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REGULAR ARTICLE

Complexity and the limits to learning

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Abstract In this paper we look at the manner in which ideas coming from complexity science change our understanding of the cognitive powers of agents that is really necessary to explain the evolution of markets and of firms. The general ideas behind complex systems dynamics and evolution are presented and then two examples are treated in detail. The first in an evolutionary model of a market in which some new product is developed by competing firms and their "task" is to find a strategy in terms of quality and price that will be sustainable. This essentially requires agents/firms to discover mutually compatible strategies, and to create thereby sustainable market niches. The second example considers the internal structure of firms, in terms of their constituent working practices and skills. It demonstrates that it is precisely their ignorance of the consequences of adopting any particular practice that generates diversity in the emergent capabilities of firms, exploring the dimension of potential demand and therefore leading to a successful and sustainable business sector. The work supports the notion that the cognitive abilities that are involved are not about deduction and logic, as a traditional view of rationality might suggest, but are about the development and contraction of interpretive frameworks, which will be different for each player. The paper links these examples to a general recognition of the idea that complex, multi-agent systems evolve through successive "structural attractors"—multi-dimensional dynamical systems—with temporary structural stability. Because real systems contain both the structure and deviations from it, then there is a constant probing of structural stability and the possibility of qualitative change to a new structural attractor. This resembles the ideas in biological evolution related to "punctuated equilibria," but it also links this to the idea of emergent and evolving networks of interaction, never of course near thermodynamic equilibrium.

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1 Introduction

General equilibrium theory in economics supposes that agents act as if they have perfect foresight about the best strategy to follow in any future state of the world (Radner 1968). The proof of existence of equilibrium requires that each agent possesses an infinite amount of knowledge. This is at the opposite extreme of an approach based on complexity in which it is assumed that agents need to know almost nothing. It is obviously of great interest to attempt to discover which of these extreme views is nearer the truth. In order to do this we shall describe an evolutionary market model inhabited by multiple agents managing firms. The agents will have bounded rationality and will survive if they succeed in finding strategies that produce goods and services that sufficient customers will buy to provide revenues greater than costs. In other words, the model will try to represent both sides of the market, supply and demand, instead of focussing on only one of these. It will also show us that what matters is not so much "knowing" a good strategy, but having the capacity to succeed in finding a successful strategy and in adapting and learning as market conditions and competitors learn change over time.

Since the "invisible hand" of Adam Smith, the idea of self-organisation has been present in economic thought. However, economics happened to evolve in a very particular way, one that avoided serious reflection on dynamic processes, by transferring ideas from equilibrium physics as the basis for understanding. This led to classical and neo-classical economics that was strong on very general and rigorous theorems concerning completely artificial systems, but rather weak on dealing with reality in practice. Today, with the development of evolutionary complex systems and the arrival of computers able to "run" systems instead of us having to solve them analytically, interest is burgeoning in complex systems simulations and modelling. And this can help us improve our quality of life and the functioning of our organisations and social institutions, by providing better knowledge for an integrated and dynamic reflection on possible policies and interventions, including the possible creative responses of agents that are affected. We need to understand how socio-economic systems "work" and more particularly how they evolve. And this means that we need to "understand" how the underlying causality of a current social situation is operating, and what the mechanical system predicts. But the difficulty with this approach is that it fails to recognise the essentially fluid nature of human behaviour, and the ability of actors to modify their previous habits in response to the new opportunities or constraints of the situation (see Fig. 1).

In several previous papers (Allen 1994, 2001a,b), it was shown how the creative interaction of multiple agents is naturally described by co-evolutionary, complex systems models in which both the agents, the structure of their interactions and the products and services that they exchange evolve *qualitatively*.

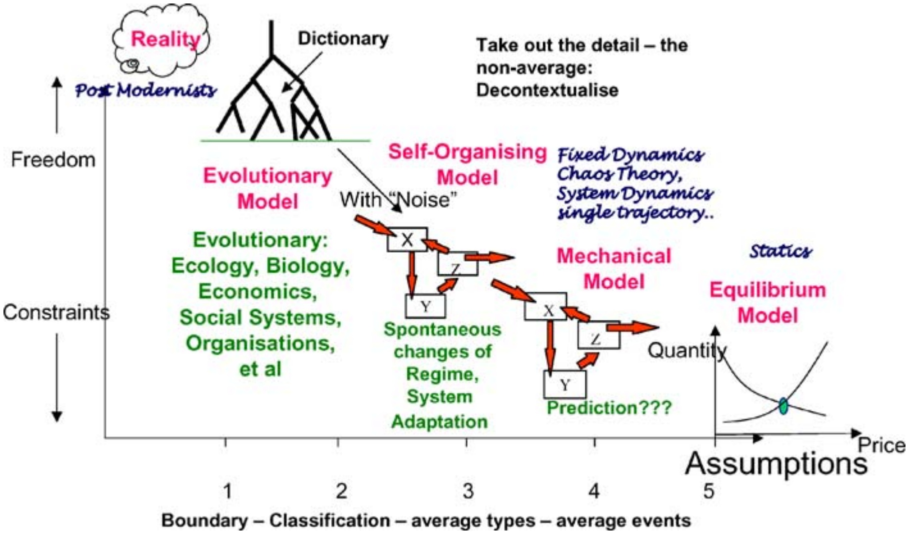

Fig. 1 The overall conceptual scheme of increasingly simplified representations of a situation, as increasingly strong assumptions are made

In reality, complex systems thinking offers us a new, integrative paradigm, in which we retain the fact of multiple subjectivities, and of differing perceptions and views, and indeed see this as part of the complexity, and a source of creative interaction and of innovation and change. The underlying paradox is that knowledge of any particular discipline will necessarily imply "a lack of knowledge" of other aspects. But all the different disciplines and domains of "knowledge" will interact through reality—and so actions based on any particular domain of knowledge, although seemingly rational and consistent, will necessarily be inadequate (see Fig. 2).

In these papers, a model was developed of agents attempting to manage firms trying to launch new products in a new market area. The model takes each firm as an "agent," characterized both by specific behavioural parameters to the outside world and also by a fairly sophisticated representation of its internal structure. However, the key element for the outside world, and in particular for potential customers and for competitors is that the variables that dominate the strategy of the agent or firm are those that are perceived by the potential customers, namely the quality of the product and its price. In addition we also have segmented demand coming from different types of consumer. In addition, the model represents the problem of investing in order to create and launch a new product, and the fact that it will take a certain volume of sales to provide a return sufficient to cover fixed and variable costs and repay these initial costs. The problem is shared in the model shown here by some six firms, and the model explores the effects of them trying to learn successful strategies with regard to product quality (and cost) and price strategy, namely the percentage mark-up on unit costs. There are economies of scale available for firms that can gain sufficient production volume, perhaps by using a low price to gain initial market share. This strategy means that higher amounts of debt and initial investment are required, and if interest rates increase this can nullify the advantage gained. However, if it succeeds, the agent/firm will have lower unit

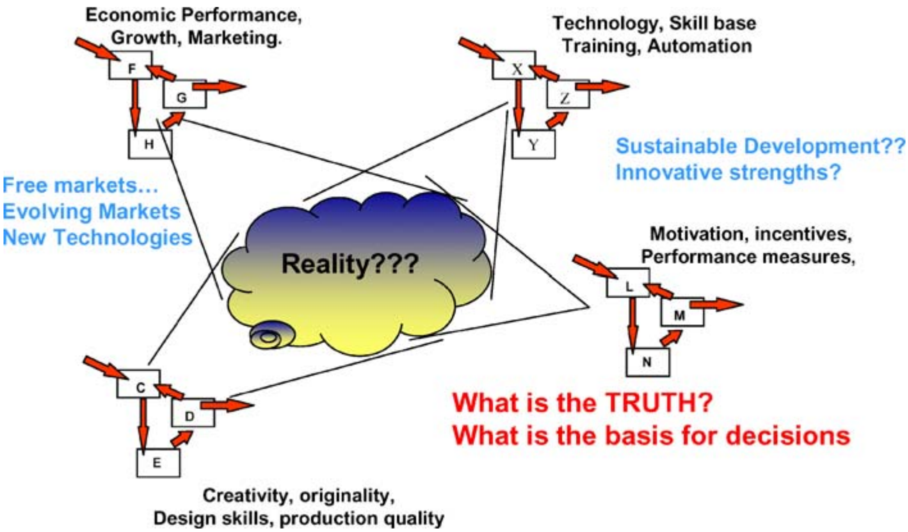

Fig. 2 Different people see the same system in different ways. Each can however be rational and consistent, whilst implying different actions or policies

costs than rivals and will be able to drop prices, and make greater profits. But this raises the issue of the "time scale" over which one must evaluate a strategy, and to what extent an agent really knows whether their strategy is valid.

The question that this paper wishes to address is that of the level of "cognition" required by agents to survive in the system or market in which they operate, and both the importance and the limits to the effectiveness of that learning. Learning is about the acquisition of knowledge and this is about the development of an interpretive framework that can turn "data" into "information." The interpretive framework is however, only developed as the result of the confirmation or rejection of conjectures concerning possible associations, classifications and interactions within the situation considered. However, there is clearly some requirement of stationarity if this is to be at all cumulative. The paper here will explore the issue of the limits to learning that characterise an evolving market place. In building the model the modeller is confronted with the problem of what knowledge an agent can have concerning the sales and revenue generation that will result from a given strategy. It may be clear that high quality products will be bought by richer potential customers than poor and that between two identical products, sales will be greater if a lower price is charged. But in reality, beyond this, the profits that can be made by an agent for a given strategy will depend on what strategies are being used by other agents and firms, and on the sensitivities of potential customers to these. Since all activity will start by investing in materials and wages in order to produce, this will show up as an initial loss. If the decision rule used by the agent is that of expanding production when profits are positive, and contracting when they are negative, then clearly, all firms will shut down as soon as they start. Because however, in the real world, firms are in fact started and new products and services are developed it is obvious that the "equation" governing the increase or decrease of production volume cannot be based on the actual profits made instantaneously.

This underlines what seems obvious after a little thought—agents must use a rule based on “expected” profits to adjust their production volume. So, firms moving into a new market area must be doing so because they “expect” to make profits in the future. It is merely a matter of a delayed dynamic, whereby profits followed according to the expectations of the competing agents.

But this raises the vital question at the heart of this paper—how much knowledge can an agent have about future, expected profits? If no firm ever went bankrupt then we might assume that considerable knowledge was present. However, the “death” of firms tells us something very important—firms cannot calculate expected profits correctly—or else they would never go bankrupt. Clearly, what really happens is that agents adopt, and probably believe in, particular strategies of quality and mark up, and some of them discover that their strategy does take them on a successful trajectory, and others that it doesn’t.

