Dynamic Decision-Making, Learning and Mental Models

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Abstract

Bounded by limited cognitive capabilities, decision-makers resort to using mental models (reduced versions of real world dynamics) for decision-making and interventions in complex tasks. Such mental models are constantly updated with new experience and knowledge acquired, facilitating a learning process. Through this learning process, mental models can be refined to better represent real world dynamics.

Systems theory suggests that updates of mental models happen in continuous cycles involving conceptualisation, experimentation, and reflection (C-E-R), which closely resembles a dynamic decision-making process (DDM).

This study investigates the learning process of decision-makers in DDM tasks. Participants involved in simulated environments (Management Flight Simulators and Microworlds) are observed, with proceedings of their DDM tasks recorded and analysed to trace and identify any patterns of learning. Updates of mental models are recognized in changes of their performance, and their perceptions towards performance indicators and systems behaviour, before and after the decision tasks.

Findings of this study show significant changes in mental models after participation in DDM tasks. However, the level of learning is questionable.

Keywords: Dynamic decision-making, mental models, learning, management flight simulators

Introduction

Dynamic Decision Making (DDM) is an integral part of everyday life, from simple tasks such as taking a shower (constantly monitoring water pressure and temperature) to managing inventory decisions in a supply chain. Given the constant practice and learning from DDM tasks, however, most managerial decisions end up in failure, or something other than the intended results (Dörner 1989, Sterman 1989, Keating et al. 1999, Brehmer 1992, Collins 2001,). This study investigates the DDM phenomenon by observing the validity of decision-makers' mental models, their perception of complex system dynamics, and their capability of learning through feedback interpretation. An experimental approach utilising two computer simulated business environments (Microworlds) is employed for this purpose. Results from this study revealed significant short-comings in all three aspects mentioned above.

Bounded Rationality

Decision-makers in complex systems are restricted in their capabilities to make totally rational decisions. As suggested by psychologists and systems theorists, including Simon (1957), Morecroft (1983), Sterman (1989) human cognitive abilities such as thinking and reasoning is severely limited in comparison to the complexity of decision environments. Therefore, "the capacity of the human mind for formulating and solving complex problems is very small" (Simon, 1957).

Bounded by such limitation, decision-makers (or indeed, all human beings) resort to using mental models as a basis of day to day decisions. Mental models are reduced versions of the real world dynamics that decision-makers carry in their minds, based on their experience and knowledge. They "parallel or imitate reality" (Craik, 1943). By reducing the level of complexity, or the "variables" involved in the real world, the mental models become manageable for the limited human mind.

Mental Models

A classic (but extreme) example of a mental model, as a reduced representation of the real world can be found in the first book of the adventures of Sherlock Holmes, A Study in Scarlet (Doyle, 1887). When Dr Watson was surprised about Holmes' ignorance about the Copernican Theory and the composition of the Solar System, Holmes' explanation was as follows:

"I consider that a man's brain originally is like a little empty attic, and you have to stock it with such furniture as you choose. A fool takes in all the lumber of every sort that he comes across, so that the knowledge which might be useful to him gets crowded out, or at best is jumbled up with a lot of other things, so that he has a difficulty in laying his hands upon it. Now the skilful workman is very careful indeed as to what he takes into his brain-attic. He will have nothing but the tools which may help him in doing his work, but of these he has a large assortment, and all in the most perfect order. It is a mistake to think that that little room has elastic walls and can distend to any extent. Depend upon it there comes a time when for every addition of knowledge you forget something that you knew before. It is of the highest importance, therefore, not to have useless facts elbowing out the useful ones."

Sherlock Holmes carried in his mind a reduced version of reality [brain function], containing only the material and information that he believes are relevant. However, due to changes in circumstances such as proceeding in cases and discovery of new evidence, the information stored in his "brain-attic" changes, by incorporating new and relevant information, and also discarding old an obsolete material so that the attic will not "get crowded out". This example, even though extreme, illustrates the functioning of mental models. Firstly, with our bounded cognitive capacity, it is impossible to fully incorporate and comprehend real world dynamics. Therefore, it makes sense to base our actions and decisions on a model of reality (that is the best that we can do). Secondly, since our mental models are incomplete, it needs constant updating to keep up with changes in circumstances. Such updates may not necessarily involve discarding old information as in Sherlock Holmes' case, but it should involve new information, or changes to old information. This update process is considered as learning, and is discussed in detail in the next section.

