has (randomly) chosen and has been engaged. This situation occurs in one of two cases: (i) she doesn't find any free component to be engaged in; (ii) she chose a phase of a component which is connected in reciprocal interdependence with other components, whose feedback is missing or delaying. In other words, she needs the collaboration of other agents, who at the moment (or definitively) are not available.
Consequently, a phase can be in one of the following six types of state:

- not-executable, because –in the case of reciprocal connection- it is waiting for a feedback, or because –in the case of sequential connection- its preceding phase has not been executed;
- executable, because there is parallel connection or –in the case of sequential connection- the preceding phase has been executed or –in the case of reciprocal connection- the feedback is ready, or because, regardless of the type of connection, it has been chosen a phase at the beginning of a component.

3.3 Norms and Coordination Mechanisms
Norms and coordination mechanisms would be not necessary if the pure chance were sufficient to assure a satisfying, even if not maximum group performance. However, as we will discuss in next section, through our model we experimented that, without some elementary norm, the performance is unsatisfying for parallel connections and nearly zero for the other two types of connection. Besides the supposition that agents are motivated to work, and so that they cannot refuse to work, we have hypothesized the following (tab. 2) norms and its corresponding coordination mechanisms (Mintzberg, 1979, 1983).
In another paper (Biggiero & Sevi, 2005) we explored the influence of each of these norms on group performance, starting from the simplest to the most complex norm. Since here we are interested to investigate the effects of relational and structural complexity on group performance, grounding on some results from that work we chose to run just the norms…

The issue of the role played by norms and coordination mechanisms pertains to the theory of coordination and not to the theory of interdependence. It's clear that while the former deals with concrete or abstract objects, like systems, tasks, activities, etc., the latter deals with and refers to agents. Tasks (systems) are connected in a certain way, and that way is defined by the technology. Agents are coordinated in a certain way, and that way is defined by the norms that somebody (or the agents themselves) sets up and applies. The rationale for the need of norms and coordination mechanisms is more complex and cannot be extensively discussed here. We can just say simply that without them the group performance results unsatisfying or just null. As we will argue in next section, the need for norms progressively more complex can be carried on as the demonstration that some type of connection is more complex than others. Moreover, the complexity of the norms can be measured as well as -and in the same way as- the complexity of the types of connections. Here we will attend an exemplar confirmation of the low of requisite variety: more complex connections can work satisfactory only by applying more complex norms. In other words: complexity can be faced only by a proportional complexity.

Tab. 2 Norms and coordination mechanisms

Type of norm	Description	Corresponding coordination mechanisms
1. Basic Norm	Once started a component, agents must end it up moving from the current to next phases.	Planning
2. Anti-inactivity Norm (1 + 2)	Agents forced to inactivity because engaged in a locked component leave it immediately and move to search another component.	Planning
3. Outplacement Norm (1+2+3)	Agents avoid to be engaged in locked components. In sequential connection they avoid components following components not yet executed, while in reciprocal connection they avoid components that are waiting for feedback.	Planning
4. Focusing Norm (1+2+3+4)	Agents give priority to choose tasks in progress.	Planning
5. Norm of Collaboration (1+2+3+5)	Agents give priority to choose tasks under working by other agents.	Reciprocal adaptation

3.4 The methodology and working of the model

Our model analyzes the relational complexity of task interdependencies, showing how, in order to give a satisfying performance, more complex connections require more complex norms. The size of the group is fixed to 3 agents (members). Group performance is measured by two indexes:

- *effectiveness*: number of executed tasks divided by the maximum number of executable tasks. This index varies between 0 and 1;
- *efficiency*: number of working steps divided by the maximum number of steps that can be employed in working. This index refers to the degree of use of inputs, which here is constituted by the agents' time actually employed for working divided by the maximum number of steps that the group can employ for working, thus excluding the steps for engagements.

Two aspects should be underlined: (i) these indexes depend on group size and on structural complexity; (ii) maximum efficiency doesn't necessary correspond to maximum effectiveness because only through an adequate coordination the agents can avoid to waste time and resources on tasks that will be not completed.

