Division of Labour and Social Coordination Modes
A simple simulation model[1]

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Abstract

This paper presents a preliminary investigation of the relationship between the process of functional division of labour and the modes in which activities and plans are coordinated. We consider a very simple production process: a given heap of bank-notes has to be counted by a group of accountants. Because of limited individual capabilities and/or the possibilities of mistakes and external disturbances, the task has to be divided among several accountants and a hierarchical coordination problem arises.

We can imagine several different ways of socially implementing coordination of devided tasks. 1) a central planner can compute the optimal architecture of the system; 2) a central planner can promote quantity adjustments by moving accountants from hierarchical levels where there exist idle resources to levels where resources are insufficient; 3) quasi-market mechanisms can use quantity or price signals for promoting decentralized adjustments. By means of a simple simulation model, based on Genetic Algorithms and Classifiers Systems, we can study the dynamic efficiency properties of each coordination mode and in particular their capability, speed and cost of adaptation to changing environmental situations (i.e. variations of the size of the task and/or variations of agents' capabilities). Such interesting issues as returns to scale, specialization and workers exploitation can be easily studied in the same model.

".... I still believe that, by what is implicit in its reasoning, economics has come nearer than any other social science to an answer to that central question of all social sciences: How can the combinations of fragments of knowledge existing in different minds bring about results which, if they were to be brought about deliberately, would require a knowledge on the part of the directing mind which no single person can possess? To show that in this sense the spontaneous actions of individuals will, under conditions which we can define, bring about a distribution of resources which can be understood as if it were made according to a single plan, although nobody has planned it, seems to me an answer to the problems which has sometimes been metaphorically described as that of the "social mind".

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(Hayek, Economics and Knowledge, in *Individualism and Economic Order* ; Chicago, The University of Chicago Press, 1948, p. 54)

1 - Introduction.

Division of labour and coordination.

It is customary to consider economic organizations as social systems which make coordination of individual plans and decisions possible. Little attention has been instead given to the connection between forms of coordination and a dynamic process which has been characterizing industrial societies: the process of increasing division of labour.

The fact that the two processes have been somewhat connected in their historical development is hardly questionable: as economic organizations increased the degree of division of labour and knowledge, the problem of coordination between a rising number of increasingly inter-related producers and decision makers became more and more complex. Coordination of distributed decisions by markets, firms and other economic institutions appears as the other side of the process of division of labour.

The historical evidence still does not clearly show whether the two processes have co-evolved as two aspects of the same phenomenon or have mainly proceeded independently, in terms of both temporal and causal relationships (cf. Polanyi 1958), but some evidence at the microeconomic level - such as analyses of the processes of design and managerial planning in modern corporations - seem to support the hypothesis of co-evolution. In economic organizations in which planning and design are highly purposeful activities, division of labour and coordination are the joint result of these very activities. But can the hypothesis of co-evolution of coordination and division of labour be extended also to the cases in which - both in markets and in organizations - they are not the outcome of a purposeful planning and design process, but are emergent and partly unintended properties of the interaction between distributed decision-making activities (cf. Hayek 1948)?

Behind this question lie two different ways of conceiving the division of labour:

1) as the outcome of a single mind, which designs, devides and coordinates: this is the view behind the Marxian capitalist and the Schumpeterian entrepreneur;

2) as the emergent, unplanned and unconscious outcome of the interaction of local and incomplete decisions.

We believe that an intermediate form can be found in real large business organizations, where both the two forms, top-down conscious design and bottom-up decisions whose outcomes are partially unintended, co-exist in a mixed and complex way. To understand why this is so we have firstly to take into considerations the role played within them by routines and contracts; both routines and contract are necessarily incomplete and partly tacit, and this implies that noticeable discretionary margin must be left to the actors and incompleteness and tacitness bring about cognitive conflicts.

To be persuaded, suppose that the top management puts into place a re-design of the organization in order to react to some kind of environmental change. The implementation of the new division of labour within the organization which is required by such a change gives rise to a complex process of adaptation which is far from what believed by the traditional theory of planning: from one hand in fact the implementation of a new organizational design requires managers and employees to re-think their jobs and revise their competences; from the other, to be effective, any new design requires local checks and readjustments, i.e. the resolution of cognitive conflicts arising from the match among the general requirements of the project and the specific, idiosincratic knowledge arising from the personal knowledge of any single agent.