The model allows us to explore strategies of “learning” as agents can attempt to respond to their situation, either taking corrective action if they appear to be failing, or increasing their profits if the strategy appears to be working. The model can be used to explore learning strategies that can keep agents from bankruptcy, including changes in quality and mark up, or alternatively deciding which other agent should be imitated.

What the models show is that although it is possible to “learn” providing other agents do not change their behaviour, if all agents are engaged in trying to learn how to perform better, then there is no clear way of ensuring success and survival.

The work leads to an important theoretical idea in which multi-agent systems evolve in a series of successive quasi-stable regimes that we are calling—Structural Attractors. They are “structural” in that they reflect the qualitative nature of the system in question—the constituent components and their dimensions and attributes. They are “attractors” in that the dynamical system underlying any particular example has at least one dynamical attractor capable of stability. The paper therefore addresses the nature of evolution and underlines the view that this is characterised by qualitative, structural changes as well as quantitative ones. Evolution is characterised by the emergence over time of new attributes, features, entities, behaviours and structures as innovations appear in the system, adding new descriptors and dimensions and of course removing some as well. So, we think of evolution as being the process by which we observe successive systems, as their component entities and attributes are changed as the result of the “invasion” of an existing system by some new behaviour, activity or entity. Evolutionary change is therefore made up of successive instabilities of previously stable sets of interacting entities. This is why we are calling them Structural Attractors as they are qualitatively different systems of interacting entities, objects and activities that change when new “nodes” are experimentally connected into the existing network of interactions.

2 An evolutionary model of an economic market

The ideas developed in the sections above have been applied to a variety of systems, but here will be applied to the structuring of economic markets, as competition creates ecologies of firms producing goods in different market niches. The fundamental process can be explored initially using a simple model in which we consider the possible growth/decline of several firms that are attempting to produce and sell goods on the same market. The potential customers of course will see the different products according to their particular desires and needs, and in the simple case examined here, we shall simply consider that customers are differentiated by their revenue, and therefore have different sensitivities to price.

The structure of each firm that is modelled is as shown in Fig. 3. Inputs and labour are necessary for production and the cost of these, added to the fixed and start-up costs, produce goods that are sold by sales staff who must "interact" with potential customers in order to turn them into actual customers. The potential market for a product is related to its qualities and price, and although in this simple case we have assumed that customers all like the same qualities, they have a different response to the price charged. The price charged is made up of the cost of production (variable cost) to which is added a mark-up. The mark-up needs to be such that it will turn out to cover the fixed and start-up costs as well as the sales staff wages. Depending on the quality and price, therefore, there are different sized potential markets coming from the different customer segments.

When customers buy a product, they cease to be potential customers for a time that is related to the lifetime of the product. For high quality goods this may be longer than for low quality, but of course, many goods are bought in order to follow fashion and style rather than through absolute necessity. Indeed, different strategies would be required depending on whether or not this is the case, and so this is one of the many explorations that can be made with the model. The mathematics of the model are explained in Appendix 1.

The model calculates the relative attractivity of a product (of given quality and price) for a customer of a given type (poor, medium or rich). This results in a

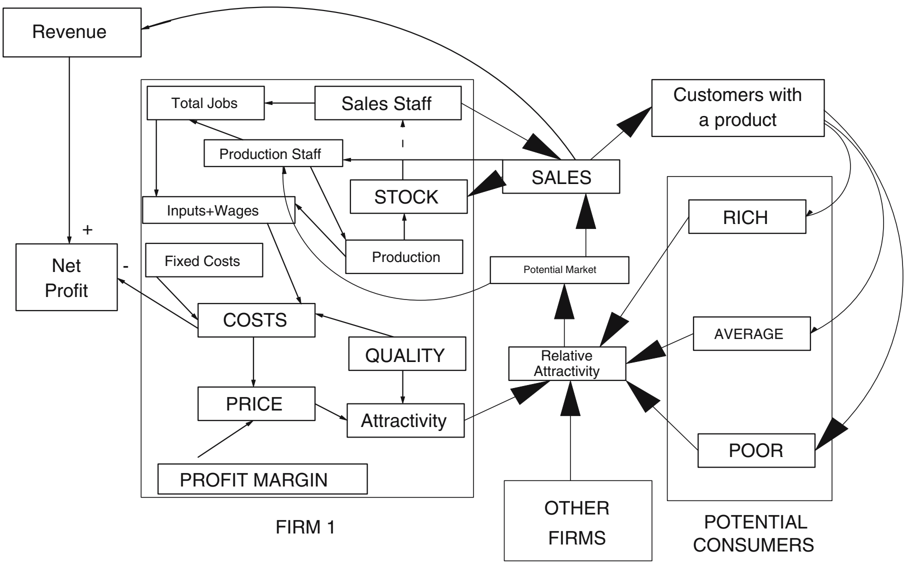

Fig. 3 The Evolutionary Market Model structure

calculation of the “potential market” for each firm at each moment, and the sales staff must interact with these potential customers in order to turn them into customers. When a sale is made, then the potential customer becomes a customer and disappears from the market for a time that depends on the product lifetime.

The revenue from the sales of a firm are used to pay the fixed and variable costs of production, and any profit can be used either to increase production or to decrease the bank debt if there is any. In this way, the firm tries to finance its growth and to avoid going near its credit limit. If it exceeds its credit limit then it is declared bankrupt and closed down. In order to continue the exploration of strategy space for successful “business conjectures,” the evolutionary model then replaces the failed firm with a new one, with new credit and a new strategy of price and quality. This either survives or fails in its turn. The model represents a kind of “Darwinian” model of market evolution in which the random strategies that work remain, and those that don’t are replaced by new, randomly chosen strategies.

In the model, interventions can be made at any time and different strategies can be tried out. Apart from the obvious ones concerning the quality and mark-up of the product, there is that of increasing the sales force, having an advertising campaign. Also the model allows the exploration of the possible impacts of increased R&D. In addition, the model could be used to explore the strategies that might be relevant to changing external conditions, as the general level of wealth increases or the age pyramid of the population changes. Similarly, some aspects of technology assessment could be investigated, by examining the possible gains that could be obtained, and over what time, as the new technology changes the competitive relationship in the market, and allows a larger market share to be tapped. But, this extra market share would have to produce extra revenue over and above that involved in the investment and training required for the change. The model might therefore suggest where market densities were such that this was advantageous, and where it might not be.

A very important issue that arises in the modelling concerns the rationality of the manager of the firm in electing to adopt whatever strategy is chosen. In traditional economic theories firms are supposed to act, or to have acted, in such a way as to obtain maximum profit. But, here, we can see that if we used the profit as the driving force for increased production, then the system could not start. *Every new action must start with an investment*. That is with a negative profit. So, if firms do start production, and increase it, then this cannot be modelled by linking the increase in production to the profit at that time. Instead, we might say that it is driven by the *expected profit over some future time*. But how does a manager form his expectations? Probably a model of the kind that is being described here is way beyond what is usually used, and in any case, there is a paradox. In order to build this model, in order perhaps for managers to formulate their expectations, the model requires a representation of manager’s expectations. But this is only a paradox if we believe that the model is about *prediction*. Really, it is about exploration, the exploration of how we think a market works, and so it is a part of a learning process, which may indeed lead participants to behave differently from the way that was supposed initially. Such an outcome would already be a triumph.

Despite this paradox, and the difficulty in knowing what is going to happen beforehand, firms do start up, production is increased, and economic sectors are populated with firms, so, even though there is this logical problem, obviously it does not worry participants in reality. Since bankruptcies also occur, then we can be sure that the expectations that drive the investment process are not necessarily related to the real outcomes. In our model therefore we simply have assumed that managers want to expand to capture their potential markets, but are forced to cut production if sales fall. So, they can make a loss for some time, providing that it is within their credit limit, but they much prefer to make a profit, and so attempt to increase sales, and to match production to this.

3 Model results

The picture that emerges from this study of a dynamically, self-organizing market sector model is that of the emergence of product niches. It is the economies and diseconomies of production and distribution that will determine the number, size and scale of these niches, and they will depend on the initial history of the market sector in question as a "lock-in" evolves. However, as new technology appears, or as the rest of society evolves, new attributes can come into play for the products. However, the effect and importance of these may be different when viewed by the producers as opposed to consumers.

A typical long-term simulation is shown in Fig. 4. This shows the 2-D space of mark up (%) and quality (Q), and the positions of the various firms. The rows at the top show the strategy, price, profit, present balance and sales of each firm, and the state of the

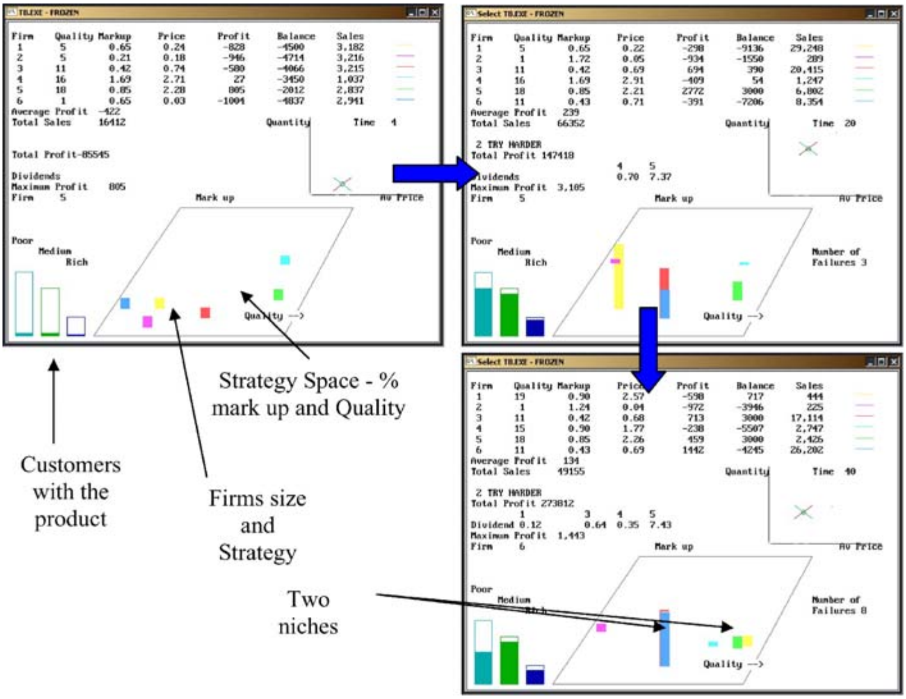

Fig. 4 A typical evolutionary run where gradually the "Darwinian" process discovers two fairly stable niches—around Q=11, %=40 and Q=18, %=85

market is shown in the lower left. The simulation shows us that using purely random initial beliefs about possible strategies and random "re-launches" of failed firms leads to a fairly reasonable distribution of the firms in the space of "possibilities" as well as to good levels of consumer satisfaction at the middle and rich end of the market.