We run 10 simulations per each test, using different values for the random generator, so to prevent its possible influence on results. Data record the mean of performance indexes given by each series of 10 simulations. Each simulation lasts 1000 intervals, and the frequency of task creation is 0,8, so that at each step there is a probability of 0,8 to be created a new task, and in average in each simulation are generated 800 tasks. Such a high frequency is justified by the aim to show significant differences between different groups, because low frequencies allow agents to easy work out all tasks. Each group is specialized in one type of interdependency, excepted for the cases of mixed-based groups.
According to a satisfying, and hence non-maximizing approach to social sciences (Simon & March, 1958; March, 1994, 1997), it is important to underlie two types of group performance: the conditions under which it is reached the maximum and the satisfying performance. In the former case it should employed norms able to give the maximum effectiveness and efficiency, while in the latter just the maximum efficiency and a satisfying effectiveness. The rationale is that groups whose members work efficiently –that is, they don't waste time in searching in vain or remain tapped in blocked phases- and whose effectiveness is acceptable can be judged positively. At least, the advantages coming from a desirable increase of further effectiveness should be compared with the disadvantages due to the employ of more numerous and/or more complex norms. Actually, a crucial point -that we will discuss in section 5- is that each norm has its own cost, and that more complex norms are more costly. Adding more and/or more complex (costly) norms increases effectiveness maybe up to the maximum, but it should be checked in each specific case whether the advantages coming from the maximum effectiveness do compensate the disadvantages coming from managing more numerous and eventually more complex norms.

4. The Effects of Relational Complexity

Classical and recent authors of organization and management sciences defined the types of interdependencies in a rather confused and incomplete way and argued that they have different degrees of complexity, and that more complex types correspond, that is they are adapted (suited) in more complex organizations. Moreover, it is argued that in more complex organizations the types of interdependencies cumulate from the simplest to the most complex ones. According to Thompson (1967: 55) "all organizations have pooled interdependence; more complicated organizations have sequential as well pooled; and the most complex organizations have reciprocal, sequential and pooled organizations".
Following this approach, organizations facing with parallel interdependencies are not complex, and don't need special devices to be effective. Proceeding with sequential and then with reciprocal interdependencies the complexity grows up, and consequently coordination becomes more complex too. This theoretical perspective sounds very consistent with socio-cybernetics and confirms the law of requisite variety (Ashby, 1956): complex organizations are characterized by complex interdependencies. However, besides that fact that all these authors confuse relational and structural complexity and also confuse the type and the intensity of interdependency, the problem that here we want to underlie and that actually moved our research is that they didn't supply any demonstration of this ordering of the complexity of interdependencies, neither developed sufficiently the implications of such ordering. Moreover, as in most fields of social sciences until few years ago, they didn't build their ideas in a formal way. Finally, the empirical support was always episodic and statistically meaningless. Thus, now we are going to fill in this gap. Our analysis will confirm their main suggestions but the radical difference is that now such statements will be based not on the "ipse dixit", that is on the reputation of these authors, but rather on a rigorous reasoning and then on a simulation model, that is on an algorithmic demonstration.
We can measure relational complexity in terms of the types of links connecting two (or more) systems (tasks). Actually Ashby (1962) formerly argued that the elementary and formally rigorous definition of organization is the existence of a functional relationship between two systems. Following this line of reasoning, the crucial point is that some links are more complex then others,

