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An evolutionary complex systems decision-support tool for the management of operations

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Abstract

Purpose – This research aimed to add both to the development of complex systems thinking in the subject area of Operations and Production Management and to the limited number of applications of computational models and simulations from the science of complex systems. The latter potentially offer helpful decision-support tools for operations and production managers.

Design/methodology/approach – A mechanical engineering firm was used as a case study where a combined qualitative and quantitative methodological approach was employed to extract the required data from four senior managers. Company performance measures as well as firm technologies, practices and policies, and their relation and interaction with one another, were elicited. The data were subjected to an evolutionary complex systems model resulting in a series of simulations.

Findings – The findings highlighted the effects of the diversity in management decision-making on the firm's evolutionary trajectory. The CEO appeared to have the most balanced view of the firm, closely followed by the Marketing and Research and Development Managers. The Manufacturing Manager's responses led to the most extreme evolutionary trajectory where the integrity of the entire firm came into question particularly when considering how employees were utilised.

Research implications – By drawing directly from the opinions and views of managers, rather than from logical 'if-then' rules and averaged mathematical representations of agents that characterise agent-based and other self-organisational models, this work builds on previous applications by capturing a micro-level description of diversity that has been problematical both in theory and application.

Practical implications – This approach can be used as a decision-support tool for operations and other managers providing a forum with which to explore a) the strengths, weaknesses and consequences of different decision-making capacities within the firm; b) the introduction of new manufacturing technologies, practices and policies; and, c) the different evolutionary trajectories that a firm can take.

Originality/value – With the inclusion of 'micro-diversity', evolutionary complex systems modelling moves beyond the self-organisational models that populate the literature but has not as yet produced a great many practical simulation results. This work is a step in that direction.

Keywords – Evolutionary complex systems, modelling and simulation, decision-support tools, management decision-making, organisational evolution

Paper type – Case study

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Introduction

Supply networks, organisations, individuals and even their decision-making processes are increasingly being viewed and treated as complex systems (Choi et al., 2001; Frizelle and Woodcock, 1995; Macbeth, 2002; MacIntosh and MacLean, 2001; McCarthy, 2003). There has also been a growing trend recently, and particularly during the last decade or so, in the modelling and simulation of such systems (Chaharbaghi, 1991; Islo, 2001; Li et al., 2003; Lim and Zhang, 2003; Nilsson and Darley, 2006; Zhou et al., 2003). However, such work has been somewhat neglected in the subject area of Operations and Production Management. This research builds on the few studies that have attempted to address this, and endeavours to form a basis with which to develop a decision-support tool offering managers practical assistance during, for example, a change management programme. The paper begins by highlighting, in the context of recent advances in complex systems thinking, modelling and simulation, the need for decision-support tools in the management of operations whilst drawing attention to a particularly problematic case, i.e., the sometimes conflicting interests, motivation and concerns of different functional managers and the potential advantages and disadvantages of these diverse priorities in terms of overall firm performance. After introducing a hierarchy of systems approaches based on modelling assumptions, an evolutionary complex systems (ECS) simulation model is then proposed. Unlike others, this approach has the capability to explore the consequences of the diversity in management decision-making processes of managers from different functional areas and the effects on the potential evolutionary trajectories that a firm can take. Following an account and justification of both the research methods that were employed and the simulation model, outcomes of management decision-making are then presented along with a discussion of the significance both in their own right and in the context of the Operations and Production Management literature. The paper concludes with some closing remarks on the research and practical implications of this work, and further research recommendations and directions.

With complex socio-economic systems, evolution and change are inevitable and the performance and survival of a firm is largely determined by its management of change (Jarratt, 1999; Macbeth, 2002; McCarthy, 2004); and with manufacturing firms, technological change in particular (Raymond et al., 1996). However, change management is fraught with problems not least getting everyone ‘singing from the same song sheet’. For example, there has long been a recognition of the differences in motivations, interests and priorities of managers from different functional areas (O'Leary-Kelly and Flores, 2002; Rhee and Mehra, 2006) which if not managed appropriately, in terms of strategic alignment (Skinner, 1969), can be a significant detriment to firm performance

(Malhotra and Sharma, 2002). This has prompted calls for decision-support tools that increase understanding of the underlying processes in the adoption and implementation of new technologies (Baldwin et al., 2005; Das and Narasimhan, 2001; Klassen and Whybark, 1999), practices (Cua et al., 2001; McKone et al., 2001; Zhu and Cote, 2004; Zhu et al., 2008) and policies (McCarthy, 2004; O'Leary-Kelly and Flores, 2002) within the context of the firm's strategic emphasis both corporate and functional (Brown et al., 2007; Leachman et al., 2005). The role and importance of management decision-making in organisational evolution can not be underestimated. Raymond et al (1996), for example, whilst investigating technology adoption in SMEs, identified the decision-making process as one of three main profiles of strategic advantage along with technological expertise and organisational capabilities.

Two approaches in the development of decision-support systems – theoretical and computational modelling – are evident in the literature. For example, Karkkainen and Hallikas (2006) explored, via case-study, the dynamics of inter-organisational network-related decision-making under a series of scenarios relating to risk management, learning and the business environment. They pointed out that not only was there a dearth of research in management decision-making processes underlying organisational change but that a holistic and systemic approach was needed to fully understand both intra- and inter-organisational decision-making. In remedying this, Meade et al (2006) applied the theories of chaos and complexity to provide an understanding of the decisions behind formulating strategies for the successful positioning of products in the technology adoption life-cycle. Using several case studies of firms within the ICT industry, this work successfully demonstrated the usefulness of this approach. In terms of computational modelling, Lim and Zhang (2003), Zhou et al (2003), and Nilsson and Darley (2006) applied agent-based modelling and created virtual factories to not only further understanding in the change management process but also to create a decision-support tool in the form of 'what-if' scenarios where the consequences of particular decisions could be analysed and evaluated. Agents in these applications typically represented different machines, sales, operations planning, warehousing, and customers. Nilsson and Darley's (2006) work is important not only for providing a rationale for the use of the complex adaptive systems perspective, but also for being the first study to produce empirically verified results of agent-based models in the subject area of Operations and Production Management. At a level of aggregation higher, Kaihara (2003), created a virtual market and explored strategies in a supply chain model based on a problem of resource allocation within a dynamic environment. The aim again, which was largely successful, was to develop a decision-support tool to most effectively optimise supply chain performance.