This require to briefly discuss the role of managers: for what has been said, we cannot clearly separate *managing* by *doing*:

> "... the blue collar worker on the most routinized assembly line must repeatedly make decisions about how to handle nonstandard situations, and in particular when to call one to the attention of the supervisor. On the other hand, sales managers, in addition to managing their salespersons, often spend considerable amounts of time with clients, engaged in selling, and thus in "doing"" (Radner 1992).

"Doing", i.e. the application of a given routine, is never a mere execution of given rules but always involves some discretionary behaviour, if anything because a fully specified routine, which does not leave any space for autonomous decision-making, would require an endless list of contingent behaviours. The essence of managerial activities seems rather to lie in the capability to fill knowledge and information gaps and in the capability to design the organization of labour and "imagine how to do".

Therefore top-down plans - which are necessarily incomplete for reasons we will discuss below - have to match pieces of knowledge and skills which are largely local and tacit and therefore they inevitably have a largely uncertain and unintended outcome.

Before discussing the reasons of the incompleteness of planning, it is useful to note that, when considered in its connections with the process of division of labour, the very notion of coordination takes a different meaning from the one implicit in neoclassical economics. For the latter coordination means making individual and independent decisions compatible: here instead the problem of coordination concerns the relationship between the top-down activity to design new organizational set-ups and the adaptive, intelligent bottom-up reactions by managers and employees, which should give rise to a better adaptation of the organization to the external environment.

Division of labour, distributed knowledge and specialization.

The analysis of the process of division of labour as a primary determinant in economic development, goes back to Adam Smith and lies at the heart of classical economics. But little of these early analytical efforts have been continued in modern neoclassical economics, and have been brought back to their central role only within recent non-neoclassical studies of the process of technological evolution (cf., for instance, Dosi *et al.* 1988).

A possibly fruitful way of interpreting the process of division of labour is to consider it within the general framework of the theory of problem-solving. From this point of view, the division of labour can be interpreted as a process of decomposition of problems into sub-problems to be solved independently. Direct observation of the behaviour of organizations and individuals as problem-solving activity - within the tradition initiated by March and Simon - suggests that such behaviour is a peculiar and unstable balance between two opposite situations: on one side purely routinized behaviour, in which a series of operations are repeated again and again, on the other side an active and conscious search for solutions to new problems or new solutions to old problems faced by the organization.

Without entering the vast debate on how to formally represent problem-solving activities, some general points are worth mentioning for their relevance to the subject of this paper.

First, problem solving activity is characterized by a search in the space of problems, which generally leads to the decomposition of the original problems into at least partially independent sub-problems. If such a decomposition is feasible, sub-problems can be solved in a parallel way and subsequently coordinated: the original problem is therefore decomposed into a set of connected sub-problems. In the language of economics and organization science, this corresponds to the expectation that the decomposition of a production process (*lato sensu*) into independent sub-systems, which can be dealt with in relative isolation and in parallel, will lead to increasing returns, in spite of the coordination costs which the decomposition brings about.

Second, the working hypothesis we propose - along the lines of Simon and March - is that the search in the problem space, based on the division of the given problem into sub-problems, is a model for the division of knowledge; even if division of knowledge and division of labour are not the same process (two employees cooperating in the same organization can have the same competences and largely overlapped knowledge but divided and different jobs) the former is necessary to the latter.

Third, it must be emphasised that the search in the space of sub-problems is a highly uncertain and conjectural process. In fact, when a problem is decomposed into a set of sub-problem, generally not all the sub-problems will be immediately solvable and consequently they will be in turn decomposed into simpler ones. The decomposition then recursively proceeds until all the relevant sub-problems have been solved. The procedure by decomposition is therefore a conjectural one for the two following reasons:

a) there is no set of decomposition rules which *a priori* allows agents to achieve a certain result;

b) subjects can verify the solvability of the original problem only when all the relevant sub-problems have been solved (cf. Egidi 1992).

This implies that plans and projects within firms are not merely executed by different subjects but they necessarily require a multi-agent process of learning and adaptation which can involve cognitive conflicts among the different actors.

These feautures allow us to consider coordination *within organizations* as the complementary part of the division of knowledge and labour which follows the realization of a new project; the further the division of labour proceeds, the more the different divided parts require coordination and the more information becomes dispersed. A crucial problem then arises: can we assume that the coevolution of division of labour and coordination take place also within markets?

A first approach (cf. Coase 1937) would claim that markets coordinate only (by means of price mechanisms) whereas the division of labour is entirely performed within organization. A more careful examination would suggest that the two processes take place in a complementary way in both the organizational set-ups, market and business organization, the main difference being the degree of awareness which characterizes the actors of the process.