The evolutionary model can be used not only explore different business strategies but also different *evolutionary or learning strategies*. We can discover resilient strategies that emerge from such systems, and in the case of particular market sectors suggest how the rules of learning can also evolve. In other words, by testing out firms with different rates and types of response mechanism, we can move towards understanding not only the emergent "behavioural rules" for firms, but also the rules about "how to learn" these rules.

The first method used for the "re-launch" of new firms was to pick new strategies purely randomly, giving us "Darwinian" evolutionary model in which selection acted on random "mutations". Other learning strategies can be tested out—initially on firms that try them out alone, with other competitors not responding, but then, more interestingly, when the new "learning" rules to diffuse to all the firms. The results are complicated, and often counter intuitive (whatever that means in such a complex system) because the rules adopted affect both the behaviour of one firm relative to the others, and also the overall market size, and the rapidity with which potential customers are "located" by salesmen.

The evolutionary model of Fig. 5 has a kind of "Darwinian" evolutionary mechanism that allows entrepreneurs to explore the "possibility space" for products

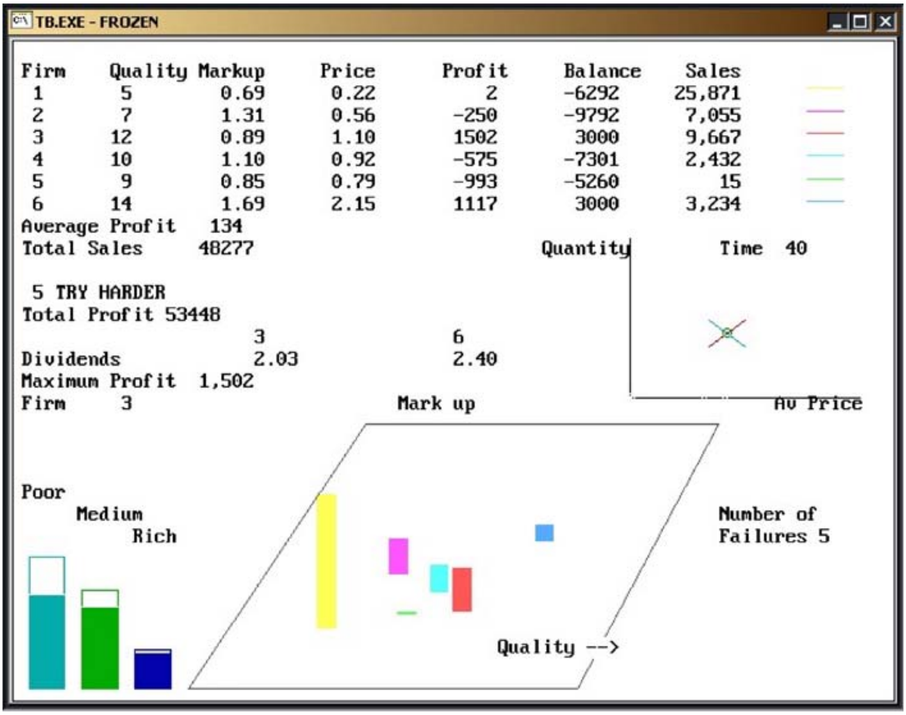

Fig. 5 The situation at t=40 uses "Darwinian" learning and shows a typical evolution in which in this case, firm 1 has survived, though has never got into profit

of this kind. The pay-off achieved by any one firm or entrepreneur depends on the strategy (product quality and mark-up) used by the other entrepreneurs present. The real evolutionary sense arises if we admit that no products have only a single dimension of "quality." There will always be such factors as performance, weight, efficiency, style, colour, noise, flexibility, etc. as well as simply price. Entrepreneurs would therefore explore different technologies, organisational forms and production factors, as well as different types of product. This process would lead inevitably to a broader coexistence of different firms, since the multiple dimensions of attribute space produce a greater spread of consumer preferences, and less intense competition in general.

The simulations can be used to examine the effects of a firm actively "hill-climbing" in profit space by exploring systematically the gain or losses of higher or lower qualities, and higher or lower mark-ups. This is very successful for a firm as we see in Fig. 6 where we see the effect of inserting the ability for firm 1 to "hill-climb" while the others do not. Firm 1 rapidly moves into profit by climbing whatever gradient it encounters. It succeeds in paying a dividend to its investors.

However, if we allow all the firms to "hill-climb," then their mutual interaction reduces the advantage of learning. There are less bankruptcies also in attaining this market structure. We see the "limits to learning" in which the speed of learning and the frequency really matter and affect the ability to survive and prosper.

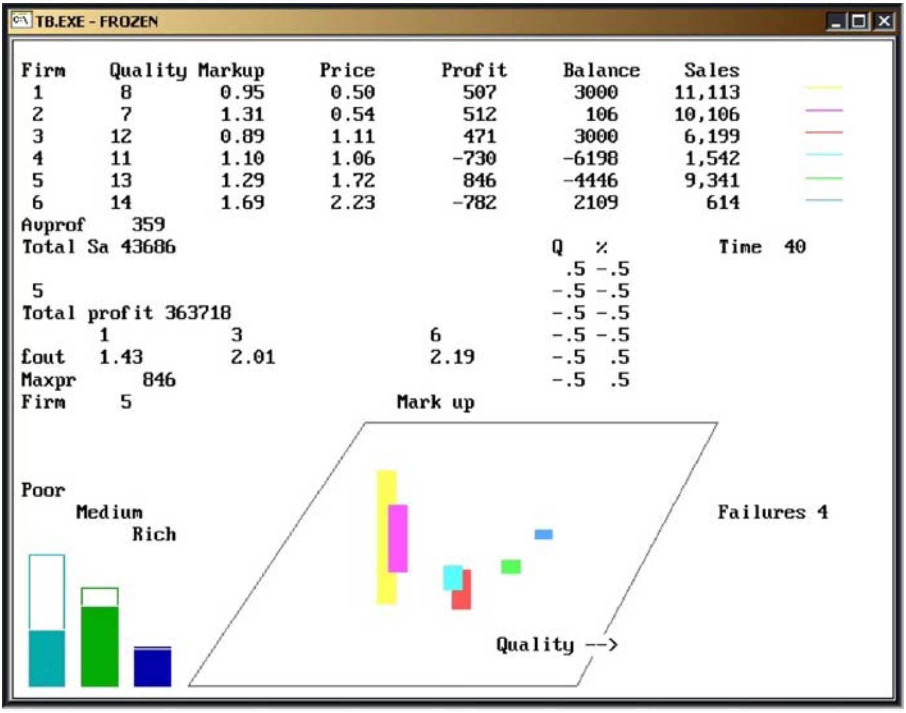

Fig. 6 This is an identical simulation to that of Fig. 5 except that here firm 1 tests the "profit gradient" and moves Q and % accordingly up-hill. It does much better, making a profit and paying a dividend to investors

In Fig. 7 the whole market evolution is different as all the firms hill climb in profit space, moving overall to higher qualities and higher mark-ups. However, for several firms this very sophisticated strategy, involving careful testing of experimental variations in mark up and quality, does not bring success. In that case, it becomes important to see what other strategies are possible, and whether they can result in better outcomes.

One such strategy is for a firm to monitor the market carefully and for it to adapt its production as rapidly as possible to copy whichever firm is currently making most profit. Obviously this might be hindered by patent laws and copyright but the model merely supposes that the quality *Q* and the percentage mark-up %, are perceived as being the same by the potential customers. The model then allows the imitator to move towards its target. Of course, it may not have the same economies of scale, but nevertheless its presence clearly increases competition at that point in strategy space, and changes the outcome for the market as a whole. In Fig. 8 we see the result for an identical simulation to that of Figs. 5, 6 and 7 except that here Firm 1 discovers which firm is most profitable and imitates their strategy.

This strategy can also emerge as a ploy to avoid bankruptcy. In Fig. 5, firm 1 goes bankrupt at least once, whereas in the simulation of Fig. 8 this doesn't happen.

We see that the number of bankruptcies "required" to shape the market varies for the different runs. For a "Darwinian" strategy of Fig. 5 it is five up to this point, and for Figs. 6, 7 and 8 it is four, six and four, respectively.

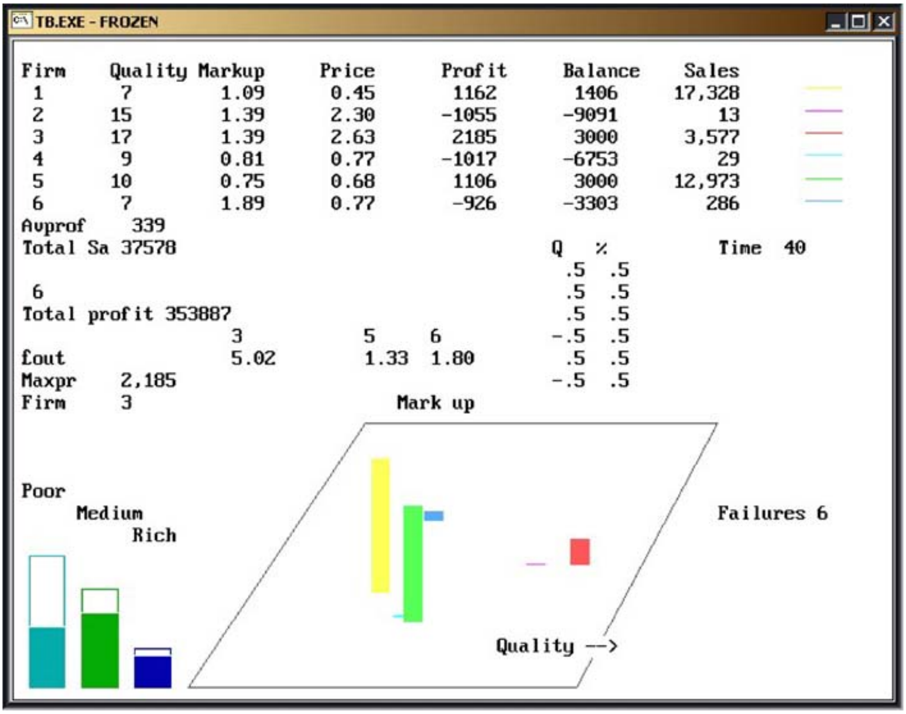

Fig. 7 The whole market is completely different when all firms can "hill-climb." Firm 1 does just get into profit but not enough to pay a dividend to investors