Sterman (1994) outlined several advantages and limitations of mental models. Compared with other forms of reduced reality, such as mechanical and mathematical models, mental models are more flexible. They can take into account both quantitative and qualitative data and they can be adapted to new situations and be modified as new information becomes available. However, due to the subjective nature of mental models, they are "not easily understood by others". Senge (1991) illustrated this point using an example of a simple mental model, that somebody (person A) is "untrustworthy". Due to subjective perceptions, biases, and availability of different information to different people, different mental models about person A may be formed. Even though person B hates person A, person C may consider person A as a totally trustworthy individual. The fact that mental models are only reductions of the real world give rise to such drawbacks.

Conceptualise – Experiment - Reflect

Given such properties of mental models, how can they facilitate decision-making and learning? Mental models affect decision maker's thinking process. Maani et al (2007) described this process as continuous cycles of "Conceptualisation – Experimentation – Reflection" (CER). Conceptualisation involves a thorough contemplation of the situation at hand, utilising any relevant information in the decision-maker's mental model, and any new information acquired from the decision environment. Note that during conceptualisation, subjective judgement and biases would have been applied on the decision-maker's perception on the task. The results from the conceptualisation phase include an understanding of the situation at hand, and a number of effective decisions and interventions (as alternatives) to address the issues. These potential decisions and interventions should be "simulated" in the mental model, by considering their implementations and possible outcomes, so that their effectiveness may be evaluated by the decision-maker (Richmond, 2005). For example, when a baby cries, his mother may think that the baby is hungry, and therefore, would prepare to feed the baby. This shows a process of conceptualisation, where the mother evaluates the current situation in her mental model while taking in new information from what is happening. New information including the time of the day, the sound of the baby's cry, and the time when the baby was last fed. The mother would also have simulated the likely outcome after feeding the baby that the baby would then be satisfied and the crying would cease.

Once a good set of decisions and interventions is developed in the conceptualisation phase, the second phase of experimentation may be carried out. This involves the implementation of the decisions and interventions devised. Maani et al (2007) referred to this phase as "learning by doing". In the experimentation phase, interventions devised from the decision-maker's mental model are "tested" in real world dynamics. Results from this phase would suggest the effectiveness of the decisions and interventions applied. In terms of the hungry baby example presented above, the experimentation phase would involve the actual feeding of the baby. As a result, the baby may cease to cry, which means the mother has made a correct decision. The evaluation of the results leads to the third phase of reflection.

The reflection phase involves the contemplation of results from the experimentation phase. This is often referred to as a "feedback" process. When the expected results are achieved, the original perception and decisions are supported. However, when the actual results deviated from what was expected, such feedback calls for serious interpretation. Questions such as "what went wrong?", "what alternative actions could have been carried out?" and "what information have I missed?" must be answered in order to better understand the situation, and to hopefully improve subsequent decisions. For example, if the baby kept on crying after he has been fed, the original assumption of hunger may be inaccurate, or incomplete. In either case, updates of the decision maker's mental model would happen. When the right decisions and interventions were implemented, for example, when the baby ceased to cry after being fed, one would be assured that under such circumstances, feeding the baby is an appropriate solution. Therefore, the original assumption will be reinforced. If, on the other hand, the feeding did not stop the baby's cry, then the original assumption becomes questionable. The decision-maker should therefore adjust his/her mental model to address such an error. This can be achieved by further conceptualising the situation, modifying the decisions and interventions, and carry out another CER cycle.

Dynamic Decision Making and the CER Cycle

The CER cycle and the example discussed above closely resemble a dynamic decision-making (DDM) process. According to Edwards (1962) and Brehmer (1992), DDM is defined as situations that require a series of continuous decisions made in real time, while considering any changes in the situation at hand, both autonomously and as a consequence of the decision-maker's actions. Outcomes of previous decisions and actions influence any subsequent decisions and actions. Putting DDM into the context of the CER cycle, the decision-making process is exactly a series of CERs where decision-makers conceptualise, experiment, and reflect (learn) about the situation, and hence, can base their next decision on an updated mental model for a new cycle of CER.