The context of shumpeterian competition is a good starting point to clarify how division of labour and cordination can take place in the market: suppose that a cluster of product innovations arise in the economic system. If the new products substitute old intermediate goods, they will activate the modification of the routines involved and a "second generation" of adaptive innovators will arise: they in turn, by using the new products will produce either new goods or the old ones in a new manner. In the first case, a dynamic innovation process arises, in which new projects lead to the modification of other projects. It must be noticed that, it is not merely a matter of spreading of an innovation. On the contrary, what we are describing is an "avalanche" of innovations which are activated recursively by the original cluster of innovations. As a consequence of the original innovative actions two different "responses" of the system could occur. The first, without altering the basic structure of the division of labour, gives rise to local dynamic processes. In other cases, - often going beyond the intentions and the expectations of the innovators - the reaction of the system causes a new definition of division of labour, knowledge and competences within the economic system.

This clarifies how a new division of labour and knowledge can take place within markets. Moreover, it bring us to a crucial point: the coordination process by market strongly involves the transmission of knowledge and competences: prices does not convey sufficient information to support coordination processes which follow a division of labour.

This importance of this point and the provisional conclusion we have reached are reinforced if we consider an intermediate organizational set-up, as does Williamson in his "fundamental transformation". When two or more contracting parts (business enterprises) engage into a new common project, this normally will require an improvement in human and physical assets internal to each enterprise, and a transfer of knowledge among the enterprises. The emergence of sunk costs in phisical and human capital guarantees the strength of the links among the parts. Even in this case, the relationship among firms which takes place in the market will involve not only price signals but also (and fundamentally!) the transmission of pieces of knowledge and information; conflicts and bargaining between the parties will most likely solved by using the voice option instead of exit (Hirshman).

As Simon points out

> Markets represent only a part, if an important part, of the channels of communication and coordination between organizations (Mattioli Lectures, forthcoming).

The moral of this part of the story is that the transfer of knowledge and competence is a fundamental aspect of coordination which takes place not only within organizations but also among organizations on markets.

Even if we believe that to try to shed light on the properties of division of labour and coordination, and on their co-evolution can add some useful clarification to the matter, to model this kind of process is far from our capacities and intentions. More modestly we intend to pick up some of the properties discussed above, and try to compare the performances of different coordination forms which arise from the division of knowledge and labour in a context of boundedly rational behaviour. In the next two sections the relevant assumptions will be formally discussed.

Division of Labour and Returns to Scale.

A fundamental question which has been already hinted at is whether and under which conditions sub-problem decomposition - that we suggest as a useful representation of the process of division of labour - can generate more efficient form of organization of production. This question can be answered in many different ways: one of first analyses was provided by Simon (1962) with his parable of the two watchmakers, called Tempus and Hora. Watches are complex objects made up of a very large number of small pieces, Tempus just assembles his watches sequentially and every time he is disturbed - for instance by his clients' phone calls - he has to start the assembly all over again. Hora instead proceeds by first assembling subunits of only a few components and then putting them together, every time he makes mistakes or is disturbed by external events he will have to start again assembling only the current subunit. His average completion time for a watch will be therefore much shorter than the one of a watchmaker who does not divide the task into subunits and has to start again from the beginning every time he makes a mistake.

In this example there is a clear advantage in the division of labour: when a perturbation occurs in a sequential system, it affects the whole system, when instead it occurs in a system made up of small independent and parallel sub-units it will not propagate outside the affected sub-unit. But if we rule out the possibility of perturbations and mistakes, this advantage disappears and the parallel system seems rather less efficient because of its higher coordination costs. Only if we consider the positive long-term effects that the division of labour might have on the individual working capability, because of learning-by-doing and specialization, can we again find advantages of an increase of the degree of task decomposition. Learning seems therefore a key factor in explaining the division of labour. But how do individual learning processes coordinate in a framework in which the very definition of tasks is an emergent property [2]? In the remaining part of the paper we will investigate this question by means of a very simple model of division of labour and a few simulations of different social coordination mechanisms.

2 - Division of labour in the accountants' model.

We try to elaborate on some of the points outlined in the previous section by means of a simple model of organization, which will be then made a little richer. The model is the accountants' model suggested by Sobel (1992) and directly addresses the problem raised by Simon's parable of the two watchmakers.