Whilst acknowledging that management decision-making is central to any organisational change/transformation, there is also rising awareness of the impact of diversity in the decision-making process (Allen et al., 2006; Poundarikapuram and Veeramani, 2004). Diversity, in the context of this research, refers not only to the different decisions that can and are made but to the range of approaches taken when decision-making due to individuals' different perspectives, beliefs, attitudes and information-processing capacities/abilities (Allen et al., 2006). Simon's (1955; 1983) notion of bounded rationality from the cognitive sciences and more recently evolutionary economics, which refers to the incomplete knowledge that people have and use (and misuse) when decision-making, is also relevant here (Nilsson and Darley, 2006). Getting a balance is key, as diversity is seen as being hugely advantageous in terms of innovative capabilities if set within a conducive organisational culture (Jarratt, 1999). It also has the potential to radically affect the evolution of a company particularly in times of change, for example, when introducing a new technology, practice or policy (Baldwin et al., 2005; Jarratt, 1999). However, capturing this level of diversity has been problematical not only in terms of theory (but see, for example, Holland, 1995; Jantsch, 1980; Prigogine and Stengers, 1987) but also, and perhaps more evidently, in application.

ECS modelling departs from the other computational modelling techniques, such as system dynamics, agent-based and other self-organisational models, as it incorporates the role and influence of *micro-diversity* along with experiential learning which are arguably the driving forces and impetus behind *evolutionary*, rather than *adaptive,* change (Allen et al., 2006). ECS theory is a European branch of complexity thinking stemming from Prigogine's (1973) Nobel Prize winning work. The approach has now been successfully applied to ecosystems, urban systems, economic markets and, more recently, in evolving an entire industry (Allen et al., 2005; 2006; 2007; Baldwin et al., 2005).

To illustrate the differences between the different systems models a consideration of underlying assumptions is needed. Modelling assumptions create a hierarchy of models from known certainties and perfect prediction through to explorations of the unknown and the least-likely of potentialities (Allen et al., 2007). All systems models have at least two assumptions: 1) that a boundary exists between the system, in this case the firm, and its environment, and 2) that the system's components, e.g., the firm's technologies, practices and policies, can be classified to produce a taxonomy.

Additional assumptions concern the system's components and their interactions. System dynamic models have components and interactions that represent the average. When everything has been averaged there is just one future path – the most probable. These models give the impression of complete understanding and knowledge, and in turn perfect predictability. But what do average components and interactions actually mean when applied to a firm? Take, for example, the implementation of line-balancing or empowering employees. Not every firm has the same approach. Indeed, if every firm's approach was scrutinised, there would be a high degree of idiosyncrasy. Furthermore, and in terms of interaction with other components (e.g. quality or inspection policies), not all implementations of line-balancing and/or empowering employees have the same outcomes. That is, what would work in one organisation, or even one point in time, may not necessarily work in another.

By introducing the non-average, the nature of the model begins to change from certainty and prediction to exploration and potentialities. Through the inclusion of all the potential types of interactions that can occur, models can begin to explore and reach many possible future scenarios through self-organisational processes (e.g. the different outcomes of line-balancing or employee empowerment implementation in the example above). The few complex system computational models found in the literature are of this type (see, for example, Chaharbaghi, 1991; Islo, 2001; Kaihara, 2003; Li et al., 2003; Lim and Zhang, 2003; Meade et al., 2006; Nilsson and Darley, 2006; Zhou et al., 2003). Although highly useful both practically and intellectually, there is, nonetheless, a limitation to these models particularly in their application to social systems. To represent diversity, these models have a stochastic mechanism that generates 'noise', which is perhaps more realistic than assuming only average conditions and interactions. However, whilst these models introduce non-average interactions, the components or, in another word, agents are still of an average type that are subject to a pre-defined, 'if-then' rule-based system. The noisy interaction of 'average' elements does not have the same outcome, or spread of outcomes as the interaction of diverse, heterogeneous individual elements. In the former case we may see different configurations or regimes of operation appearing, but in the latter case, new combinations of different elements leading to new, emergent capabilities and dimensions of performance can occur. This is the essential characteristic of evolutionary change – a process of qualitative, not just quantitative, change.

It is heterogeneous components that distinguish ECS models from self-organisational models (Allen et al., 2007). Representing all possible types of components, through the introduction of internal or micro-diversity, as well as all possible interactions produces a more realistic representation of true evolutionary processes. Whilst blind adaptation is associated with self-organisational models, ECS models mimic co-evolution through experiential learning. Control devolves fully from the global/system level to the local/individual level and is an expression of singular behaviours and their performance and success relative to others within the system; evolution proceeds through fully de-centralised, rather than centralised, decision-making. In addition, evolution, being an open process, ensues through a combination of not only the determinism of the individuals' purposefulness but also by chance events. The intake of new kinds of individuals, or the changing views and thoughts that they may have is not a rational, calculated process because the implications of any particular heterogeneity is not known until after an evolutionary step has occurred in system behaviour. In this way, the evolution that does occur is not really predictable but results from the interplay of individual heterogeneity and the differential performances of the resulting organisations. This is largely characterised by an inevitable lack of pre-existing knowledge of the link between individual and system behaviour and can be thought of as resulting from a degree of 'error-making' (Allen et al., 2006). The role of chance is fundamental, however, creating a rich medium for experiential learning through continuing experiments in behaviour space (Allen et al., 2007). As the approach incorporates diversity at all levels of description, it is appropriate when trying to attain a better understanding of the role of diversity in decision-making and the impacts on a firm's evolutionary trajectories.

Research Methods and Preliminary Results

The development of the ECS model, which simulated a firm's evolutionary trajectory reflecting management assumptions, was achieved by: a) building a profile of a firm through a case-study approach involving observation and simple semi-structured interviews; and then b) gauging, via a quantitative questionnaire, the managers' perception of how the firm's technologies, practices and policies (also referred to as 'character-states') interacted with one another in the context of their overarching operations strategy. In so doing, it was possible to compare and contrast different decision-making capacities, which enabled an exploration of decision-making consequences resulting from potentially diverse information sources and assumptions.