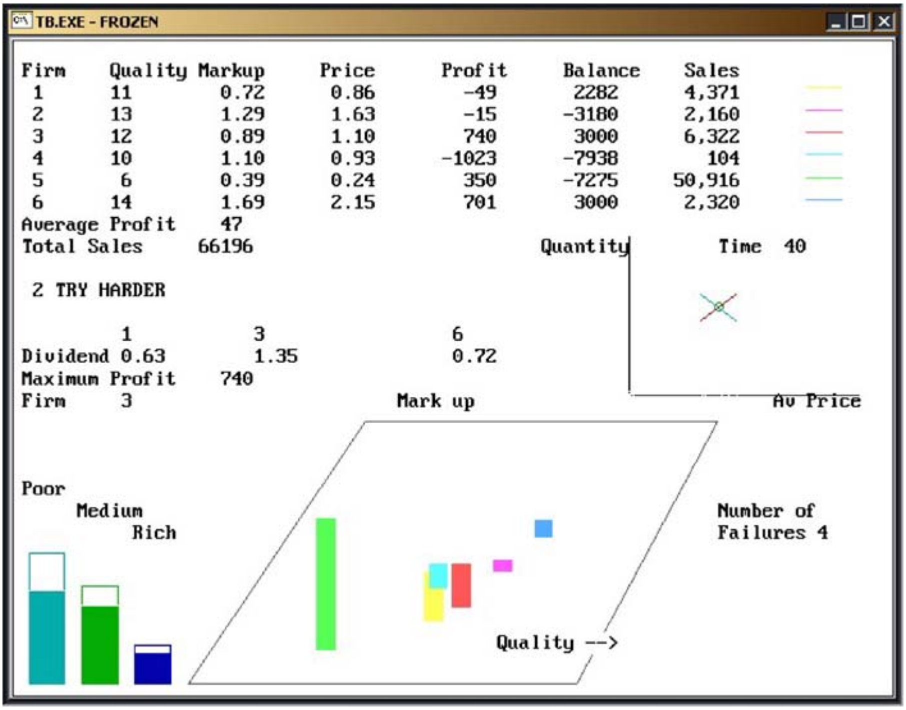

Fig. 8 If firm 1 imitates whoever is currently winning, then this can lead to success. It is in the "mid-range" niche and so will probably survive. It avoided a bankruptcy that occurred in Fig. 5

In the next simulation, we consider the impact of the idea of imitation of the firms making up the market. If firm 1 can avoid a pathway leading to bankruptcy, then it shows that it is "risk reducing" strategy. Rather than taking the risk of finding out whether one's own, individual strategy will really work, it seems tempting to imitate whichever strategy is making maximum profit. At least the "decision-maker" is not going to be alone, and obviously it must be a good strategy since it is already making more profit than any other. So, the idea can be tested. What happens if all the players decide to imitate whoever is making the most profit? The answer is shown in Fig. 9. It shows us that all the firms move to the same place in strategy space, and in so doing increase the degree of competition that they each feel. As a result, there are more bankruptcies (nine) than in any of the other simulations.

What might have seen a "risk averse" strategy turns out to be the opposite! To imitate in a market of imitators is highly risky.

In a previous paper concerning the emergence of different strategies among fleets of fishing boats (Allen 1998), it was shown that what mattered was that an ecology of strategies emerged. Instead of having agents that are susceptible to adopting the same strategy, what really matters is that there should be real micro-diversity such that whatever happens, there will be a diverse set of strategies being played out in the collective system. This is equivalent to insisting on the opposite of "Best Practice." In the next simulation of Fig. 10 we see the outcome for a situation in which some firms imitate winners and others hill-climb.

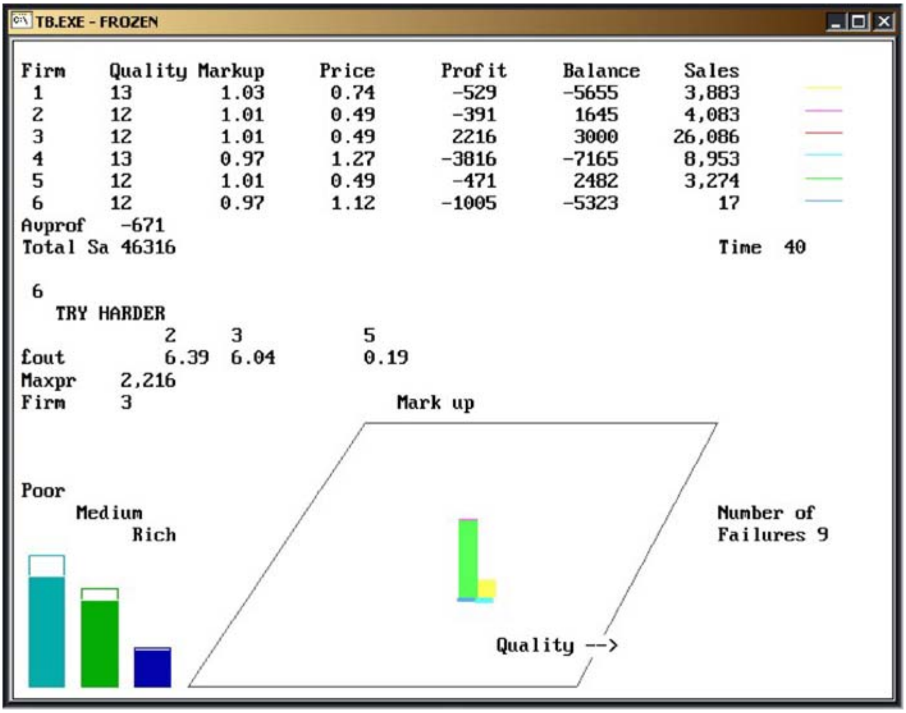

Fig. 9 If all the firms adopt the "imitate a winner" strategy, then the outcome is bad. In trying to avoid risks, they actually increase them as there have been nine failures up to this point

We see that it is not particularly successful for firm 1, but that it has actually produced an overall market structure that has been largest in total profits, and which has only suffered three bankruptcies.

This introduces an interesting point about the different levels at which we can look at market evolution—that of the internal capabilities of firms and of their products, the strategy of one firm relative to the others and finally the overall outcome of the different capabilities and strategies adopted by participating firms. In some ways, for public policy what matters is the level of customer satisfaction, and the level of overall profit for the sector. In our accounting for overall costs we need to include that of bankruptcy since every time that it occurs in our model, the social system, other firms etc. lose 10,000 units. In the real world the costs can be more devastating still to those involved and could even lead to a serious limitation on the willingness of actors to innovate.

We can examine the question as to the overall outcomes for the "industry" of different strategies. In order to look at this, we have calculated the overall profits of the whole market, and we have included the costs of bankruptcies, in which often, a loser takes trade away from others in an attempt to keep going, but eventually crashes with debts. In the Fig. 11 we show the over all outcome for four different learning strategies. They are:

– Darwinian (random strategies, no learning)
– Old strategy (if profit less than half average, reduce %)

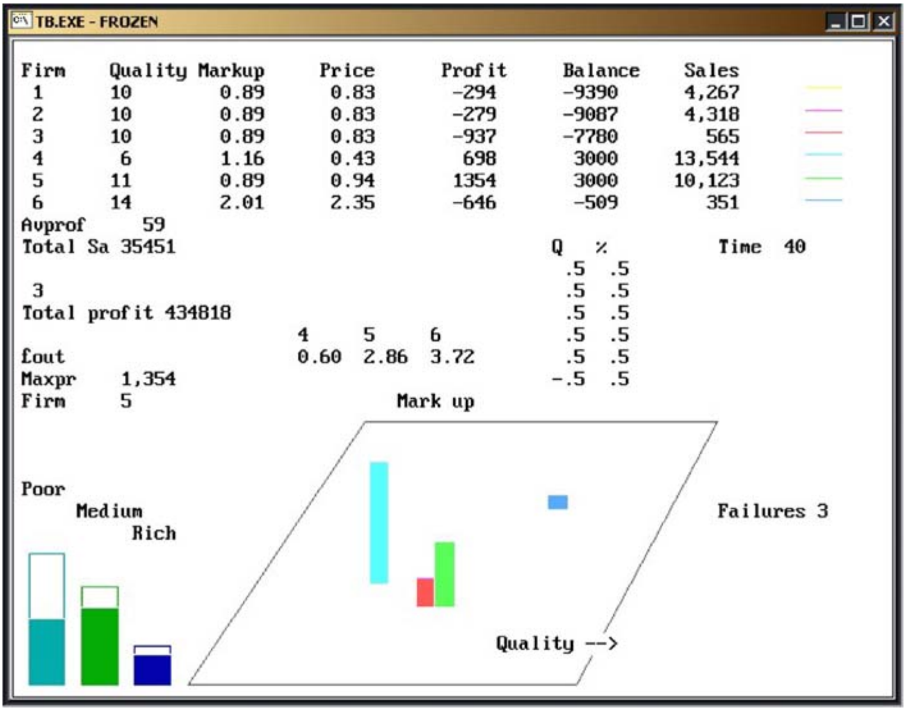

Fig. 10 The situation at t=40 for a set of mixed strategies. Firms 1 to 3 imitate and firms 4 to 6 hill-climb. There are only three bankruptcies and good overall profits

– Hill-climbing
– 3–6 hill-climbers, 1–3 imitators

The comparative results for the overall profit profile for the market are shown in Fig. 11. However, here we have also performed four different runs for different sequences of random numbers, implying simply a different sequence of chance events.

The important result that emerges is that in general, hill-climbing in profit space is a good strategy, but a system that mixes this with some firms that imitate success seems even better. However, what is really significant is that the particular random sequence that seed 6 provides and that of seed 5 differ remarkably in the overall outcomes. Seed 6 has high values for the industry with all strategies other than pure Darwinian. However, seed 5 only has value under one strategy. Indeed, using the Darwinian strategy the value of the whole sector is still increasingly negative. This shows us that for the same potential demand, for the same technology, the same strategies and the same interactions, chance can still allow great variation in market structures to emerge, some very favourable some very unfavourable, and this tells us that the "structural attractors" of economic markets are diverse and of very different overall efficiency. The invisible hand seems to be highly capricious.