Suppose that the problem to be solved is counting an unknown and possibly very large number of items, for instance dollar bills, and deliver a correct answer. Each accountant is characterized by a certain productive capacity, i.e. the number of bills he can successfully count in a given time interval, or, alternatively, by a certain probability of making mistakes, which we can plausibly assume to increase with the time he spends counting, because he gets more and more tired and error-prone, and/or more and more bored and likely to have his attention turned away from his job. In the first case the accountant cannot simply work anything more than his productive capacity, in the second he has no given limit, but the likelihood of him making a mistake will increase with the size of his workload. If an accountant makes a mistake and does not realize it, he will jeopardize the result of the entire counting process, if he is aware of the mistake he will instead be forced to start again counting from the beginning. In all these cases - as already discussed in the introduction - splitting the task into sub-tasks is necessary to ensure the efficacy and efficiency of the production process.

Of course the decomposition of the global task into subtasks must be technically possible, which is usually the case only to a certain extent, in the sense that there are usually technical indivisibilities. Our example of the counting bills problem is in this sense a very simple one because of the total decomposability of the problem into whatever subtasks of whatever dimension, limited only by its integer size (i.e. the minimum subtask is counting one bill and no less).

Suppose that the global task is to count a stack of N bills of one dollar. Suppose also that each accountant can successfully count at most k bills in a given time interval, at the end of which he issues a new bill whose face-value corresponds to the amount of one dollar bills he has counted (at most k). Such bills are put in a new smaller stack and can be counted by other accountants who will issue new higher-valued bills and so on and so forth, until a stack of "fictitious" bills is obtained whose size is no bigger than k and can be therefore entirely counted by one single accountant, who will be able to announce the total number.

Let us illustrate the problem with a trivial example: suppose that N=10,000 one dollar bills is the size of the task and all accountants have a counting capacity of k=10 bills. We will need therefore L_1= 1000 accountants at the first level, who will count the 10,000 bills and issue 1000 bills of face value $10 and put them in a new stack. To count this new stack L_2= 100 accountants are needed, who will now issue 100 bills valued $ 100 and put them in a new stack which needs L_3= 10 accountants to be counted. Finally only one accountant (L_4= 1) is

[2] The problem of coordination of learning processes within an economic organization has been also studied, in a framework in which the division of labour is given, in Marengo (1992).

needed to count these 10 bills of $ 1,000 and finally announcing the result of the entire counting process. All in all we need 1111 accountants to complete the task in 4 time units, and we obtain a perfect pyramidal subdivision of subtasks.

More in general, if $N=k^n$, i.e. the size of the task is an integer power of the individual productive capacity, the optimal hierarchical structure is formed by

$$n = \log N / \log k$$

levels, each of them formed, respectively, by 1, k, k^2, ..., k^{n-1} accountants.

In less special cases the ratio log N / log k is not an integer number and therefore the number n of levels of the pyramid will be the first integer greater or equal to such ratio, this implies that the pyramid must necessarily contain some slack resources which cannot be fully exploited[3]: let us consider a general task of size N bills, if every accountant can count up to k bills, the lower level of the organization will produce N/k bills, the second N/k^2 and so on up to level w such as $N/k^w \leq k$. If we have exactly $N/k^w = k$ all resources in the pyramid will be fully exploited, otherwise the productive capacity of the accountant at the top of the hierarchy will not be entirely exploited. Moreover the numbers N/k, N/k^2 .... N/k^w might not be all integer: some idle resources will therefore appear at each level for which the ratio is not an integer number.

The ratio between size of the task N and total amount M of labour required for its completion is given by

$$R(k) = N/M = k^n / 1+k+k^2 .... k^n = (1-k)k^n / 1-k^{n+1}$$

thus $R(k) \rightarrow 1$ as $n \rightarrow \infty$ and the process exhibits asymptotically constant returns to scale.

If the number N of bills to be counted increases, the organization can respond by increasing the level of employment and/or the productive capacities k. The latter can increase also with N constant (increase of productivity, or marxian exploitation).

3 - Division of labour and coordination.

If, as argued in the previous section, dividing complex tasks into sub-tasks to be handled separately is usually necessary and/or more efficient than carrying it out altogether, this very process of division of labour determines a growing and non-trivial coordination problem. The previous section analyzed some formal properties of a toy model of division of labour and showed under which condition a pyramidal structure can implement an optimal sub-division of a given task. In this section we examine instead how such a structure could emerge in different institutional set-ups and adapt to random environmental disturbances.