Routine involvement in DDM activities provide decision-makers with many opportunities for "practice" and updates of mental models. Would it be safe to assume then that decision-makers are getting better and better in understanding real world dynamics by equipping themselves with mental models that are more and more congruent with situations they are dealing with? Studies of decision-making and learning (Sterman 1989, Gary 2005, Maani & Maharaj 2004, Fu & Gonzalez 2006) seems to suggest otherwise, that all the practising have only limited contributions to mental model improvements, that learning is often impaired because system feedbacks were usually misperceived.

<u>The Study</u>

This study seeks to explore learning through updates of mental models. Theoretically, decision-makers involved in dynamic decision-making processes undergo continuous cycles of conceptualise – experiment – reflect. The facilitation of such CER cycles result in continuous updates of mental models, and therefore, continuous learning. Mental models of decision-makers should therefore become better informed and resemble the real world dynamics more closely. However, such learning effect seems to be lacking in reality. A common view of such phenomenon is that decision-makers often misperceive feedback from systems, and therefore, the contribution of any "reflections" are questionable, for the validity of mental models. This study intends to further explore such misperceptions of feedback in learning processes, and thus proposes two research questions (RQs) with respect to learning:

RQ1: Do decision-makers learn from dynamic decision-making tasks?

RQ2: If so, does the learning result in valid improvements in mental models?

These questions are addressed by this study through the analysis of decision-makers ability in terms of:

1. Validity of mental models;

2. Awareness of dynamics and key variables in complex systems; and

3. Learning (updates of mental models) through repetition.

<u>The Research Approach</u>

This study bases the data collection and analysis methodologies on Brehmer's (1992) experimental approach, which is commonly used for studies of decision-makers' behaviour; for example, Dörner et al. (1983), Brehmer (1992) and Maani & Maharaj (2004). Such approach studies the properties of participants in complex tasks, by observing their actions and performance in a complex problem (usually a simulated environment). Responses from these experiments are then evaluated to assess the effects of the characteristics of the system on the behaviour of participants in dynamic tasks in order to enable the investigator to make inferences about how they develop mental models and formulate strategies.

For this study, the behaviour of participants in decision tasks are facilitated and observed during experiments with computer simulation models (Microworlds). The two Microworlds used in this study are the Service Quality Microworld (SQM) developed by the MIT Systems Dynamics Group, and the Brand Management Microworld (BMW) developed by Strategy Dynamics Ltd. Both models are well-developed and tested for simulating real-world dynamics. The simulated environments facilitate a DDM scenario for the participants, with a reasonable level of flexibility allowed in decision-making.

Two Microworlds were chosen for this study to ensure a variety of business circumstances being modelled and tested. These models have similar interfaces for game-play, yet the natures of the businesses being modelled are significantly different. Details about the two Microworlds are discussed below.

The Service Quality Microworld (SQM)

The SQM simulates the operations of a generic service company. The simulation starts at a "steady state" where "output variables" such as incoming orders, orders completed, work backlog, rework, hiring, personnel turnover, time pressure (employee), monthly profit, and monthly expenses are held at a constant rate.

During the experiments, participants can manipulate the values of three "decision variables" (along the course of 60 months) in order to achieve certain goals, such as maximising cumulative profits, minimising rework, or maximising production. The decision variables are monthly "Net Hiring", "Production Goal", and "Quality Goal". By intervening with any/all of these three input variables, various output variables will be affected through complex dynamics. The simulator generates the behaviour over time of a number of KPIs as graphs and reports.

Brand Management Microworld (BMW)

The BMW simulates a business organization at its start-up, introducing a new brand of drinks in an established market. The participants are given a "launch budget" (£20 million by default) at the beginning which they may utilise throughout the course of the product's launch (12 years). Output variables include consumer awareness of the brand, sales, stores stocking the brand, advertising campaign reach, monthly profits. Since the model represents an organisation at start-up, unlike SQM, the model does not begin at a steady state.