The case-study approach was selected to better illustrate and exemplify the utility of the ECS modelling technique (Eisenhardt, 1989; Meredith, 1998) and is consistent with similar research in Operations and Production Management research (e.g. Meade et al., 2006; Nilsson and Darley, 2006). As is common with case study research, sampling was purposive (Saunders et al., 2007). That is, a number of firms were pre-screened to determine whether they had a suitable profile that would help achieve the research aim. A mechanical engineering firm was approached and consented to act as the case study. The CEO, and three senior managers, responsible for Marketing, Manufacturing, and R&D, participated.

Interviews were based on a simple, semi-structured, qualitative questionnaire, which was sent to each participant prior to the interview, and was accompanied by pre-prepared paper-based check-list of common operations practices and policies, which was not made known to the participants to avoid interviewer bias. To maximise internal validity (Saunders et al., 2007), the interview schedule and practice check-list was first piloted on two industrialists and an academic familiar with Operations and Production Management after which small adjustments were made. Interviewer and interviewee biases were minimised through the selection of neutral settings for interviews and through a standardised presentation of non-leading questions (Saunders et al., 2007). Interviews were recorded but due to the basic nature of this part of data collection and analysis, were not transcribed. They were instead directly interpreted and coded using the pre-prepared practice list as a guide. Essentially, if the practices from the list were mentioned then it was marked for inclusion for the next quantitative questionnaire phase plus any additional practices and policies identified. This was conducted during the interview. There was then a post-interview analysis of the recordings to verify the list of practices. No further practices were added at this stage.

The interview firstly encouraged a discussion of the firm's operations strategy, by asking participants what they deemed important for the survival of the company in terms of performance, using as the basis for discussion both the Four Competitive Priorities (cost, quality, time and flexibility), from Hayes and Wheelwrights (1984) and the Five Performance Objectives (quality, speed, dependability, flexibility and cost), from Slack et al (2007). These performance criteria were familiar with the interviewees and are consistent with both the literature and previous empirical research on manufacturing performance (see, for example, Brown et al., 2007; Cua et al., 2001; Das and Narasimhan, 2001; Fynes et al., 2005). From the interviews, four main performance criteria, i.e., product quality, cost efficiency, customer relationship, and schedule adherence, were found to be relevant and there was also an indication that they had differing degrees of importance which is consistent with the literature (Hayes and Wheelwright, 1984; Skinner, 1969). Three out of the four performance criteria, i.e., product quality, cost efficiency and schedule adherence, directly mapped on to Hayes & Wheelwrights' (1984) Competitive Priorities and Slack et al's (2007) Performance Objectives. Customer relationship although alluding to aspects of flexibility and dependability, had a much more informal element relating to social relationships of trust building, which is more relevant to aligning organisational cultures and corporate strategies.

The interview process then encouraged a discussion of what 'characterised' the company, by asking questions about the firm's technologies, practices and policies covering, in a sequential manner, the workforce, scheduling, suppliers, quality, R&D and production processes. The pre-prepared check-list consisted of 47 practices (see appendix) which were elicited from the literature particularly from Womack et al's (1990) and McCarthy et al's (1997; 2000) work on the evolution and development of the automotive industry supported by the generic manufacturing practices alluded to in Kinni (1996), Schonberger (2008) and Slack et al (Slack et al., 2007). Although, this level of data collection is fairly basic and could have been achieved using a questionnaire survey based on generic operations technologies, practices and policies, a better understanding of the idiosyncrasies of the firm was attained through interviews. Furthermore, different descriptors, which were more relevant to that particular organisation, were identified, along with additional technologies, practices and policies (i.e., not on the pre-prepared check list). The interviews also ensured both participation in the next quantitative questionnaire phase and more importantly it gave participants a better understanding of their requirements in this phase. Twenty-five character-states (listed in table 1) were identified as the most important technologies, practices and policies for continued successful firm performance providing the basis for the quantitative questionnaire.

The quantitative questionnaire was designed to gather the managers' views of how the 25 character-states interacted with one-another in relation to the overall performance of the firm. To achieve this, the questionnaire had three parts. The first asked participants to rank the overall importance of the four performance criteria to the company, for example, 1st: customer relationship; 2nd: schedule adherence, and so on. Three out of the four (the CEO, and the marketing and R&D managers) ranked customer relationship first followed by product quality, schedule adherence and cost efficiency. The Manufacturing Manager indicated a ranking of product quality, schedule adherence, customer relationship followed by cost efficiency. The second part asked participants to rank the impact or strength of association of each of the character-states on each of the performance criteria; for example, CS1, R&D investment, may be associated 1st with product quality, 2nd with customer relationship, 3rd with cost efficiency and 4th with schedule adherence, etc. These first two sections determined whether different practices contributed to some performance criteria more than others, i.e., whether some practices were more important than others, and provided a basis for weighting mechanisms in the ECS model enabling a reflection of the character-states' impact on the overall operations strategy. However, due to the informal nature of the customer relationship performance criterion, the majority of technologies, practices and policies, did not directly contribute, i.e., scored poorly, and as such was excluded from the weighting mechanism.