Generally speaking, we can imagine at least three different ways of attaining coordination:

a) a central planner can use the model outlined in the previous section to design the optimal organization and adapt it to changes of the size of the task and/or changes of the

[3] The presence of such idle resources is a possible reason for the existence of economies of scale in this technology: a multiplicity of tasks can in fact be internalized in one single organization, which can therefore reduce the amount of idle resources. In the above example, two separate tasks of 5,000 $ would be more efficiently handled by a single organization rather than separately. But this issue lies outside the scope of this paper.

workers' capabilities. To perform this task, he or she needs to know at every moment in time the exact values of every worker's productive capacity and the size of the global task [4].

b) a boundedly rational central coordinator, instead of attempting an exhaustive plan, can adaptively adjust the organizational structure by moving workers where needed. Such a coordinator can operate as a sort of Walrasian auctioneer: he or she receives messages on all the flows between the different levels of the organization and on unused resources and moves workers in such a way as to fill the gaps between demand and supply between adjacent levels of the hierarchy.

The information requirements of this boundedly rational coordinator are quite different from a fully rational central planner's: while the latter needs precise information about the size of the overall task and the characteristics of each accountant, the former needs information on all the flows between different hierarchical levels. It must be also pointed out that whereas the central planner needs precise information - as even small amounts of noise will make the entire organization ineffective - the boundedly rational coordinator will generally only need some signals (even qualitative ones) on supply-demand disequilibria. Moreover this boundedly rational coordinator can be also fully replaced by inter-level coordinators which take care only of the demand-supply equality at one interface between levels regardless what happens in other parts of the organization.

As to the kind of cognitive capabilities which are required by the two different kinds of decisions which the central planner and the boundedly rational coordinator have to take, the former has to develop a highly abstract and general decision rule. This involves that the problem has been understood in its general features and decomposed into sub-problems. The boundedly rational coordinator on the contrary can adaptively implement the organizational structure, with a process of trial and error which can proceed without a general understanding of the problem (cfr. Dosi and Egidi (1991), Dosi et al. (1994)).

But the process of adaptive coordination involves a cost, given by the loss of efficiency incurred during the very process of adaptation. While in fact the perfectly rational central planner computes the optimal organization in his mind, the central coordinator carries out the design process in real time and corrects mistakes only after experiencing the loss of efficiency they cause.

On the other hand if the central planner makes mistakes, these are likely to damage more persistently the organization, because the latter is unable to process signals which detect the presence of inefficiencies and adjust consequently, and thourough re-design is always needed even to cope with small perturbations.

c) coordination can be achieved also with a completely decentralized mechanisms, a quasi-market in which each accountant adjusts his production and/or his position according to quantity and/or price signals which are independently processed by each individual. Each interface between levels of the organization constitutes a market where the accountants of the lower level sell the "fictitious" bills they produce and the accountants of the higher level buy them. Demand and supply in each of these markets depend on the number and productive capacity of the accountants at the two levels. Suppose, for instance, that the overall productive capacity at the lower level is not sufficient to supply the accountants at the higher level with enough bills, some of them will not be able to produce enough because of insufficient input level and will therefore tend to move to other parts of the organization. These adjustments could take place simply through simple quantity signal or through a more complex price

[4] This requirement seems rather paradoxical. Indeed if the planner knew exactly the amount of bills to be counted there would be actually no need to carry out the counting process. Although less strikingly, this paradox arises also in less caricatural production processes. Fully centralized and exhaustive planning would require perfect knowledge of every aspect of the production process: only in this case could the coordination problem be solved in the planner's mind without the need of local adjustments.

mechanisms of Marshallian type (for instance: excess demand generates a price increase which raises the profits of sellers, this attracts new sellers who make the supply increase and balance the initial excess demand).

A decentralized coordination mechanism of this kind requires only local information processing: each accountant can autonomously process disequilibrium signals according solely to his own local information (knowledge about his own characteristics) and without any need of directly knowing other accountants' characteristics. On the other hand such a mechanism requires a strong system of incentives: the search, by all the agents, for maximum profits. Finally, as in the case of a central coordinator, also decentralized coordination takes place through costly adjustments in real time.

To summarize, in case a) all the decision-making capability is concentrated in the central planner's mind, who has developed a highly context-independent coordinating rule ($n = \log N / \log k$). The accountants in the organization do not even have the possibility to send to the central planner signal of inter-level disequilibria. In case b), on the contrary, the central coordinator follows a behavioural routine based on disequilibrium signals sent by the accountants

In the next section of the paper we will study, by means of a simulation model, how coordination could emerge as an adaptive property in the different environments defined by centralized and decentralized coordination mechanisms and explore some of their properties.

4 - Division of labour and the emergence of coordination: a simulation model.