These models of market evolution show us that the best "strategy" cannot be deduced from a Game Theory approach based on the long-term equilibrium. Market evolution involves players entering and leaving the game, players who do not, and cannot know

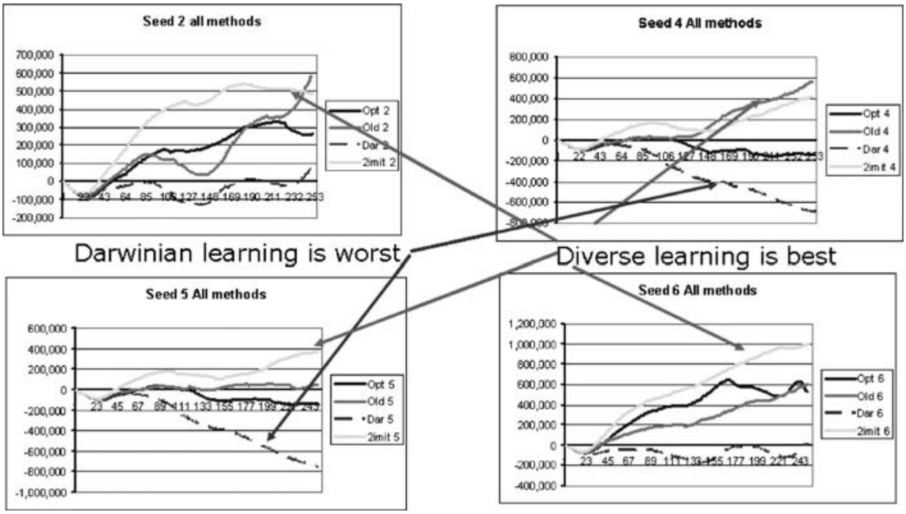

Fig. 11 Hill-climbing in profit space is a good strategy, but a mix of this with imitation of success is best. However, luck (the random sequence) can lead to very different market outcomes from highly profitable to only marginally so

the "pay-offs" that a given strategic choice will have either for themselves or for the other players. It does not therefore lead to a Nash equilibrium (Nash 1950a,b, 1953), Even the attempt to extend Game Theory to situations of incomplete information does not really correspond to the reality of the uncertainty involved in market evolution. Harsanyi (1977) introduced the idea of considering the possible strategies of different possible types of player. This then showed that the incomplete information problem can be replaced by a different, complete information problem. However, this is still an inadequate reflection of the uncertainty present in a real system which has changing qualitative structure as players enter and leave, and is also dynamic. As a result the pay-offs, the actual profits, arising form a given strategy and type of player only become apparent over time, and during this time other players in the game may enter or leave or change their strategy, as may the initial player in the light of their learning. Complexity is all about the acceptance of this kind of simultaneous, parallel learning of players, where the outcome cannot be predicted from the initial conditions, because the precise course of events is dependent both on market processes and mechanisms, and also on contingent and contextual details that affect responses to, and generate the inherent uncertainty.

Having looked at the level of the market place, we can now look at the problem at the level below, inside the competing firms. How do they gain their capacities to produce and deliver products and services sufficiently effectively to survive?

4 Manufacturing evolution

The previous sections demonstrate theoretically how micro-diversity in character space, tentative trials of novel concepts and activities, will lead to emergent objects and systems. However, it is still true that we cannot predict what they will be.

Mathematically we can always solve a given set of equations to find the values of the variables for an optimal performance. But we do not know *which* variables will be present, as we do not know what new "concept" may lead to a new structural attractor, and therefore we do not know *which* equations to solve or optimise. The changing patterns of practices and routines that are observed in the evolution of firms and organisations can be looked at in exactly the same way as that of "product" evolution above. We would see a "cladistic diagram" (a diagram showing evolutionary history) showing the history of successive new practices and innovative ideas in an economic sector. It would generate an evolutionary history of both artifacts and the organisational forms that underlie their production (McKelvey 1982, 1994; McCarthy 1995; McCarthy et al. 1997). Let us consider manufacturing organisations in the automobile sector.

With these characteristics (Fig. 12) as our "dictionary" we can also identify 16 distinct organisational forms:

– Ancient craft system
– Standardised craft system
– Modern craft system
– Neocraft system
– Flexible manufacturing
– Toyota production
– Lean producers
– Agile producers
– Just in time
– Intensive mass producers

Standardisation of Parts	1
Assembly Time Standards	2
Assembly line layout	3
Reduction of Craft Skills	4
Automation (Machine paced shops)	5
Pull Production System	6
Reduction of Lot size	7
Pull procurement planning	8
Operator based machine maintenance	9
Quality circles	10
Emloyee innovation prizes	11
job rotation	12
large volume production	13
mass sub-contracting by sub-bidding	14
exchange of workers with suppliers	15
Training through socialisation	16
Proactive training programmes	17
Product range reduction	18
Automation (Machine paced shops)	19
Multiple sub-contracting	20
Quality Systems	21
Quality Philosophy	22
Open Book Policy with Suppliers	23
Flexible Multifunctional workforce	24
set-up time reduction	25
Kaizen change management	26
TQM sourcing	27
100% inspection sampling	28
U-Shape layout	29
Preventive Maintenance	30
Individual error correction	31
Sequential dependency of workers	32
Line balancing	33
Team Policy	34
Toyota verification of assembly line	35
Groups vs. teams	36
Job enrichment	37
Manufacturing cells	38
Concurrent engineering	39
ABC Costing	40
Excess capacity	41
Flexible automation of product versions	42
Agile automation for different products	43
In-Sourceing	44
Immigrant workforce	45
Dedicated automation	46
Division of Labour	47
Employees are system tools	48
employees are system developers	49
product focus	50
Parallel processing	51
Dependence on written rules	52
Further intensification of labour	53

Fig. 12 Fifty-three characteristics of manufacturing organisations

- European mass producers
- Modern mass producers
- Pseudo lean producers
- Fordist mass producers
- Large scale producers
- Skilled large scale producers

The evolutionary tree of Fig. 13 can be deduced from cladistic theory, and this shows the probable sequence of events that led to the different possible organisational forms. However, in the spirit of complex systems thinking and that of the formation of networks, we want to consider the synergy or conflict that different *pairs of attributes* actually have. Instead of only considering the different list of characteristic features that constitute the different organisational forms, we also look at the pair-wise interactions between each pair of practices, in order to examine the role of "internal coherence" on the organisational performance. In this "complex systems" approach, a new practice can only invade an organisation if it is not in conflict with the practices that already exist there. In other words, we are looking at "organisations" not in terms of simply additive features and practices, but as mutually interactive "complexes" of constituent factors.

From a survey of manufacturers (Baldwin et al. 2003) concerning the positive or negative interactions between the different practices, a matrix of pair interaction was constructed allowing us examine the "reasons" behind the emergent organisational forms, with successful forms arising from positive mutual interactions of constituent practices. This is shown in Fig. 14.

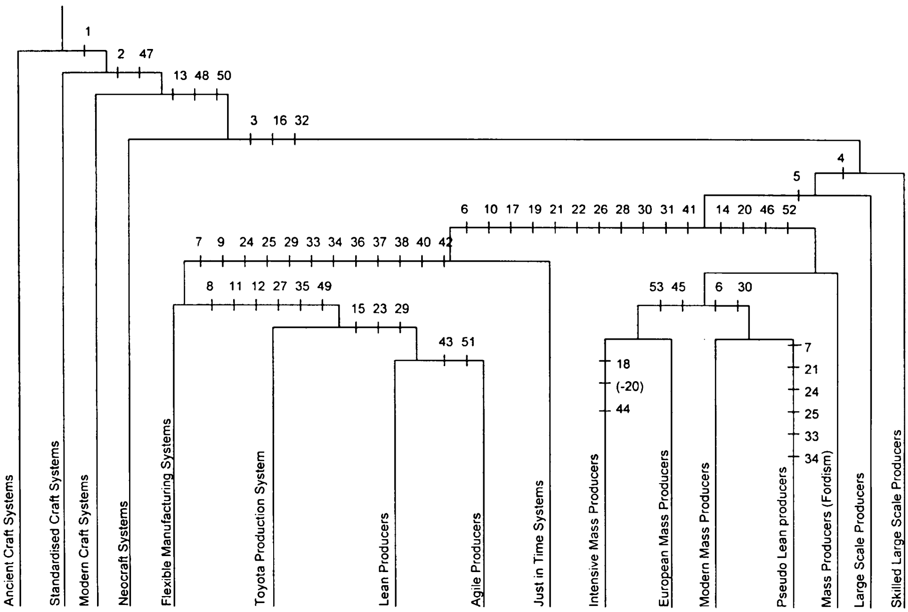

Fig. 13 The cladistic diagram for automobile manufacturing organisational forms (McCarthy et al. 1997)

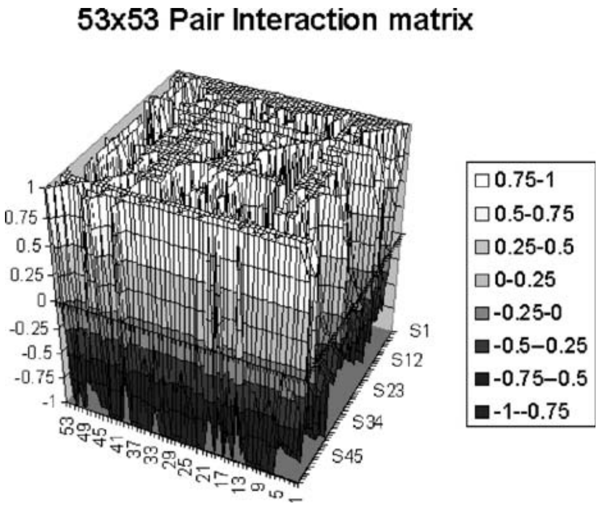

Fig. 14 The 53×53 matrix of pair interactions of the characteristic practices. It allows us to calculate the net attraction or conflict for any new practice depending on which ones are present already

We have then been able to develop an evolutionary simulation model, in which a manufacturing firm attempts to incorporate successive new practices at some characteristic rate. There is an incredible range of possible structures that can emerge, however, depending simply on the order in which they are tried. But, each time a new practice is adopted within an organisation, it changes the "invadability" or "receptivity" of the organisation for any new innovations in the future. This is true illustration of the "path dependent evolution" that characterises organisational change. Successful evolution is about the "discovery" or "creation" of highly synergetic structures of interacting practices.

In Fig. 15 we see the changing internal structure of a particular organisation as it attempts to incorporate new practices from those available. In the simulation, the number available start from the ancient craft practice on the let, and successively add the further 52 practices on the right. At each moment in time the organisation can choose from the practices available at that time, and its overall performance is a function of the synergy of the practices that are tried successfully. We see cases where practice 4, for example, is tried several times and simply cannot invade. However, practice 9 is tried early on and fails, but does successfully invade at a later date. The particular emergent attributes and capabilities of the organisation are a function of the particular combination of practices that constitute it. Details of the mathematical model are given in Appendix II.