Table 1 - Firm character-states (CSs): Number, label and description

No.	Label	Description
1	R&D investment	Significant R&D investment on product quality and process efficiency improvements.
2	Continuous production	Three production shifts ensure non-stop production.
3	Cells with automated equipment	Factory layout is based on the cell principle with a significant substitution of human labour with mechanised labour.
4	Setup time reduction	Setup processes for machinery/equipment are analysed in order to reduce time between setups for different production runs.
5	Setup automation	Set-ups between production runs are largely automated rather than manual.
6	Preventive maintenance	Operators and in-house engineers perform routine maintenance on a regular basis on workstations and process machinery including, cleaning, oiling/greasing, adjustment, and parts replacement to avoid breakdowns.
7	Outsourced corrective maintenance	All but the simplest machine/equipment breakdown repairs are largely outsourced.
8	MRP system (material replenishment)	Materials Requirement Planning software system to aid production planning and inventory control.
9	ERP system (organise/monitor resources)	A number of software based Enterprise Resource Planning modules are currently being implemented to organise and monitor resources with the aim of replacing the existing MRP system.
10	Full resource visibility	ERP manufacturing module enhancing the visibility of resources through stock to production.
11	Resource priority control	A Pareto based control system to prioritise purchasing, stocking and allocation of resources.
12	ERP supply chain integration	ERP supply chain management module to facilitate communication and information sharing to reduce costs and enhance both responsiveness and quality.
13	Supplier co-operation	The organisation has an open book, co-operative relationship with suppliers and customers.
14	TQM sourcing	Vendors are vetted according to stringent quality standards to ensure consistently high quality sourced components and raw materials.
15	Quality systems/standards	A series of standards for quality management systems maintained by the International Organisation for Standardisation and administered by accreditation and certification bodies.
16	5S's programme	The 5S's programme involves: 1. Sort/Segregate (keeping only essential equipment/tools/materials at workstations); 2. Simplify/Straighten (workstations anthropometrically designed to improve efficiency of movements); 3. Shine/Sweep (workstation cleanliness); 4. Standardise (removing variations in movement/flow); 5. Sustain/Self-discipline (periodic motivational reviews of employee performance).
17	Decentralised error detection and correction	Operators are largely responsible for detecting and rectifying quality problems as and when they occur at their workstations.
18	100% inspection	To ensure the highest quality, each and every product is inspected.
19	Production process traceability	A quality system to enhance traceability along the production process.
20	Line-balancing	Tasks are assigned to workstations to level overall time requirements and fluctuations.
21	Job rotation	Operators regularly work on other qualitatively different tasks.
22	Flexible workers	Flexibility is achieved mainly through multi-skilling but also includes both time flexibility (PT/FT, specific working times, and to cover variable demand) and location flexibility for 'indirect' manufacturing jobs (i.e., occasional home-working to fully mobile).
23	Empowering employees	Employees are empowered through both suggestion involvement (i.e., suggest process improvements) and 'job involvement' (i.e., redesign processes to improve efficiency/quality).
24	Employee multi-skilling	Operators develop a set of skills to enable work on qualitatively different tasks.
25	Proactive annual training	Operators are intensively trained annually in current and future practice to support multi-skilling and flexibility.

*Note: 'character-states' will be abbreviated in the text to 'CS' when referred together with a particular technology, practice or policy; for example 'CS1, R&D investment'

The final part of the questionnaire asked participants to gauge the interactions between each of the character-states in terms of the overall performance of the firm. The answer options were based on a 7-point Likert scale (-3 to +3) determining the degree of positive/neutral/negative interactivity. That is, for example, participants could indicate say a moderately synergistic interaction between CS1 and CS2 as '+2' and a strongly antagonistic interaction between CS1 and CS3 as '-3' and so on. These scores were weighted in accordance with their impact on the ranked performance criteria. The ECS model drew directly from these weighted scores. Piloting for the questionnaire, involving two academics and two industrialists, was in two stages after which minor/incremental adjustments were made to the questionnaire to ensure construct validity (Saunders et al., 2007).

The Simulation Model

With ECS modelling, structures and the organisation of different practices may be explored. The work presented here traces its origins back to the insights expressed in the works of Prigogine (1973), colleagues (Glansdorff and Prigogine, 1971; Kondepudi and Prigogine, 1998; Nicolis and Prigogine, 1977; 1989; Prigogine and Stengers, 1987), and others (Allen, 1982; 1984; Haken and Mikhailov, 1993; Jantsch, 1980) who have all demonstrated how complex systems evolve through the emergence of fluctuations and instabilities within a system. Prigogine (1973) developed a simple model, known as the 'Brusselator' (after the Brussels' School of Thermodynamics), which described how non-equilibrium systems become unstable and begin oscillating. The conditions to be met are that the system is open, that the gradient (i.e. flow of matter and energy) creates a far-from-equilibrium state, and that there are autocatalytic steps in the reaction chain. Autocatalysis is the process where molecules participate in reactions necessary for molecules of their own kind (Jantsch, 1980) and can create both positive and negative feedback (Atkins, 1984). The scheme is as follows:

$$A \rightarrow X$$
$$B + X \rightarrow Y + D$$
$$2X + Y \rightarrow 3X$$
$$X \rightarrow E$$

The inflow of species A and B and the outflow of D and E are maintained to keep the system in non-equilibrium (Kondepudi and Prigogine, 1998). The autocatalytic step can be seen in the second and third step of the reaction system (where X produces Y, in the second step, which then produces X in the third step). Autocatalysis creates the non-linearity responsible for the patterns or organised states that emerge (Jantsch, 1980). This demonstrated that the interdependencies of the variables could create as well as destroy structure and organisation as the system evolves through self-organisational processes.

Building on these principles, Allen (1976) developed a mathematical expression describing the introduction and growth of new 'behaviours' into a system, such as new species in a natural ecosystem. The ECS model developed for this study was adapted from this and was designed to simulate the interaction between the firm's character-states drawing directly from the four decision-makers' questionnaire data. In terms of manufacturing, the behaviours/species and their interactions represent the manufacturing firm's technologies, practices and policies and how they work together. Biological evolution, through selection, surrounds the diffusion and proliferation of innovative behaviours determined by their success, or relative performance, in birth and death rates. Birth and death rates represent, for example, the performance in the competition for resources, mating success, avoiding/catching prey, and rearing offspring. In terms of manufacturing, the success of character-states reflects the importance of the character state to the organisation in terms of, for example, product quality, schedule adherence and cost efficiency. Successful bundles of practices and behaviours will experience positive feedback and growth when their particular characteristic performances correspond to that which the selection environment requires.