In the present section some of the properties of the coordination modes outlined in the previous section will be further investigated by means of a simulation model of adaptive learning based on Genetic Algorithms and Classifiers Systems (cf. Holland 1975 and 1986, Goldberg 1989, Holland *et al.* 1986).

Let us consider a population of h accountants. Each of them is characterized by two variables: his position in the hierarchy (i.e. the integer number which identifies the hierarchical level where the agent is placed) and his productive capacity (i.e. the maximum number of banknotes he can count in a given time interval). Both variables can be encoded by their binary representations: in our examples we have used a six-bits string to represent each accountant: the first three bits for his position in the hierarchy (levels 0 to 7) and three bits for his counting capacity (from 0 to 7 banknotes for unit of time). The i-th accountant is represented by the string:

$$A_i: \quad p_1p_2p_3k_1k_2k_3 \qquad p,k \in \{0,1\}$$

a set of h of such strings provides therefore, at each moment in time, a complete representation of the organization whereby the position in the hierarchy (level) and the task of each individual (productive capacity) are specified.

Accountants can both move (or be moved) across hierarchical levels and modify their productive capacity according to signals of input-output disequilibrium either at the individual (in the case of decentralized coordination) or at the inter-level interface (in the case of a boundedly rational central coordinator). Such signals, appropriately interpreted, constitute the condition part of the adaptively learning system.

1) case of the boundedly rational coordinator: the boundedly rational central coordinator is able to adapt the entire organization according to signals of disequilibrium/equilibrium at the interface between different levels of the hierarchy. He can be thus represented by a set of

condition-action rules where the condition classifies such signals and the action defines a complete organizational structure. More in details we have:

-.environmental messages (equilibrium/disequilibrium signals) are given by the catenation of 8 binary strings (one for each inter-level interface, including the interface between the last level and the "final demand"). Each one of these 8 sub-strings is composed by 2 digits:

$$s_1 s_2 \quad s \in \{0,1\}$$

where the first digit is set to 1 when there exists an excess supply at that interface and is set to 0 otherwise; the second digit is set to 1 when there exists an excess demand at that interface and is set to 0 otherwise.

- conditions are therefore strings of the same length (16 bits) as the environmental message which they classify:

$$c_{11}c_{12}c_{21}c_{22} \;\; c_{81}c_{82} \qquad c \in \{0,1,\#\}$$

- action parts are binary strings of length 6h which, as already mentioned, define a whole organizationally structure:

$$p_{11}p_{12}p_{13}k_{11}k_{12}k_{13} \;\; p_{h1}p_{h2}p_{h3}k_{h1}k_{h2}k_{h3} \qquad p,k \in \{0,1\}$$

An adaptive and boundedly rational central coordination can be in this way represented by a classifiers system. Here we just briefly remind its basic features (more details can be found, for instance, in Holland 1986, Holland *et al.* 1986, Goldberg 1989)

The adaptively learning system, which in our case is a model of a boundedly rational central coordinator, is a system of condition-action rules such those so far described. In addition, each rule is attributed a <u>strength</u> coeffcient - which, as a first approximation, measures how successfull that rule has been in the past - and a <u>specificity</u> coefficient (the number of bits in in the condition part which are different from the wild card #) - which measures the strictness of the condition, meaning that the smaller is the cardinality of the set of environmental messages which satisfy that condition, the higher is its specificity (the highest specificity belonging to rules whose condition are satisfied by only one environmental message).

This set of rules is processed along the following cycle throughout the simulation process:

I <u>Condition matching</u>: a message is received from the environment which informs the system about the disequilibrium/equilibrium conditions at the inter-level interface. Such message is compared with the condition of all the rules and the rules which are matched, i.e. those which apply to such a state of the world enter the following step.

II <u>Competition among matched rules</u>: all the rules whose condition is satisfied compete in order to designate the one which is allowed to execute its action, i.e. to implement the organizational structure specified by its action part. To enter this competition each rule makes a bid based on its strength and on its specificity. In other words, the bid of each matched rule is proportional to its past usefulness (strength) and its relevance to the present situation (specificity):

$$Bid(R_j,t) = k_1(k_2 + k_3 Specificity(R_j)) \, Strength(R_j,t)$$

Where k_1,k_2 and k_3 are constant coefficients.

The winning rule is chosen randomly, with probabilities proportional to such bids.