During the simulation, participants can manipulate the values of three "decision variables" (along the course of 12 years, ie. 144 months) in order to achieve certain goals, such as maximising profits, maximising sales, maximising the number of stores stocking the brand. These decision variables are "Wholesale Price", "Advertising per Month", and "Size of Sales Force". By changing any/all of these three input variables, various output variables will be affected through the complex dynamics. A large selection of KPIs is also available as graphs, tables, and reports.

The experiments carried out in this study involve individual participants managing the simulated environments to maximise cumulated profits. The average duration of the experiment sessions is two hours, where data regarding the participant's decisions, interventions, and performance are collected.

258 responses were collected from 129 participants in this study over a 3 year period. Participants, aged between 14-54, include business students and practitioners at various levels, from highschool to postgraduates, and from managers to CEOs. Besides their diverse backgrounds, participants also have varying levels of understanding in systems thinking theory and experience in simulation game-play.

Data Collection and Analysis

The experiment sessions are carried out in the context of Conceptualisation, Experimentation, and Reflection, consistent to the dynamic decision making environment (Brehmer 1992) and the thinking and learning process (Maani et al. 2007). Besides the dynamic nature of the Microworlds, all participants are required to go through two rounds of game play, administered with a worksheet on which they are required to state in detail their pre-game strategy (before

they play the game), and their post-game comments (when they finish the game). Thus, throughout the session, two major rounds of CER cycles are recorded with details of the participant's thinking. The participants' strategies and comments should be based upon their mental models regarding business dynamics and also the information given in the briefing at the beginning of the session. An example of a participant's response on the worksheet is attached in appendix A.

Data collected from these worksheets (258 rounds of experiments) are analysed and coded to identify participants' learning in terms of the validity and updates in mental models. The coding of data is carried out according to the guidelines by Miles & Huberman (1984), Dey (1993), and Sweeney & Sterman (2000), focusing upon (1) the validity of the participants' mental models, (2) the participants' awareness of key dynamics and variables in complex systems, and (3) any evidence of learning (updates and improvements in mental models).

(1) Validity of Mental Models

During the experiments, participants were required (before playing the game) to outline on their worksheets a detailed strategy to maximise profits, and behaviour over time (BoT) graph of their expected outcome (profit level) over the simulated period. The derivation of their strategies and their prediction of performance are based on the participants' existing mental models and the briefing given at the beginning of the sessions about the basic dynamics of the Microworlds. By comparing these initial sketches with the actual simulated BoT of profits (after completing the game), the validity of the participants' mental models are gauged. This is carried out with a coding system derived from the "Bathtub" experiments by Sweeney & Sterman (2000). All responses are coded based on three scoring criteria:

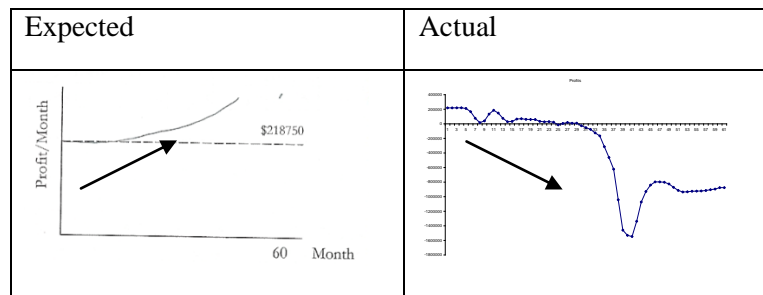1. The 'expected' BoT curve begins at the correct initial profit value ($218750 for SQM, $0 for BMW) For example:

	Correct Responses	Incorrect Responses
SQM		
BMW		

2. The 'expected' BoT curve correctly portrays the general trend of 'actual' profits. For example:

Correct:

Expected	Actual
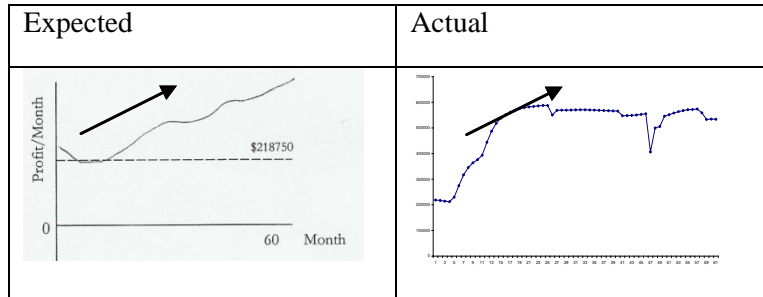
Incorrect:

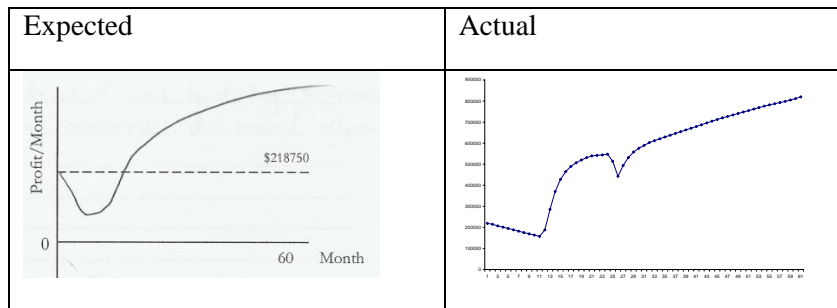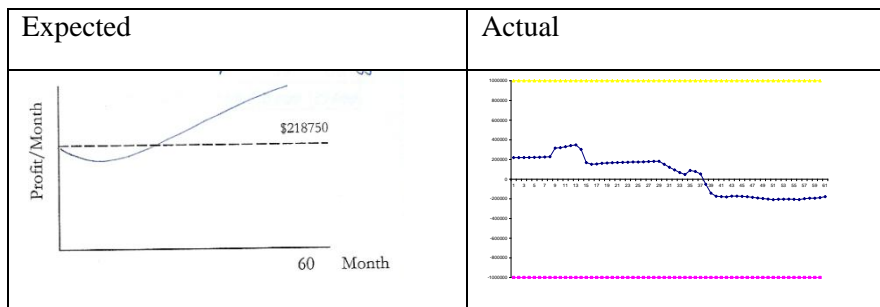| Expected	Actual

3. The overall shape of the 'expected' BoT curve is similar to the corresponding 'actual' performance. For example:

Correct:

Expected	Actual

Incorrect:

Expected	Actual

(2) Awareness of key dynamics and variables in complex systems

Analysis in this part focuses on two properties of the Microworlds, systems delays and 'time pressure' as a key variable.

<u>Systems Delay</u>

The awareness of systems delays during decision tasks is chosen as another observation basis for learning in terms of updates of mental models. The criticality of systems delays in managing complex systems has been addressed frequently in the research literature (such as Sterman 1989, Senge 1991, Brehmer 1992, Paich et al. 1993, Anderson et al. 1997, Keating et al. 1999). Very often failures in the management of such systems are attributed to the managers' ignorance of the time lag between interventions and the intended (and unintended) effects. A common ignorance of systems delays by decision-makers, as shown in the aforementioned studies, made the awareness of systems delay by decision-makers a good observation point for identifying learning effects in decision-tasks.

Systems delays are generally defined in systems thinking theory as "the time lapse between a cause and its effects" (Maani et al. 2007). They are inherent in systems. In the two Microworlds used in this study, two distinct types of delays are at play. They are 'accumulation' and 'built-in' delays.

Accumulation delays happen when an intervention in the system results in an initially unnoticeable impact on another variable, which accumulates through time and only becomes visible or apparent after some time, for example, investments in advertising campaigns to boost sales. During the initial phases, the effect of the advertising campaign may be relatively minute, and therefore no apparent changes in sales can be seen. These small impacts (of the initial investment), however, accumulate through time (for example, noticing of bill-boards and flyers, work-of-mouth, build up of brand image). Eventually, the effects of advertising become visible and increases in sales can be seen after a period of time. This type of delay can happen to unintended effects as well. Unintended consequences may be comparatively minute at their initial state but, through the continued impacts from the intervention, they build up eventually to a level where the originally intended effect is undermined. An example of such dynamics was noted in the Improvement Paradox by Keating et al. (1999), where an increase in a quality target resulted in an immediate increase in the output's quality level, along with an incremental increase in the workers' stress level due to the increased quality expectation. This increase in stress eventually builds up, causing a reduction in the output's quality level, thus undermining the original intention.