The model starts off from a craft structure. New practices are chosen randomly from those available at the time and are launched as a small "experimental" value of 5. Sometimes the behaviour declines and disappears, and sometimes it grows and becomes part of the "formal" structure that then conditions which innovative behaviour can invade next.

Different simulations lead to different structures, and there are a very large number of possible "histories". This demonstrates a key idea in complex systems thinking. The explorations/innovations that are tried out at a given time cannot be logically or rationally deduced because their overall effects cannot be known ahead of time.

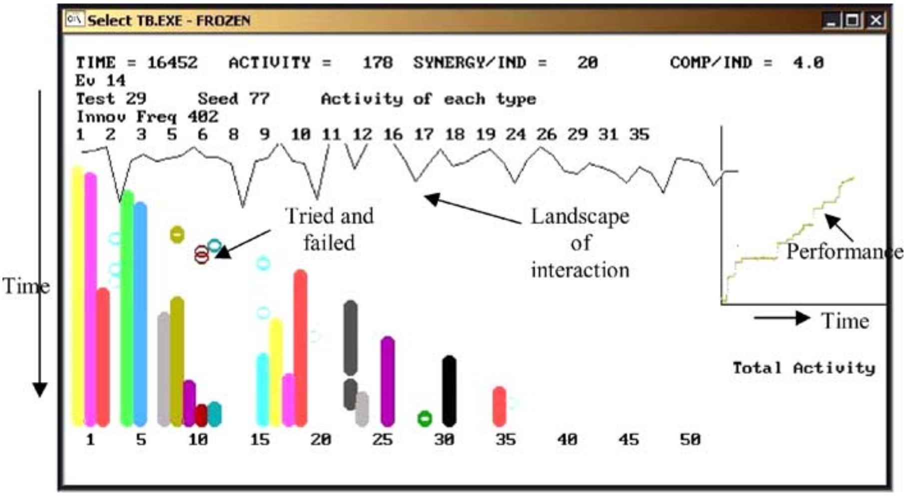

Fig. 15 An evolutionary model tries to "launch" possible innovative practices in a random order. If they invade, they change the "invadability" of the new system

Therefore, the impossibility of prediction gives the system "choice". In our simulation we mimic this by using a random number generator to actually choose what to try out, though in reality this would actually be promoted by someone who believes in this choice, and who will be proved right or wrong by experience, or in this case by our simulation. In real life there will be debate and discussion by different people in favour of one or another choice, and each would cite their own projections about the trade-offs and the overall effect of their choice. However, the actual success that a new practice meets with is pre-determined by the "fitness landscape" resulting from the practices already present and what the emergent attributes and capabilities encounter in the marketplace. But this landscape will be changed if a new practice does successfully invade the system. The new practice will bring with it its own set of pair interactions, modifying the selection criteria for further change. So, the pattern of what **could** then invade the system (if it were tried) has been changed by what **has already** invaded successfully. This is technically referred to as a "path dependent" process since the future evolutionary pathway is affected by that of the past.

Our results have already shown, Fig. 16, that the evolution through the tree of forms corresponds to a gradual increase in overall "synergy." That is, the more modern structures related to "lean" and to "agile" organisations contain more "positive" links and less "negative" links per unit than the ancient craft systems and also the mass-producing side of the tree. In future research we shall also see how many different structures could have emerged, and start to reflect on what new practices and innovations may be available today for the future.

Our work also highlights a "problem" with the acceptance of complex systems thinking for operational use. The theory of complex systems tells us that the future is not completely predictable because the system has some internal autonomy and will undergo path dependent learning. However, this also means that the "present" (existing data) cannot be proven to be a *necessary* outcome of the past—but only,

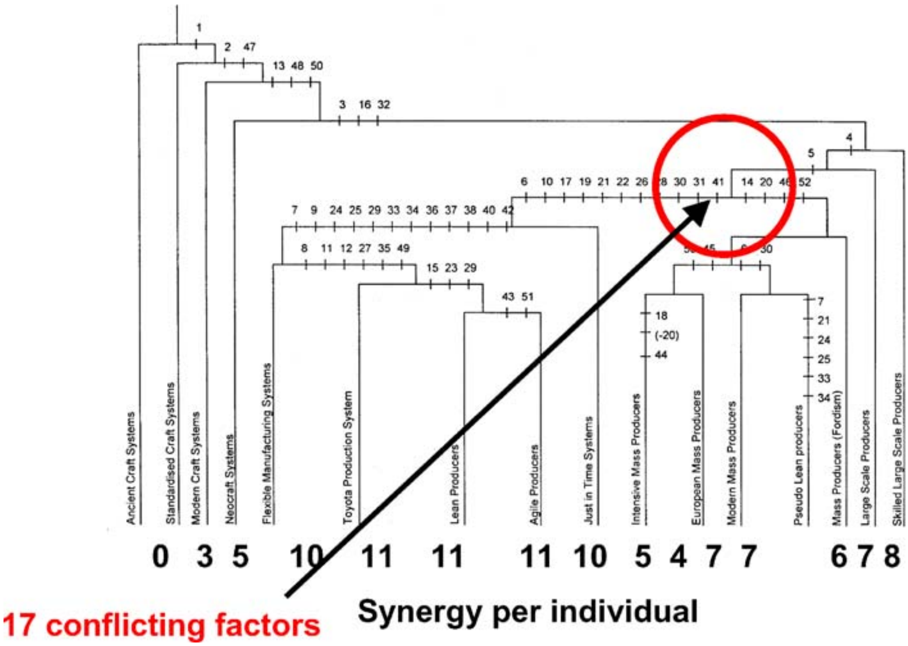

Fig. 16 Knowledge of the pair matrix for the different characteristics allows us to calculate the synergy/individual in the different organisations

hopefully, a *possible* outcome. So, there are perhaps so many possible structures for organisations to discover and render functional, that the observed organisational structures may be 16 in several hundred that are possible. In traditional science the assumption was that "only the optimal survive," and therefore that what we observe is an optimal structure with only a few temporary deviations from average. But, selection is effected through the competitive interactions of the other players, and if they are different, catering to a slightly different market, and also sub-optimal at any particular moment, then there is no selection force capable of pruning the burgeoning possibilities to a single, optimal outcome. Complexity tells us that we are freer than we thought, and that the diversity that this freedom allows is the mechanism through which sustainability, adaptability and learning occur.

This picture shows us that evolution is about the discovery and emergence of structural attractors (Allen 2001a,b) that express the natural synergies and conflicts (the non-linearities) of underlying components. Their properties and consequences are difficult to anticipate and therefore require real explorations and experiments, to be going on, based in turn in diversity of beliefs, views and experiences of freely acting individuals.

5 Structural attractors

There are several important points about these results. The first is that the model above is very simple, and the results very generic. It shows us that for a system of co-evolving agents with underlying microdiversity and idiosyncracy, then we *automatically* obtain the emergence of structural attractors such as Fig. 12. A structural attractor is the temporary emergence of a particular dynamical system of limited dimensions, from a much larger space of possible dynamical systems and dimensions. These are complex systems of interdependent behaviours whose attributes are on the whole synergetic. They have better performance than any single, pure homogeneous behaviour, but are less diverse than if all "possible" behaviours were present. In other words, they show how an evolved entity will not have "all possible characteristics" but will have some that fit together synergetically, and allow it to succeed in the context that it inhabits. They correspond to the emergence of hypercycles in the work of Eigen and Schuster (1979), but recognise the importance of emergent collective attributes and dimensions. The structural attractor (or complex system) that emerges results from the particular history of search and accident that has occurred and is characteristic of the particular patterns positive and negative interactions of the components that comprise it. In other words, a structural attractor is the emergence of a set of interacting factors that have mutually supportive, complementary attributes.

These structural attractors result from:

– Differential growth and decline of individual types of agent or element, who are characterized by multiple dimensions and attributes, some shared by the aggregate view of a formal description, and others that are not shared. The natural "turnover" in any population will, as a result of the microscopic freedom and uncertainties, inevitably lead to an exploration of the multiple dimensions of diversity that can exist. The differential growth of these—selection—leads to vastly increased performance because the initially homogeneous system, characterised by intense internal competition and low symbiosis, is replaced by one with complementarity and synergy. Different roles and specializations emerge, reducing internal competition and creating real synergies.
– The whole process leads to the evolution of a complex, a "community" of agents whose activities, whatever they are, have effects that feed back positively on themselves and the others present. It is an emergent "team" or "community" in which positive interactions are greater than the negative ones.
– The diversity, dimensionality and attribute space occupied by the final complex is much greater than the initial homogeneous starting structure of a single population. However, it is much less than the diversity, dimensionality and attribute spaces that all possible individuals would have brought to the system. The structural attractor therefore represents a reduced set of activities from all those possible in principle. It reflects the *discovery* of a subset of agents whose attributes and dimensions have properties that provide positive feedback. This is different from a classical dynamic attractor that refers to the long-term trajectory traced by the given set of variables. Here, our structural attractor concerns the *emergence* of variables, dimensions and attribute sets that not only coexist but actually are synergetic.
– A successful and sustainable evolutionary system will clearly be one in which there is freedom and encouragement for the exploratory search process in behaviour space. Sustainability in other words results from the existence of a

> capacity to explore and change. This process leads to a highly co-operative system, where the competition per individual is low, but where loops of positive feedback and synergy are high. In other words, the free evolution of the different populations, each seeking its own growth, leads to a system that is more co-operative than competitive. This is clearly a different vision from that usually presented of a free market economy as a cut-throat situation in which selfish competitivity dominates.

The most important point really is the generality of the model presented above. Clearly, this situation characterizes almost any group of humans: families, companies, communities etc., but only if the exploratory learning is permitted will the evolutionary emergence of structural attractors be possible. If we think of an artifact, some product resulting from a design process, then there is also a parallel with the emergent structural attractor. A successful product or organisation is one in which the "bundling" of its different components creates emergent attributes and capabilities that assure the resources for its production and maintenance. However, the complication is that the emergent attributes and capabilities are not simply an additive effect of the components. If a change is made in the design of one component it will have multi-dimensional consequences for the emergent properties in different attribute spaces. Some may be made better and some worse. Our emergent structural attractor is therefore relevant to understanding what successful products and organisations are and how they are obtained. Clearly, a successful product is one that has attributes that are in synergy, and which lead to a high average performance. From all the possible designs and modifications we seek a structural attractor that has dimensions and attributes that work well together.

The structural evolution of complex systems is as shown in Fig. 17 how explorations and perturbations lead to attempts to suggest modifications, and these lead sometimes to new "concepts" and structural attractors that have emergent properties. The history of any particular product sector can then be seen as an evolutionary tree, with new types emerging and old types disappearing. But in fact, the evolution of "products" is merely an aspect of the larger system of organisations and of consumer lifestyles that also follow a similar, linked pattern of multiple co-evolution.