The model is based on the equations given in Allen et al (2007), developed in Turbo Basic® and run in the Microsoft Dos® operating system. The mathematical model describes the growth in the total health of a manufacturing firm, 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 the questionnaire data from the four senior managers concerning their view of the synergy, neutrality or conflictual nature of the 25 practices, which defines how each of the 25 practices impinges on each other (a 25 by 25 matrix). The degree of synergy is taken into in the internal practices present in the firm. For a firm with a given set of practices the pair matrix of synergy and conflict is used to construct the net synergy encountered by each of the particular practices in the presence of the others. For each practice of the firm, the net effect (synergy or conflict) of the other practices actually present can be calculated which leads to a net synergy:

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

Where *h* is an individual character-state; *k* is the population of character-states; and, *P* is the overall 'health' or 'survival' of the system. This gives an indication of the overall survival or health of the system/firm. The limits to 'health' however will be set by the size of the practices already present:

$$MaxHealth(h) = \sum \left(\frac{P(k)}{(1 + Dist(h,k))}\right)$$

A dynamic equation is then calculated representing the growth (*b*) or decline (*m*) of each practice in the presence of the others (summing from 1 to 25):

$$\frac{dP(h)}{dt} = (b(h)*P(h)*(1+.01*P(h))*(1+.2*Synergy(h))*\left[1-\left[\frac{MaxHealth(h)}{N}\right]\right]-m*P(h)$$

After each time step the size of the different practices are updated and the total health of the system/firm is calculated as the sum of the *P(h)*:

$$Synergy(h) = \sum_h P(h)$$

For the running of the ECS model, several variables can be manipulated and calibrated, three of which require more explanation. The first is the running time of the simulation. This may be adjusted to permit finding stable solutions which are typically found within 10-50,000 arbitrary time units. The second variable is the number of character-state initiations in the model that allows exploration of particular organisational forms. The third is the performance value of the character-state. Performance may lie between 0-30 arbitrary units. The higher the value, the better the performance and importance within the organisation. The simulations presented here launched the character-states with a starting value of 5 performance-units.

Before the results are presented there are two qualifications that need to be highlighted. The first is that the particular simulations presented here are among many possible trajectories dependent on initial conditions. All simulations of the different managers, however, begin with identical initial conditions. However, selecting particular solutions is somewhat problematical when dealing with evolutionary systems as an infinite number of possible evolutionary trajectories are possible. Nonetheless, the simulations selected for presentation were deemed fairly representative of a series of repeat simulations. The second qualification is that, unlike reality, the simulations depict an evolution of the firm with all character-states starting as equal (with 5 performance-units). Nonetheless, the results from this procedure do highlight differences (and similarities) between the different decision-makers.

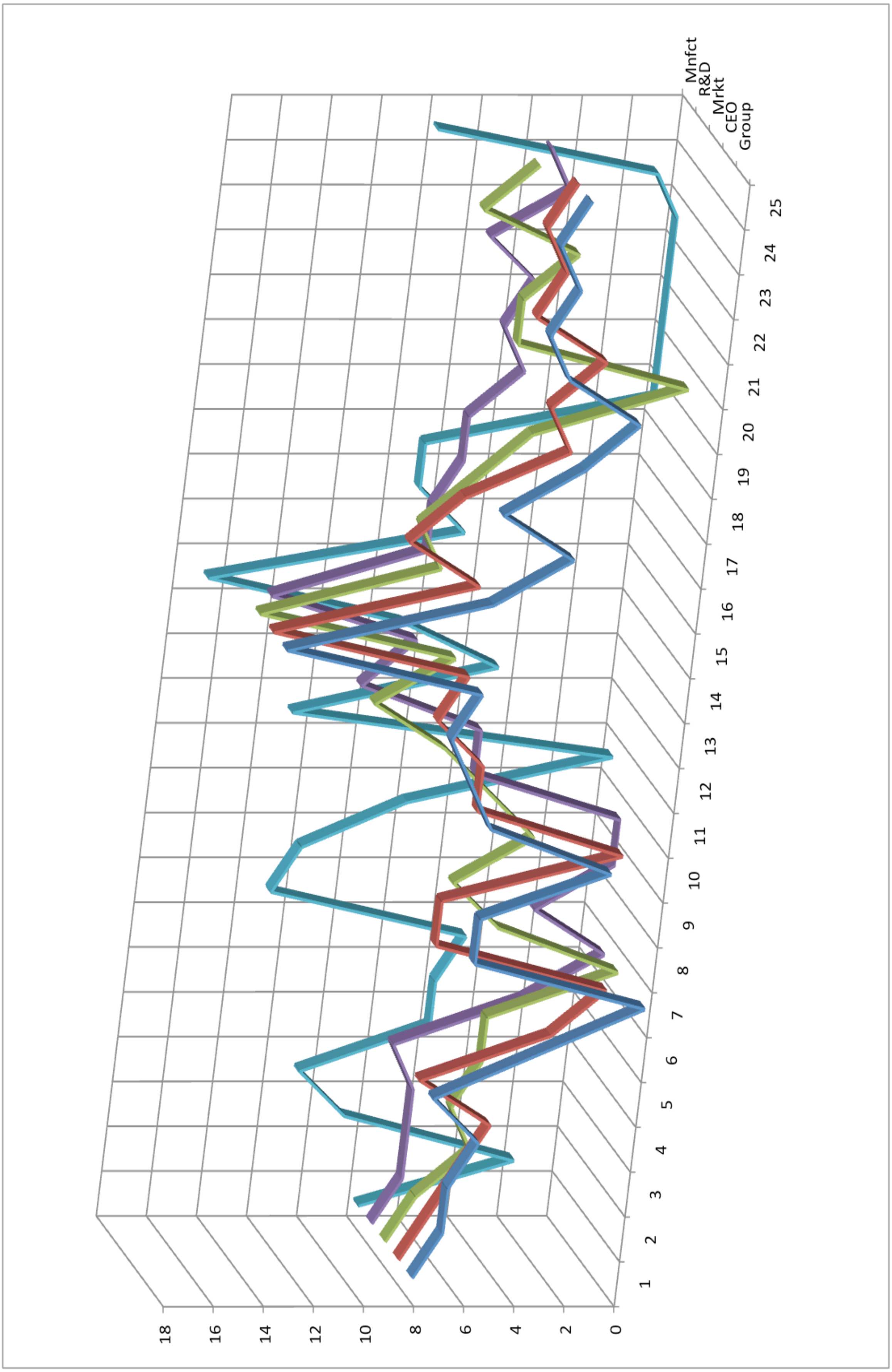
Simulation Results and Discussion

To fully appreciate the effects of diverse decision-making capacities, five simulations are presented and discussed. Figure 1 depicts, in simplified form, five separate evolutionary trajectories of the firm. The first line, to the front of the graph, represents the results of a simulation in which all the managers' scores were averaged out – the group simulation. The second, third, fourth and fifth lines represent the results of simulations based individually on the CEO's, Marketing, R&D, and Manufacturing Managers' scores, respectively. Each point of the line represents a character-state's 'performance'; the number indicated below each point on the line corresponds to the character-state numbers in the list of practices in table 1. The height of the line in the line graph is an indication of the performance or the value to the firm of that particular character-state relative to the other character-states in terms of the performance criteria (i.e., customer relationship, product quality, schedule adherence and cost efficiency). The presentation of results has been simplified using Microsoft Excel®.