Built-in delays happen due to the inherent nature of the variables in a system. These include factors such as review periods and the responsiveness of variables. An example of such delays was shown in the Beer Distribution Game (Senge, 1991), where retail, wholesale and factory managers in a supply chain create damaging fluctuations in inventory by over- or under-ordering during shipment and production delays (there is a 4 week lead time inherent in the system which contributes to the delayed effects.)

Time Pressure

The awareness of time pressure as performance indicator is chosen as one of the observation basis for updates of mental models. This is due to its nature as a qualitative (or soft) measure of performance. Such performance indicators are often ignored in management because it is difficult to quantify. However, soft variables are usually powerful factors that influence the dynamics of complex systems (Maani et al 2007). For example, burnout, morale, commitment, loyalty, confidence, care and learning capacity. These indicators can be regarded as the measures of the internal health and vitality of the system (Keating et al 1999). Yet, most managers choose not to take them into account due to their subjective nature and the difficulty in measurement. As commented by Warren (2002), "when it comes to softer issues...managers are left with little guidance – everyone knows they matter, but how do they affect an organization's performance?"

In the SQM Microworld, time pressure is quantified and represented as a non-negative value, defined by the following ratio:

$$TimePressure = \frac{EffectiveTimeRequired}{ProductiveTimeAvailable} [1]$$

Effective time required is the time required to service the desired number of customers at the current quality standard. Productive time available is estimated from total personnel and work intensity. Time pressure of 1 assumes a normal workload where all the work can be completed if personnel work a normal work week. Time pressures above 1 lead to greater work intensity, high turnover (attrition), and eroding quality standards.

Qualitative data (the participants' pre-game strategies and post-game reflections) are coded at three different levels of awareness:

1. Participant's acknowledgement of the significance of systems delays/time pressure as a key variable.

2. The timing of the participant's acknowledgement (before game play, or only after game play).

3. Type of actions taken with respect to systems delays/time pressure (proactive, reactive, or no action).

Coding schemes for the awareness of systems delays and time pressure are described below.

Level 1: Acknowledgement of Systems delays/Time Pressure as Key Dynamics/Key Variable

In this level of categorisation, the participants' responses are grouped into two categories based on their acknowledgement of systems delays as key dynamics, and time pressure as a key variable, in the Microworlds.

- Acknowledgement of Systems delays

  • Participant has mentioned that systems delays exist in the Microworlds

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[1] This information is available in the documentation of the SQM Microworld.

For example, '…advertising spending was increased, but the number of active consumers did not increase until 6 months later…'

- Participant has not mentioned that systems delays exist in the Microworlds.
  For example, '…I have increased advertising spending in month 1 but nothing happened.'

- Acknowledgement of Time Pressure

  - Participant has mentioned that 'time pressure' is a key variable for performance measure in the Microworld
    For example, "…there was a sharp increase in time pressure in period 15 due to the lowered monthly hiring figure…"
  - Participant has not mentioned that 'time pressure' is a key variable for performance measure, or that the participant has only quoted the value of 'time pressure' without relating it to any related previous interventions nor any corresponding future actions and effects.
    For example, "…the time pressure is sitting at 1.25."

Level 2: Timing of Acknowledgement

In this level of categorisation, the responses that acknowledged systems delays/time pressure as a key factor affecting performance in the Microworlds are further broken down into sub-groups based on the participants' mental models shown in their responses. This is carried out by considering whether their acknowledgement is based upon their own assumptions stemming from their mental models, or the learning process during the decision task. The criterion is based on whether the participant's acknowledgement is shown in their pre-game strategy or in their post-game reflections. If the acknowledgement is shown in the strategy, that means the understanding of systems delays is based on the participant's assumptions, thus, his/her mental model. If the acknowledgement is shown only in the reflections, that suggests the understanding comes from the learning process during the decision task. The following sub-groups are therefore defined:

- Acknowledgement of Systems Delays

  - The acknowledgement of systems delays in the Microworlds is mentioned in the participant's pre-game strategy.
    For example, 'I propose to increase Net Hiring in the first month of the simulation. The workers' expertise is expected to double after a period of 24 months…'
  - The acknowledgement of systems delays is only mentioned in the participant's post-game reflections.
    For example, '…I have increased the Net Hiring level in an attempt to improve the expertise of my workers. However, the effect did not kick in until 24 months later…'

- Acknowledgement of Time Pressure

  - The use of 'time pressure' as a key variable for performance measure is mentioned in the participant's proposed strategy.
    For example, 'I propose to increase the quality goal initially. This may result in an increase in actual quality, and an increase in time pressure. When time pressure reaches 1.5, I will increase net hiring…'

- The use of 'time pressure' as a key variable for performance measure is only mentioned in the participant's post game reflections.

  For example, '…the main contributor to my failure was the aggressive stance in production goal, which has driven time pressure to a high level (3.5)…'

Level 3: Actions related to Systems Delays/Time Pressure issues

This level investigates the participants' behaviour in terms of how they have acted in response to the anticipated or observed systems delays/changes in time pressure in the Microworlds. The criterion is based on whether they have derived their decisions with these factors in mind, and whether such precautions are derived in a proactive or reactive manner. If the actions are derived in a proactive manner that suggests the understanding of systems delays comes from the participant's assumptions, stemming from his/her mental model. If the precautions are derived in a reactive manner, that suggests a modification of the participant's mental model during the decision task. The following sub-groups are therefore defined.

- Actions in Dealing with Systems Delays

  - The participant has proactively dealt with the expected systems delays.
    For example, 'Quality Goal was improved to drive up Actual Quality. With a higher Quality Goal, however, Time Pressure will also build up, which may result in a decrease in Actual Quality after a period of time. Therefore, along with the increase in Quality Goal, more workers were hired to avoid the build up of Time Pressure.'
  - The participant has reactively dealt with the observed systems delays.
    For example, 'In the middle of the game, there was a major increase in Time Pressure. This was due to an earlier decision to increase Quality Goal, without increasing hiring to share the workload. In response to this, I have increased hiring…'
  - The participant has barely acknowledged the existence of systems delays, without showing any proactive or reactive actions in response.
    For example, 'After increasing Advertising Spending, there were no improvements in Active Consumers for the next 3 months. The cost of advertising ate into the budget…'

- Actions in Dealing with Time Pressure Issues

  - 'Time pressure' is proactively used as a performance measure.
    For example, 'I have strived to maintain a low level of time pressure through the time of increased production goal by employing more workers beforehand, thus offsetting the build up of pressure…'
  - 'Time pressure' is reactively used as a performance measure.
    For example, '…after 20 months of high quality goal, I realised that time pressure has been driven up to a very high level (5.6). In order to rectify this situation, I have lowered the quality goal and have hired more workers to share the workload…'
  - The participant has barely acknowledged 'time pressure' as a performance measure, without showing any proactive or reactive actions in response.
    For example, '…the failure was due to a high level of time pressure, which was caused by the high work backlog towards the end of the simulation'.

(3) Evidence of Updates and Improvements in Mental Models

In this part of data analysis, the validity of participants' mental models are compared between their results from the first and second round of game play in order to identify evidence of updates and improvements in mental models through repetition of the decision task.

Discussion of Results

Here in this study we have explored three aspects of decision behaviour: (1) the validity of the decision-makers' mental models, (2) their awareness of dynamics and key variables in complex systems, and (3) updates of mental models through repetition of decision tasks.