III Action and strength updating: the winning rule executes the action indicated by its action part and has its own strength reduced by the amount of the bid and increased by the payoff that the action receives, given the occurrence of the "real" state of the world. If the j-th rule is the winner of the competition, we have:

$$\text{Strength}(R_j,t+1) = \text{Strength}(R_j,t) + \text{Payoff}(t) - \text{Bid}(R_j,t)$$

IV Generation of new rules: the system must be able not only to select the most successful rules, but also to discover new ones. This is ensured by applying "genetic operators" which, by recombining and mutating elements of the already existing and most successful rules, introduce new ones which could improve the performance of the system. In this way new rules are constantly injected into the system and scope for new opportunities is always made available. Genetic operators in our simulations - as in standard classifiers systems - are crossover and mutation.

2) case of the decentralized coordination: in this case each accountant can automously move across the hierarchical levels of the organization and change its own productive capacity according to individual signals of disequilibrium. Some kind of market mechanism is thus necessary to generate such local signals which reflect global disequilibria. One of the simplest ways in which such a quasi-market could operate [5] is by delivering quantity signals through rationing: if at an interface between levels there is an excess demand, some (possibly all) of the accountants of the higher level will not be able to get all the bank-notes they would like to and will be subject to rationing on the demand side. If instead there is excess supply, some (possibly all) of the accountants of the lower level will not be able to sell all the bank-notes they would like to and will be subject to rationing on the supply side.

Thus, in this case, each accountant is an independent decision-maker which can be modelled by an autonomous classifier system, and the links between the different classifier systems are given by such rationing signals. Each accountant is thus represented by a set of condition-action rules where the condition classifies such signals and the action defines his own position/capacity pair. More in details we have:

- environmental messages (equilibrium/disequilibrium signals) are in general different for each accountant and given by a two-digit binary string:

$$s_1s_2 \quad s \in \{0,1\}$$

where the first digit is set to 1 when the accountant has been rationed on the demand side (i.e. there exist an excess demand at the interface between that accountant's level and the lower one) and is set to 0 otherwise; the second digit is set to 1 when the accountant has been rationed on the supply side (i.e. there exist an excess supply at the interface between that accountant's level and the higher one) and is set to 0 otherwise.

- conditions are therefore strings of length 2 bits which classify such environmental messages:

$$c_1c_2 \quad c \in \{0,1,\#\}$$

[5] Markets with prices are much more complex and to model them correctly we should introduce a series of hypotheses on individual utility functions, which would take us quite far from the core issue of the paper.

- action parts are binary strings of length 6 which define the accountant's position in the hierarchy and his productive capacity:

$$p_1p_2p_3k_1k_2k_3 \qquad p,k \in \{0,1\}$$

Each one classifier system of this type is then processed exactly through the execution cycle already described for the centralized coordination case.

The two coordination systems have been tested in a simple problem: the task is to count 25 bills, there are 6 accountants, whose capacity can vary between 0 and 7 banknotes and whose position in the hierarchy can vary from level 0 to level 7. Level 0 is a stand-by position: accountants in this position do not enter the production process [6]. Let us examine more in details the nature of the environmental signals which characterize the two institutional set ups:

1) in the case of the boundedly rational central coordinator, the winning rule's action part is decoded in order to obtain the corresponding organizational design. The productive capacity of all the accountants which are placed at the hierarchical level one is then summed up, in order to obtain the total demand of bank-notes at this level. If such total demand is smaller than 25, the environmental message will signal, in the following iteration, an excess supply (the first digit will be set to 1 and the second to 0) If, on the contrary, the total demand is bigger than 25, the environmental message will signal an excess demand (the first digit will be set to 0 and the second to 1). Only if the total demand is equal to 25 will the environmental message signal an equilibrium situation (both digits set to 0). The total supply of level 1 can now be computed in this way:

- if the total demand is smaller or equal to 25, all accountants of level 1 will be able to fully exploit their own productive capacity and thus the total supply will be given by a number of notes equal to the number of accountants, and each of them will have a face-value equal to the productive capacity of the accountant who produced it;

- if instead the total demand is bigger than 25, some accountants (randomly chosen) will be unable to fully use their own productive capacity. Total supply will be given by a number of bank-notes equal to the number of accountants of the first level who received at least one bank-note and the face-value of each of them will be given by the amount of used productive capacity of the accountant who produced it.

Once the total supply at the interface between levels 1 and 2 has been so computed, we can determine the total demand as, again, the sum of the productive capacities of all the accountants who are placed at level 2 of the hierarchy. We can then set the third and fourth digits of the environmental message according to the disequilibrium/equilibrium situations which are thus realized. The same procedure can be repeated for all the organizational level. At the last level we will suppose the existence of a "final" demand of one bank-note of face value 25. If more bank-notes are offered, an excess supply will be signalled and the face-value of the only purchased bank-note will determine the overall payoff to the organization: if such value is equal to 25 the organization (i.e. the winning rule) will receive a positive payoff, otherwise it will receive a negative payoff proportional to the absolute difference between 25 and the face-value itself.