and this degree of complexity is into the "degree of constraint" that the connected systems put over each other. As we have seen (fig. 1), in parallel connection the two systems are almost independent, because they are linked just through resources (input) sharing and/or through the contribution to the same output. These are very weak constraints indeed.
The strength of the constraint increases moving to the sequential connection because the following system *depends* on the output of the preceding one. It is not just a temporal sequence, like in the case of the parallel sequence, where a task is just executed after another one but in terms of direct input-output connections they are independent. Here the execution of the successive task depends on the input given by the preceding task. Thus, according to our definition of complexity in terms of the degree of constraint, the sequential is more complex than the parallel connection.
Finally, the reciprocal connection has the highest degree of constraint because it operates in both directions: system B depends on the input coming from A's output, and vice versa. Here we see a double constraint, and then the reciprocal is the most complex connection. Moreover, the double constraint makes a radical difference, because it constitutes the essence of feedback, and therefore the essence of the cybernetic quality. We could say that, lacking the feedback relationship, parallel and sequential connections are not cybernetic interdependencies. From this reasoning we conclude that the ranking of the three basic types of interdependencies in ascending order of complexity is the following: parallel, sequential, reciprocal. Biggiero & Sevi (2005) express this reasoning in formal terms.
The results of our simulation model (tab. 3) confirm the conclusions of the previous reasoning. The Basic Norm guarantee a satisfying performance only to the group working tasks connected with parallel interdependency, while in the other two cases agents are locked into components that cannot be executed. In the sequential case too many agents engage into components successive to others not yet completed. In the reciprocal interdependency they wait too long for a feedback from other components. In almost all simulations agents are almost all locked already in the first step, so that the group enter in an irreversible paralysis.
The Anti-inactivity Norm prescribes that agents locked into a phase leave it immediately (during the same interval when they engage in it) and search for another phase. Hence, this norm works out the situation of inactivity but doesn't prevent it, because it intervenes on the effects and not on the causes of inactivity. This norm leaves untangled the performance of the parallel group because there is no inactivity to be worked out, but improves a little bit the sequential group. The performance of the reciprocal group remains definitely unsatisfactory. Indeed agents consume a lot of time in the activity of searching. We need another norm, able to prevent choosing locked components. This is the Outplacement Norm.
While the parallel and the reciprocal groups remains untangled into its respective acceptable and bad performance, the sequential group shows a satisfactory performance, reaching the maximum efficiency and half effectiveness. This norms implies that agents know the right sequence of execution of each task. However the performance of the reciprocal group is still very low because, even if agents avoid to choose locked components (that are waiting for feedback), agents don't focus their efforts in executing the same tasks. This problem can be by-passed through another norm.
The Focusing Norm prescribes that agents choose with priority incomplete tasks. This way we attend a sharp increase of performance, which jumps to the maximum for both parallel and sequential groups. Focusing on the same tasks all the efficiency generates effectiveness. Even the reciprocal group benefits substantially from this norms, but doesn't yet reach the maximum performance.
To this aim it is necessary another norm, the Norm of Collaboration, which prescribes that agents should choose with priority tasks *currently* under working, that is, incomplete tasks on which agents are currently engaged. As it can be seen, this norm is more restrictive than the previous one, because, in order to get priority, it is not enough that a task is incomplete. It is even necessary that in that task other agents are currently working on. By adding this norm all the three types of

interdependency reach the maximum performance. It is very important to underlie that this norm is qualitatively different from the previous ones: it establishes a coordination between agents, while the others intervene on the relationships between agents and tasks.

Tab. 3 Main results from the simulation model

		Effectiveness	Efficiency
1. Basic Norm	**P**	0.27	Max
	S	0	0
	R	0	0
2. Anti-inactivity Norm	**P**	0.27	Max
	S	0.15	0.78
	R	0.04	0.59
3. Outplacement Norm	**P**	0.27	Max
	S	0.45	Max
	R	0.07	0.72
4. Focusing Norm	**P**	Max	Max
	S	Max	Max
	R	0.78	0.79
5. Norm of Collaboration	**P**	Max	Max
	S	Max	Max
	R	Max	Max

We used the norms in a cumulative way, that is, the norm 2 includes the norm 1, and the norms 3, 4 and 5 include its respective previous one. If measured in terms of the degree of constraint –as we did for the interdependencies- moving from the first to the fifth norm the degree of complexity increases. It means that at each upper level there are more prevented agents' behaviors. There is a growing number of fiat, until the highest complexity of the Norm of Collaboration, that acts directly on the coordination between agents. Being more complex means that its implementation and working becomes more difficult, and supposedly costly.

Conclusions

Our simulation model tells us that groups working on more complex interdependencies can reach an acceptable performance only by means of more complex norms. Reciprocal interdependency can be managed satisfactory only through the Focusing Norm, and reaches the maximum only through the Norm of Collaboration, which actually includes 5 norms. The sequential interdependency can be satisfactorily managed by applying the Outplacement Norm, which includes 3 norms, and the parallel interdependence manifests a minimum (low) performance already with only the Basic Norm. Here we can find an exemplar confirmation of the law of requisite variety: complex interdependencies can be manage only through complex norms.

These results have also a normative side: it is redundant to employ complex norms to coordinate groups working on tasks connected by simple interdependencies. Of course these results, and especially this normative side should be taken with prudence, because our model is still extremely simple. The introduction of knowledge exchange, competencies, personal conflicts, learning processes, and task specificity could change them significantly. However, by now we obtained two relevant results: 1) an algorithmic confirmation of the law of requisite variety; 2) an algorithmic demonstration of the ordering of interdependencies in terms of complexity. This latter result confirms suggestions proposed in organization science, but left theoretically and empirically unproved.

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