6 Conclusions

Returning to the original question that we are addressing in this paper, we can now draw some conclusions concerning the level of "cognition" required by firms/agents in surviving in evolving markets. Considering the market dynamics, we see that in the Darwinian model, no knowledge is required for a market to evolve towards a set of coherent quality/price niches. Firms/agents are launched with "random" strategies and either survive or they don't. If they don't survive, new random entrants replace them, and eventually the evolutionary system will discover a structure that is stable. As we saw however, this learning strategy is potentially more costly than the whole market is worth. In the further simulations, slightly more sophisticated learning methods are supposed in which either successful competitors are imitated, or trials

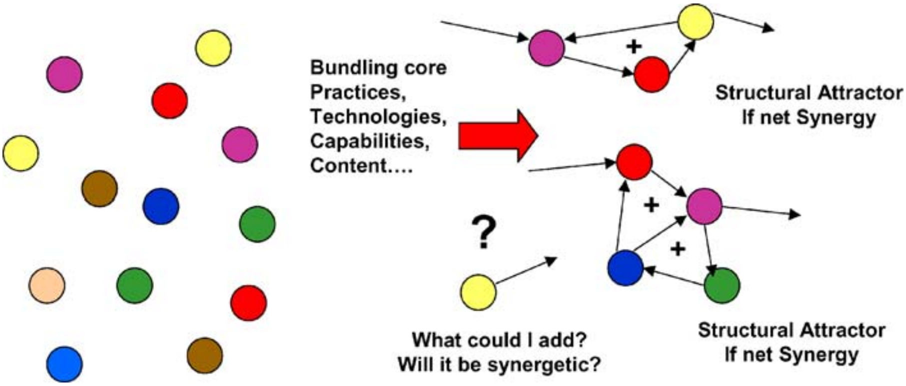

Fig. 17 On the left we have "dictionary" of possible core concepts, practices or ideas. These are "bundled" on the right and if the different elements have synergy then the structure is successful

are conducted to allow "hill-climbing" behaviour of the profit slope, but all of these require only very limited cognitive power. The "intelligence" that apparently underlies a coherent market structure lies not within the agents/firms that participate within it, but in the non-linearities inherent in the economic interactions that are present—the economies of scale, the fixed and variable costs, the degree of discrimination of potential customers.

Our simple, pragmatic models based on what different agents can know is in contrast to the usual ideas of economic rationality, where potential demand and production functions are assumed known. Knight (1921), in his book on risk and uncertainty already made clear the importance of these issues in economics. Furthermore, it led on to a view of uncertainty as a precondition for intelligence, allowing diverse interpretations and classifications to be considered by different agents. This view is one in tune with Hayek's (1949, 1952) theory of the mind in which the brain develops systems of relationships rather than deductive power, and this also leads in a similar direction to the ideas on cognition of Kelly (1955) in which experiences lead to the development of interpretive frameworks and personal constructs. In this latter view it is quite possible that individuals can develop quite incommensurable concepts and values in their interpretations of reality, which is an underlying reason why communication and shared problem solving would be a creative experience in which new behaviours can emerge. This is very much in agreement with the complex systems perspective on cognitive powers, where learning is about the development of subjective interpretive frameworks (sets of response rules), are path dependent and contingent on many chance factors. It is this however, that generates the micro-diversity of responses that underlies the capacity of a market system to evolve, and it is very different from the usual idea of "rationality" that is used in economics.

In the second example of structural evolution at the level of the internal structure of competing agents/firms, we see that it is the very ignorance of actual consequences of adding one practice rather than another that generates diversity of the different agents/firms, and allows a successful evolution of the industry. The evolutionary models described above show us the importance of the multi-level nature of socio-economic systems. Individuals with characteristic and developing skills and particularities form groups within companies, generating specific capabilities and also particular receptivities for possible future changes. The products and services that emerge from this are perceived by a segmented and heterogeneous population of potential consumers, who are attracted by the qualities of a particular product or service and the low price at which it is offered. This results in a market share and in changing volumes of activity for different firms. When volume increases, economies of scale occur and allow further price decreases and greater attractiveness for potential customers. However, debts can be cleared quicker if higher prices are practiced, and since there is an interest rate in the model, paying off debt is also a way of reducing costs.

Basically, then, the competition between different quality and pricing strategies is subtle, as the true "value" of a strategy cannot be seen at a particular moment, but instead is only apparent over time, as gradually market share, or profits accumulate and investors can be paid a dividend. The important result from these multi-agent, complex systems simulations above is that instead of showing us *the* optimal strategy for a firm, it tells us that there is no such thing. What will work for a company depends on the strategies being played by the others. The overall lesson is that it is better to be playing in a diverse market ecology than in one involving mainly imitation. So, having a unique identity and product may seem "risky," but it is better than simply packing into the same strategy as others. Coupled with having an individual product and strategy, it is an advantage to "learn." So, exploring the landscape sufficiently to enable "hill-climbing" in profit space is generally better than not doing it. However, it does not necessarily solve all problems because the pathway "up-hill" can be blocked by other firms. In this case a more radical exploration is required with the possibility of a "big jump" in the product and strategy space.

The model shows the limits to learning because firms may all conclude that they should all be "learning" and "hill-climbing," leading to collective movements reminiscent of a flock of birds as firms move up market (Q) and up mark-up space, and then start to try to spread out as a result of their competitive interactions. This still results in the failure of some firms as we saw, and so simply "hill-climbing" is not necessarily a solution. What is best is to have a different strategy from the others, and also to be able to move into new dimensions of quality and of product definition. This basically allows more space within which to be "individual" and hence can allow more specialised niches to be created, and more diverse firms to co-exist.

The lower level evolutionary model of Section 4 shows us how firms explore possible functional innovations, and evolve capabilities that lead either to survival or to failure. They describe a divergent evolutionary diffusion into "possibility space". Each of these is then either amplified or diminished depending on the "performance" of the products or services provided, which depends on the internal trade-offs within them, on the synergies and conflicts that it encounters or discovers in its supply networks, retail structures and in the lifestyles of final consumers.

Similarly, at the level of the market place, firms with different strategies or capabilities also try to "invade" and remain in the system. Exploratory changes lead to a divergent exploration of possibilities. New elements are amplified or diminished as a result of the dual selection processes operating on one hand "inside them" in terms of the synergies and conflicts of their internal structures, and also "outside them," in their revealing of synergy or conflict with their surrounding features in the market. So, a new practice can "invade" a system if it is synergetic with the existing structure, and this will then either lead to the reinforcement or the decline of that system in its environment if the modified system is synergetic or in conflict with its environment. Because of the difficulty of predicting both the emergent internal and external behaviours of a new action, the pay-off that will result from any given new action can therefore generally not be anticipated. It is this very ignorance that is a key factor in allowing exploration at all. Either the fear of the unknown will stop innovation, or divergent innovations will occur even though the actors concerned do not necessarily intend this. Attempting to imitate another player can lead to quite different outcomes either because the internal structure or the external context is found to be different.

Throughout the economy, and indeed the social, cultural system of interacting elements and structures we see a generic picture at multiple temporal and spatial scales in which uncertainty about the future *allows* actions that are exploratory and divergent, which are then either amplified or suppressed by the way that this modifies the interaction with their environment. Essentially, this fulfils the early vision of dissipative structures, in that their existence and amplification depend on "learning" how to access energy and matter in their environment. Can they form a self-reinforcing loop of mutual advantage in which entities and actors in the environment wish to supply the resources required for the growth and maintenance of the system in question. In this way, structures emerge as multi-scalar entities of co-operative, self-reinforcing processes.

What we see is a very generic theoretical framework for an understanding of the internal evolution of firms, as well as that of the markets in which they operate. This encompasses the resource-based theory of the firm (Penrose 1995), since clearly the internal details and resources of the firm will both dictate its costs, capabilities, and initial strategy which will then determine what and how it learns. And, this same co-evolutionary paradigm applies not only to firms, but to the market and to the social and economic system as a whole. It is the complex systems dialogue between explorations of behaviour and characteristics at one level that has unpredictable effects at both the level below and the level above, and these then feed back on the initial level structure. There is a dialogue between the "trade-offs" or "non-linearities" affected inside and outside the particular level of exploration. But it is also true that all levels are exploring. Unless there is an imposition of rigid homogeneity up and down the levels of the system, there will necessarily be behavioural explorations due to internal diversity. In this way, multi-level systems are precisely the structures that can "shield" the lower levels from instantaneous selection, and allow an exploratory drift to occur, that can generate enough diversity to eventually DISCOVER a new behaviour that will grow. Without the multiple levels, selection would act instantly, and there would be no chance to build up significant deviations from the previous behaviour.

This paper suggests the basis for an integrated theory of economic and social evolution. It shows how different types of people channel their needs into particular patterns of demand for different products and services. These are delivered according to the non-linear interactions of synergy and conflict that lead to particular retailing structures, both expressing natural "markets" and also complementarities between product categories and lines. Products themselves exist as embodiments of attributes that are synergetic (internally coherent) clusters, and different product markets emerge naturally as a result of inherent conflicts between attributes. For example, a palmtop computer cannot have a really easy to use keyboard (under existing design concepts) and so notebooks and laptops exist in a different market to palmtops. Similarly, toasters and telephones also occupy separate markets because answering a call on a toaster/telephone can set your hair on fire. So, again it is the "complementarities and conflicts" of possible attributes that structures the space of possible product or service markets.

On the supply side, the capabilities of organisations, and the products and services that they create, are the result of a creative evolutionary process in which clusters of compatible practices and structures are built up, in the context of the others, and discover and occupy different niches. At each moment, it is difficult to know the consequences of adopting some new practice—such as "best" practice, since the actual effect will depend on both the internal nature of the organisation and its actual context and relationships it had developed. For this reason it is bound to be an exploratory, risky process to try new practices, and new products. In the short term it will always be better to simple optimise what already exists, and not to risk engaging on some innovation. But over time, without engaging in evolution, extinction becomes, not simply possible, but actually certain.

The synergies and conflicts of the supply network exhibit similar properties as new technologies provide possible opportunities and threats, and it may be necessary for new technologies and new knowledge to be adopted if extinction is to be avoided later. It is necessary to couple the driving potentials of "human needs" to the products and services that are consumed to satisfy them, and the technologies, the structures and the organisations that form and evolve to create new responses to their changing embodiments. The whole system is an (imperfect) evolutionary, learning system in which people learn of different ways that they could spend their time and income, and what this may mean to them. Companies attempt to understand what customers are seeking, and how they can adapt their products and services to capture these needs. They attempt to find new capabilities and practices to achieve this, and create new products and services as a result. These call on new technologies and materials and cause evolution in the supply networks. Technological innovation, cultural evolution and social pressures all change the opportunities and possibilities that can exist, and also the desires and dreams of consumers and their patterns of choice and of consumption.