There are several general points to discuss here. The first is that the simulations reveal several potential management concerns, both collectively (in terms of group decision-making) and individually, that can then be flagged up for further discussion and exploration, similar to the 'what-if' scenario building of Nilsson and Darley's (2006) work. Taking the collective concerns as an illustration, when the managers' opinions are aggregated (the first line, to the front of the graph in figure 1), CS7, outsourced corrective maintenance, fails, indicating a consensus that this practice is problematical. The simulation also flags up concerns over CS6, preventive maintenance, CS20, line-balancing and CS10, full resource visibility, which were low performers relative to other character-states. Overall, the integrity of the organisation was very good, however, signifying that as a decision-making group the managers are more complementary than not.

The second point concerns the nature of the model, the micro-diversity that has been captured and the potential insights that this gives. As can be seen from the research methods, the model draws directly from the opinions and views of managers rather than from logical 'if-then' rules and averaged mathematical representations of agents that characterise agent-based and other self-organisational models, particularly those proposed by Lim and Zhang (2003), Zhou et al (2003), Li et al (2003), and Poundarikapuram and Veeramani (2004). However, the micro-diversity is represented here by the individual managers' opinions, which cannot be fully appreciated in the first simulation.

Figure 1. Simulations of firm evolution: 1) Managers' average; 2) CEO; 3) Marketing Manager; 4) R&D Manager; and, 5) Manufacturing Manager.



This limitation exists in previous research (see, for example, Baldwin et al., 2005) where opinions of manufacturing managers, operations managers, CEOs and company managers were averaged out. As such, significant information is lost. In Baldwin et al's (2005) study, there was an indication that the informants had very diverse views of how technologies and practices interacted with one another. Unfortunately, the methodology prevented a thorough analysis of views of the individual respondents. This was due to the large numbers of characteristics; that is, the survey instrument had to be divided into four parts with one informant only giving their opinions on a quarter of the total number of characteristics. To further illustrate this limitation, the means and standard deviations of the character-state performances resulting from the grouped managers' opinions are presented in table 2.

Table 2 – Means and standard deviations of the character-state performances

CS	Mean	SD	CS	Mean	SD	CS	Mean	SD
1	8.00	0.60	**10**	3.25	3.59	**18**	8.50	0.58
2	5.75	2.50	**11**	4.75	3.20	**19**	4.75	3.40
3	6.75	1.71	**12**	8.50	3.11	**20**	3.00	3.46
4	6.75	1.50	**13**	9.00	2.83	**21**	4.50	3.32
5	7.25	2.63	**14**	8.50	0.58	**22**	5.00	3.37
6	4.25	1.50	**15**	16.00	0.82	**23**	4.75	3.40
7	1.50	2.38	**16**	8.25	0.96	**24**	5.50	3.42
8	7.25	4.35	**17**	9.75	0.96	**25**	7.25	1.89
9	6.75	4.99						

Figure 2 graphically displays the results from 100 simulations of the performance of individual character-states giving an indication of variability among the managers' scores whilst also the degree of character state failure throughout the simulations. As can be seen, character-states with the most variability, in descending order are: CS9, ERP system; CS8, MRP system; CS10, full resource visibility; CS20, line-balancing; CS24, employee multi-skilling; CS23, empowering employees; CS19, production process traceability; CS22, flexible workers; CS21, job rotation; CS11, resource priority control; and, CS12, ERP supply chain integration. Character states that had high failure rates, in descending order, are: CS7, outsourced corrective maintenance failing in 23% of simulations; CS20, line-balancing (14% failure rate); CS10, full resource visibility (13% failure rate); CS21, job rotation (12% failure rate); and CS22, flexible workers, CS9, ERP system, and CS11, resource priority control, all failing in 10% of simulations.

An important point to make here is that the degree of failure rate in the simulations is not a sufficient indicator of a problem in actual practice, if, for example, it is accompanied with high variability which is an indicator of management disagreement. However, if a high failure rate in combination with low variability is found then the likelihood of a genuine problem in practice is high. This is most evident with CS7, outsourced corrective maintenance, which has the highest failure rate together with only low-to-moderate variability.

This limitation is addressed here in that the opinions of different managers in a firm are considered fully and can be explored individually. Thus, to explore this variability in more detail, the next step was to analyse the opinions of the different decision-makers separately and compare and contrast the results. Figure 1 also shows a simulation of the CEO's opinions at the stable solution (the second line in the graph). Interestingly, this simulation largely mirrors the first simulation where all the managers' opinions are aggregated. This raises several questions. Does the CEO have a more overarching model of the 'mechanics' of the firm reflecting the consensus of the group of managers? Or does the CEO have the ability to project his understanding/influence onto the other managers in their particular fields of functional expertise? This may reflect in some respects, for example, what Jarratt (1999) sees as achieving the right balance between centralised and de-centralised systems in the management of diversity. An important observation is that the CEO's results did not have any character-state failures. This gives a strong impression that the CEO does indeed have at least a healthy view of the organisation and, in contrast to the other managers, sees how all the character-states work and fit together. However, the CEO did appear to have concerns over CS6, preventive maintenance, CS7, outsourced corrective maintenance, CS21, job rotation and CS10, full resource visibility, which, apart from CS21, job rotation, reflects the simulation of the aggregated opinions.