2) in the case of decentralized coordination inter-level supplies and demands are computed in exactly the same way, but environmental messages are separately determined for each accountant, by means of a random rationing, as explained above. If, for instance, a given interface between level demand is higher than supply, supplied bank-notes are assigned, one

[6] The possibility of exiting the organization must be necessarily allowed if we want the system to be able to adjust optimally also when more accountants exist than the optimum number.

by one, to a randomly chosen accountant who has still some unused productive capacity. All accountants on the supply-side will therefore have sold all the bank-notes they produced, and at the following iteration will receive a message whose second digit is set to 0. As to the accountants on the demand side, some (possibly none) of them will have been given all the bank-notes they required and at the following iteration will receive a message whose first digit is set to 0, the others (possibly all of them) will find themselves with at least a part of their demand unmet and at the following iteration will receive a message whose second digit is set to 1. The organizational payoff is in this case distributed to all the accountants' winning rules through a bucket-brigade mechanism (cf. Holland 1986).

Simulations have been carried out in order to test the adaptive performance of the systems in different environmental conditions. Let us briefly examine the main results.

1 - A first set of results concerns the simplest situation of an error-free and stationary world. The stack of bank-notes to be counted contains always 25 notes and no mistakes can happen in the counting process, i.e. the counting can always be performed without any disturbance and the face-value of the output always equals the amount of used productive capacity. In this situation the centralized coordination mechanism is considerably more efficient in finding the optimal structure as far as both the speed of convergence to an effective organizational design and its stability are concerned.

It must be pointed out that the structure of the payoff function plays a crucial role in determining the speed of convergence and the type of organization which emerges. In particular, punishments for unused productive capacities are essential for reducing slack resources, and a payoff function decreasing in the total task-completion time is necessary to obtain an equal distribution of capacities across agents.

2 - In error-prone environments instead accountants can make mistakes. Two different kinds of mistakes are possible. In the first case accountants are aware of the mistakes they make and correct them by re-starting the counting process: random disturbances can happen during each accountant's counting task and force him to start his counting process all over again. In this case the payoff function contains a penalty for the time (steps of the counting process) taken to perform the overall task. A second type of mistake is instead represented by a random variable (with mean 0) which may cause a deviation between the amount of productive capacity used by an accountant and the face-value of the bank-note he produces. In this case accountants are not aware of the mistakes they make and deliver a result which is not correct.

In both cases the decentralized mechanism is more efficient: local adjustments seem therefore to increase the efficiency at coping with local disturbances.

5 - Conclusions and directions for further research.

So far we have pointed out that the division of labour determines a hierarchical structure of tasks of pyramidal form. Does this structure directly relate to power relations within organizations, i.e. is the hierarchical system of tasks division connected to the hierarchical system of power and control? The answer is, generally speaking, no. The pyramidal structure of our example emerges only from functional relations (each agent has to use a multiplicity of inputs coming from different agents) and is independent of control and power relations. But, on the other hand, the very shape of the pyramid can have some important consequences on the relationship between agents. The number of agents in fact decreaeses as we climb the hierarchy and thus, if the relations between to adjacent levels are managed by a market, such a market cannot be a competitive one because of its strong asymmetry. Market power will be higher for agents placed in higher hierarchical positions.

In our simple model we have supposed that movements of workers across hierarchical levels can take place instantaneously and at no cost: this is clearly a mostly unrealistic hypothesis. Different positions in the hierarchy require different capabilities and knowledge of different routines. There is likely to be a trade-off in the organization between the time a worker takes to learn the routines connected to a different hierarchical level and the increase of production time and number of mistakes due to increase of individual work loads.

Moreover in real organizations also the type of knowledge required at different hierarchical is normally quite different: higher levels in the hierarchy involve a broader but less precise kind of knowledge (regardless the actual intellectual capabilities of workers). The division of labour usually involves a strong cognitive asymmetry between different levels of tasks as a part of the general decomposition of knowledge: this element does not appear in our accountants' model.

Finally, real economic organizations always possess some mechanism of control, whose task is to spot elements which do not work properly either because of real problems or because of opportunistic behaviour and a parallel and connected system of incentives which tries to avoid the appearance of such problems.

All this elements should be embodied in our model (which could become a sort of "beehive" rather than accountants' model) to make it more realistic.

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