This supports the view of evolutionary economics driven by "restless capitalism" (Metcalfe 1998, 1999). This imperfect learning process means that decisions will tend to reflect the short-term positive performance of something with respect to the dimensions of which we are aware, but obviously, in a complex system, there will be all kinds of less obvious factors that are adversely affected, perhaps over the longer term, but even quite immediately. In other words, what we choose to do is dependent on "what we are measuring," and so the system changes reflect our limited understanding of what will actually affect us. This is because our actions are based on our limited understanding and knowledge of the complex systems we inhabit. And their evolution therefore bears the imprints of our particular patterns of ignorance. So, we may grab economic gain, by pushing "costs" into the "externalities," or we may seek rapid satisfaction from consuming some product that actually harms us, or our community, or our region, or the ozone etc. over the longer term.

In response to the question that this paper addresses—do economic systems reflect nearly perfect knowledge or very imperfect knowledge—we see that multi-agent simulations support the latter view. We cannot know how effective a particular strategy will be, because it will depend on the strategies practiced by others—as well as on consumer tastes and needs. In addition, although having a learning strategy is better than not having one, it doesn't necessarily solve the problem, because either the hill-climbing path may be blocked by other firms, or more probably they are all learning too. In effect, the successful working of the market requires underlying heterogeneity—both of potential consumers and of the agents on the supply side. Diverse strategies are required, and ones that are maintained even when some other strategy is working better. Fortunately, the evolutionary model of organisational forms shows us underlying reasons for the creation of such diversity. Since the future is not known there is an element of randomness in precisely which new practice or innovation is tried. But there is an element of non-randomness as to whether, if tried, it can invade. If it does not fit with the current internal practices, then it can't invade, but if it does then it can. However, if it does invade, then it changes the receptivity of the system to future innovations. So, the fact of uncertainty about the future leads naturally to a divergent, branching evolution of possible structures, which then compete and co-operate leading to a selection of a compatible sub-set, and creating a future that cannot be foreseen.

Acknowledgement This work was supported by the ESRC NEXSUS Priority Network. It also benefited from some very helpful and insightful comments of a reviewer concerning the view that complexity supports the view of cognition as one based on structural relationships as opposed to the idea of "rationality" based on deduction and logic that is used most commonly in economics.

Appendix I: The market model

In this simple model we assume that each firm makes a single product. The model consists of equations governing the production of each firm *i*, and each product(*i*). The strategy to be investigated here is that of product quality and mark-up on each product. The aim is to see whether there are winning choices of quality and mark-up, or whether what matters more is the way to change strategy in the light of events.

For firms of type *i*, and potential customers of type *k*:

The potential market (PotMark(*k*, *i*)) for product *i* among customers of type *k* is:

$$\mathrm{PotMark}(k,i) = \left(\mathrm{pop}(k) - \sum_i \mathrm{cu}(k,i)\right) * \frac{A_{ik}}{\sum_j Ajk}$$

Because Pop(k) is the total population of people of type k and cu(k, i) is the number of them who already have product i. By summing cu(k, i) over i we get the number of people of type k with a product of any kind. The term (pop(k)—Σcu(k, i)) is therefore the total number of people of type k without a product and who are therefore "in the market." A_{ik} is the attractivity of product i as viewed by customer of type k, and so all together the term calculates the potential market for product i for people of type k, taking into account how much the quality and price of the product i accord with the preferences of population type k.

The rate at which sales of product i can be made to potential customers of type k depends on the size of the potential market and the size of the sales effort of a firm. It also depends on the time it takes to "deal" with each sale—τ.

$$\text{Sales}(i,k) = s(i) * \text{salesmen}(i) * \frac{\text{Potmark}(i,k)}{(1 + s(i) * \tau * \text{Potmark}(i,k))}$$

The rate of "intersection" of a salesman, or sales effort, with potential customers is $s(i)$, and if the potential market is enormous and there are few salesmen, then the number of sales made is simply the number of salesmen divided by the time it takes to complete a sale—salesmen(i)/τ. However, if the potential market is small, then the number of sales is limited by the rate at which potential customers can be encountered, and in the limit the rate of sales becomes $s(i)$*salesmen(i).

The attractivity of a particular product I for a customer of type k is:

$$A_{\text{ik}} = e^{R*U_{\text{ik}}}$$

Where R is kind of rationality or homogeneity of the population k, and U_{ik} is the "utility" of the product i as viewed by population type k. In our model this will be represented by some negative dependence on price (alpha is negative) and some positive dependence on quality. Clearly the utility of product I for population type k depends on the values of alpha and beta appropriate for the type k. In fact in this paper, we have assumed that everyone would like the same quality of product (same beta(k)) but have different price sensitivities alpha(k), corresponding to a difference of disposable income.

$$U_{\text{ik}} = \alpha(k) * \text{Price}(i) + \beta(k) * \text{Quality}(i)$$

The price of a unit of product is obtained by adding a percentage profit margin to the cost.

$$\text{Price}(i) = \text{Cost}(i) * (1 + \text{Markup}(i))$$

The unit cost is a function of the quality of the product in terms of the input materials and the wage costs required per unit, of the volume of production and of the fixed and variable costs. It also depends on the costs of stocking the finished products as they wait to be sold. The number of salesmen changes dynamically over time to try to keep the stock of unsold finished products low. In the model, it is governed by being a changeable fraction of the total workforce.

If $f(i)$ is the fraction of the workforce that is selling, then we make it increase with the size of the stock(i).

$$\frac{\mathrm{d}\,\mathrm{Stock}(i)}{\mathrm{d}t} = \mathrm{prod}(i) - \sum_k \mathrm{Sales}(i,k)$$

$$\frac{\mathrm{d}f(i)}{\mathrm{d}t} = g * \frac{\mathrm{Stock}(i)}{\mathrm{Pr\,od}(i)}$$

One of the exciting results of the modeling was that it was found that producers could not adjust their production as a result of current profits. The reason was that initially they start with an investment in their new product and so this shows up in the calculations as a negative profit. Because of this, all the firms that launch a new product simply close down immediately. Neither, it turns out do firms calculate exactly the "expected profits," since they cannot make this calculation since it depends on what strategy the other firms adopt. Since most start-up firms close down within a short time, this is clearly consistent with a general impossibility to calculate their expected profits correctly. Instead of this, we adopt the view that firms adopt a strategy and believe in it, finding out whether or not they make a profit, and then either simply continuing until bankruptcy or adopting a strategy to change their strategy on quality or percentage profit. The actual equation that we use is:

$$\frac{\mathrm{d}\,\mathrm{Pr\,od}(i)}{\mathrm{d}t} = r * \mathrm{Pr\,od}(i) * \left\{ 1 - \frac{\sum_k \mathrm{Sales}(i,k)}{\sum_k \mathrm{Potmark}(i,k)} \right\}$$

Where r is some rate of response and production increases if sales are less than potential market.

The number of customers of type k that have a "working" product i is given by the equation:

$$\frac{\mathrm{dcu}(i,k)}{\mathrm{d}t} = \mathrm{Sales}(i,k) - \mathrm{cu}(i,k)/T$$

In this case we suppose an average lifetime, T, of the product and clearly this will be very different for a refrigerator for example, or a newspaper.

In the simulations, firms are launched with initially random choices of quality and percentage profit (mark-up). They have made an initial investment, which shows as a negative bank balance, on which they must pay interest. If they have a high mark-up on each unit, then they will make more profit per sale, but may make less sales than a firm with a product with a lower mark-up. However, too low a mark-up can mean that a firm makes enormous sales, all at a loss and goes bankrupt.

Clearly, as production grows, there are economies of scale, and so the costs of production fall. If these are passed on to customers by keeping the mark-up fixed, then sales will increase and production volume increase further, causing still lower costs. This is a virtuous circle of high sales leading to low costs leading to high sales. However, the market is not infinite and so, at some point there is simply no room for more sales as the potential market drops and we move to market saturation.

This leads to a shakeout of the market. The market switches over from selling products to people without them, to simply replacing the used products.

The model can be made to explore different strategies of learning—from imitation whoever is making most profit to learning how to climb the profit slope around the current quality and mark-up of a firm.

Appendix II: The mathematical model of organizational cladistics

Our model describes the growth in the total production of an organization, which is seen as the sum of the activities of its constituent practices. It is the synergy, neutrality or conflict between its practices that affects the size of each one, and therefore the total output or sum of them all. The model uses a pair matrix defined from survey data from manufacturers concerning their view of the synergy, neutrality or conflictual nature of the 53 practices, to define how each of the 53 practices impinges on the each other. This is a 53 by 53 matrix.

In our model we want to take into account the degree of synergy in the internal practices present in the organization. For an organization with a given set of practices we can use the pair matrix of synergy and conflict to construct the net synergy encountered by each of the particular practices in the presence of the others.

For each practice *h*, of the organization we can calculate the net effect (synergy or conflict) of the other practices actually present to calculate a net synergy:

$$Synergy(h) = \sum_k \left(\frac{Pair(k,h) * P(k)}{(1 + dist(h,k))} \right.$$

This clearly must play a role in increasing the potential market for the production. The limits to production however will be set by the size of the practices already present:

$$Max\,Pr\,od(h) = \sum \frac{P(k)}{(1 + Dist(h,k)}$$

We then calculate a dynamic equation that calculates the growth or decline of each practice in the presence of the others:

We sum from 1 to 53:

$$\frac{dP(h)}{dt} = (b(h) * P(h) * (1 + .01 * P(h)) * (1 + .2 * Synergy(h))) * \left(1 - \frac{Max\,Pr\,od(h)}{N}\right) - m * P(h)$$

After each time step the size of the different practices are updated and the total output of the organization is calculated as the sum of the *P*(*h*):

$$\text{Production} = \sum\nolimits_{\text{h}} \text{P(h)}$$

The receptivity for any new practice, *j*, can be calculated from the Synergy(*j*), for the practices currently present. This allows us to derive a dynamic receptivity which is changed whenever a new practice succeeds in invading the organization.

The model is “run” by starting out with only an artisanal organization, and then launching new practices at random intervals. Sometimes the practice will not survive if the receptivity is too low, and at other times it will take off and add to the total synergy of the organization. With these equations we can make multiple runs corresponding to the possible evolution of a firm from the initial time to the present, and we can consider the relative performance of firms if they were competing during their evolution. Clearly, firms that evolve faster, to greater total production and higher synergy, will probably eliminate the firms that transform themselves more slowly.

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