Figure 2 – Variability of character-state performance and degree of failure

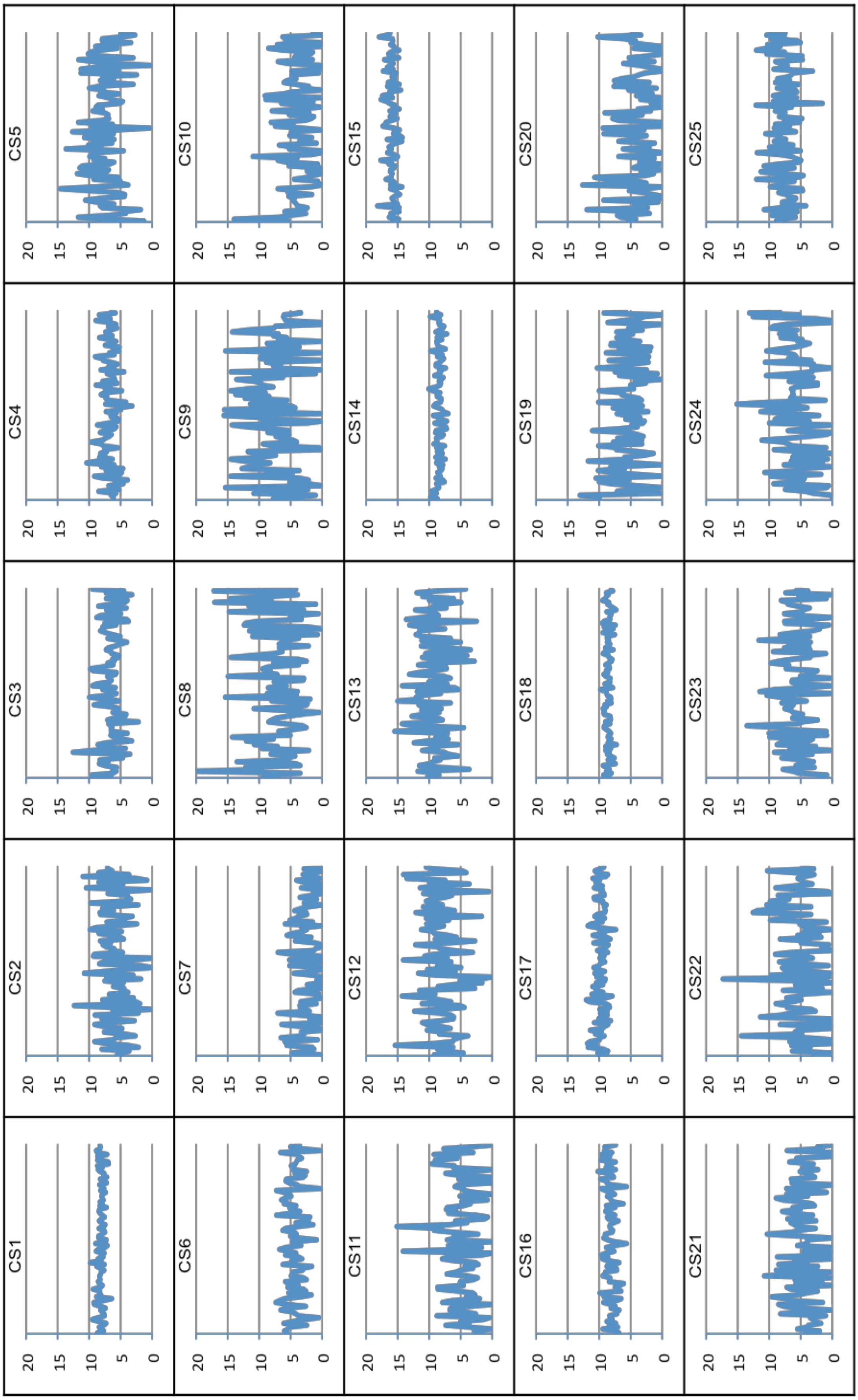


Figure 1 portrays the Marketing Manager's simulation at the final solution (the third line in the graph). This begins to demonstrate the significant role that individual differences or diversity has in the management decision-making process and adds support to the arguments of Allen et al (2006), Poundarikapuram and Veeramani (2004), and O'Leary-Kelly and Flores (2002). In the Marketing Manager's simulation there are several differences that need to be highlighted. The first is that only seventeen of the twenty-five character-states improved on their starting value. This is in contrast to the first two simulations where there were improvements for twenty of the aggregated scores and nineteen of the CEO's scores. However, seven of the nine character-states that surpassed 8 performance-units agreed with the CEO. The main difference, particularly in terms of the CEO's results, was that two character-states, CS7, outsourced corrective maintenance, and CS20, line-balancing, failed altogether. Although the performance of the former character-state reflects the aggregated results and to a degree the CEO's simulation, the latter is opposed to the opinion of the CEO. The Marketing Manager's negative impression of line-balancing may be a symptom, for example, of functional barriers (Malhotra and Sharma, 2002; Rhee and Mehra, 2006) and is another area for further management analysis.

The R&D Manager's simulation at closing is shown in figure 1 (fourth line in the graph). The results largely agreed with the latter two managers but with obvious exceptions. Agreement surrounded CS15, quality systems/standards, CS17, decentralised error detection and correction, CS16, 5S's programme, CS13, supplier co-operation, and CS1, R&D investment, which all had good performances with end values of over 8 performance-units (that is, eight out of ten character-states in agreement with the CEO). Furthermore, both CS7, outsourced corrective maintenance and CS10, full resource visibility, failed for the R&D Manager – the CEO and Marketing Manager's simulations also resulted in low scores for the latter with 1 and 4 performance-units, respectively. The point of divergence concerns both CS9, ERP system, which had no place in the final solution, and, CS8, MRP system, which had a very weak performance relative to most other character-states. In this instance, a plausible explanation is the fact that the firm has both ERP and MRP systems running simultaneously, where the former should be in replacement of the latter. However, no other managers' simulation flagged this.

The final simulation at conclusion (see figure 1; the fifth line in the graph), based on the Manufacturing Manager's opinion scores, took on the most extreme final configuration and was in stark contrast to the rest of the decision-makers' simulations and is the best example of the significant role and impact of diversity among decision-makers alluded to by Nilsson and Darley (2006), Allen et al, (2006) and Jarratt (1999). The most obvious difference was that six character-states failed with an additional two barely surviving, finishing with less than 2 performance-units. Of the eight character-states that failed or underperformed, six surrounded policies concerning employees (i.e. employee multi-skilling, line-balancing, job rotation, flexible workers, empowering employees, and continuous production). This pattern indicates that the Manufacturing Manager has issues with the way the workforce is utilised. Suggested reasons could be that the employee policies are not working as intended or that the manager has different preferences. With only fifteen character-states gaining on the original values, it was, however, interesting that twelve of these reached or exceeded 8 performance-units, which was the most out of all simulations. With both the failures and high scoring character-states, this simulation represents the most extreme potential evolutionary trajectory of the firm out of the five presented here. This simulation when compared to the other simulations also lends significant support for a long standing call voiced by O'Leary-Kelly and Flores' (2002) and Malhotra and Sharma (2002) for more integration and understanding between functional areas and particularly between operations and other functions.

On a general reflection, a consensus is evident among all managers surrounding the importance of a good proportion of character-states including (indicated by 8 performance-units or above in the majority of simulations): CS15, quality systems/standards, CS14, TQM sourcing, CS18, 100% inspection, CS17, decentralised error detection and correction, CS7, 5Ss programme, CS5, setup automation, CS12, ERP supply chain integration, CS13, supplier co-operation, and CS1, R&D investment. The practical usefulness perhaps lies more in the exploration of the more problematical areas (Nilsson and Darley, 2006). Character-states in need of review and discussion (signified by multiple failures) include CS7, outsourced corrective maintenance (3 failures) and CS20, line-balancing (2 failures). The results suggest that the policies concerning employees may also need revisiting, as a good proportion faired relatively poorly rarely breaching 8 performance-units. In terms of methodology, the findings also strengthen the consistency/reliability of the data collection procedure adapted from previous work (Allen et al., 2005; 2006; 2007; Baldwin et al., 2005).

Closing Remarks

In terms of practical value, ECS models and simulations, along with other similar tools such as those advocated by Nilsson and Darley (2006) and Meade et al (2006), offer a more realistic decision-support tool for management with which to explore the strengths, weaknesses and consequences of different decision-making capacities within the firm. In this research, for example, out of the four decision-makers, the CEO appeared to have the most balanced view of the organisation as all character-states successfully survived. Both the Marketing and R&D Managers had similar simulation outcomes to the CEO but with two to three character-state failures. The

Manufacturing Manager's simulation took the most extreme evolutionary trajectory and highlighted the potentially disastrous effects of diversity in decision-making.

On a more academic note, further case studies are still required; firstly, to strengthen the reliability and validity of the methods employed; and, secondly, to encompass more management decision-making scenarios. In future research, clarification could be sought into the potential underlying reasons and consequences for the successes and failures of particular technologies, practices and policies. Unfortunately, in this instance, the empirical setting could not be re-visited. Not long since the main investigation was conducted the case study firm ran into difficulties and ceased operations, approximately a year after the questionnaire survey (late 2006). There are several other avenues for future research that builds on and can extend this work. Firstly, the approach may be used to explore underlying opinions, beliefs and attitudes along with their potential consequences on the evolutionary trajectory of a firm when introducing an entirely new manufacturing technology, practice or policy. At the time of this study, a new ERP system was being implemented and the simulations revealed particular synergies as well as conflicts with other practices. Ideally, this modelling approach should have been applied prior to implementation, perhaps with the input of external experts, and would have perhaps highlighted the most prevalent issues and potential pitfalls. Alternatively, firms may explore a significant change in operations strategy, say from low cost strategy to a high quality or differentiation strategy. The ECS model could then explore the performance of current practice and how new practices could further help (or hinder) the firm. There is also a possibility to model at a level of aggregation above, i.e., the supply chain or perhaps an industrial sector. With the former, supply chain practices in the context of supply chain strategies may be simulated highlighting both what practices (and individual firms) would help or hinder the overall performance of the supply chain.

To conclude, this research aimed to provide insights into the potential evolutionary effects of the diversity in management decision-making and attempted to add to both the theoretical development of complex systems thinking and to the application of computational models and simulations which is still arguably lacking in the particular area of Operations and Production Management (Macbeth, 2002; McCarthy, 2004; Nilsson and Darley, 2006).

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Appendix 1

Pre-prepared check list of operations management technologies, practices and policies (adapted from McCarthy et al., 1997; Womack et al., 1990).

✓	TECHNOLOIES, PRACTICES AND POLICIES		✓	TECHNOLOGIES, PRACTICES AND POLICIES
	1. Standardisation of parts			29. U-shape layout
	2. Assembly time standards			30. Preventive maintenance
	3. Assembly line layout			31. Individual error correction; products are not re-routed to a special fixing station
	4. Reduction of craft skills			
	5. Automation (machine paced shop)			32. Sequential dependency of workers
	6. Pull production system			33. Line balancing
	7. Reduction of lot size			34. Team policy (motivation, pay and autonomy for team
	8. Pull procurement			35. Groups Vs teams
	9. Operator based machine maintenance			36. Job enrichment
	10. Quality circles			37. Manufacturing cells
	11. Employee innovation prizes			38. Concurrent engineering
	12. Job rotation			49. ABC costing
	13. Large volume production			40. Excess capacity
	14. Suppliers selected primarily on price			41. Flexible automation for product versions
	15. Exchange of workers with suppliers			42. Agile automation for different products
	16. Socialisation training (master/apprentice)			43. Insourcing
	17. Proactive training programmes			44. Immigrant workforce
	18. Product range reduction			45. Dedicated automation
	19. Autonomation			46. Division of labour
	20. Multiple sub-contracting			47. Employees are system tools and simply operate machines
	21. Quality systems (tools, procedures, ISO9000)			48. Employees as system developers; value adding
	22. Quality philosophy (TQM, culture)			49. Product focus
	23. Open book policy with suppliers; cost sharing			50. Parallel processing
	24. Flexible multi-functional workforce			51. Dependence on written rules; unwillingness to change rules as the economic order quantity
	25. Set-up time reduction			
	26. Kaizen change management			52. Further intensification of labour; employees are considered part of the machine to be replaced by machines
	27. TQM sourcing; suppliers selected on quality			
	28. 100% inspection/sampling			