Validity of Mental Models

Validity of the participants' mental models is based on comparisons between their 'expected' outcomes of their pre-game strategies and the actual outcomes. Comparisons are made based on (1) having the correct initial profit value in the behaviour over time curve, (2) correctly portrayed the general trend of profit over the simulated period, and (3) correctly identified the behaviour over time shape in the expected outcome sketch. Results from this analysis is summarised in the following table:

Table 1 Results of Analysis - Validity of Mental Models

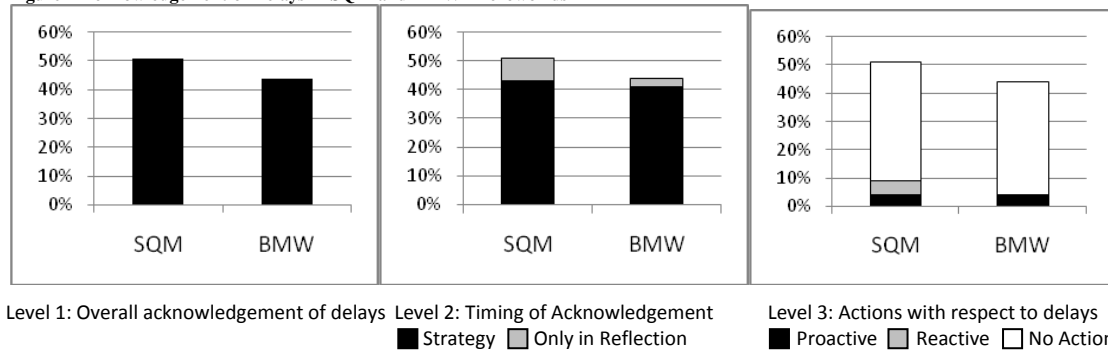| Total Responses	Correct Initial Value	Correctly Portrayed General Trend	Correctly identified BoT Shape
258	55.81%	32.17%	2.33%

As shown in table 1, about half of the participants (144) have correctly identified the initial profit values. Thirty-two percent (32%) of the participants (83) were able to portray a correct direction of the actual profits' general trend, while only 2.33% (6 participants) illustrated an expected behaviour over time curve similar to that of the actual profits. These results show a rather disappointing level of validity in the participants' mental models.

These findings may be attributed to two factors. Firstly, the inadequacy of the participants' mental models to understand the complex dynamics of the Microworlds. This is shown by the failure to even partially portray the dynamics involved in the system (such as the initial value and the general trend of variables). Secondly, the ineffectiveness of the original strategies, which called for changes to be made under the influence of the system's feedback, and thus, a different behaviour over time of profits. This infers, once again, the limited understanding by the participant of the Microworlds' dynamics.

Awareness of Dynamics and Key Variables in Complex Systems

The participants' awareness of the dynamics (delays) and key variables (time pressure) is observed in three levels. (1) Their acknowledgement of effects caused by delays and time pressure, (2) the timing of such acknowledgements, and (3) actions taken with respect to delays and time pressure issues identified. The results are as follows:

Figure 1 Acknowledgement of Delays in SQM and BMW Microworlds

Level 1: Overall acknowledgement of delays Level 2: Timing of Acknowledgement Level 3: Actions with respect to delays
■ Strategy ▨ Only in Reflection   ■ Proactive ▨ Reactive ☐ No Action

As shown in figure 1, the first level of categorisation showed a 51% and 44% acknowledgement of delays in the SQM and BMW environments respectively. Such acknowledgement is further categorised at level 2 according to the timing of their acknowledgement. As shown in figure 1, the majority of acknowledgements (43% and 41% for SQM and BMW respectively) are made before game play, while 8% and 3% (respectively) acknowledged delays only after game play. Finally, at level 3, the acknowledgement of delays are further categorised according to actions carried out explicitly with respect to delays. The three categories for such actions are 'proactive' (when actions are carried out in anticipation of delays), 'reactive' (when actions are carried out after delays are evident, to rectify negative impacts), and 'no action' (when no actions are carried out with respect to delays, or when participants blamed negative results on delays without any remedial actions). The actions of participants who have acknowledged delays in SQM show a distribution of 4%, 5%, and 42% across the three categories of 'proactive', 'reactive', and 'no action'. Those in BMW show a distribution of 4%, 0%, and 40% respectively.

In summary, approximately half of the responses for both Microworlds have shown that the participants are aware of delays. The majority of this group have anticipated this before the start of game play by noting the possible delays that they are going to encounter in their pre-game strategies. However, even though half of the responses have shown awareness, only a small proportion (about 4% of the entire sample) have shown proactive considerations of delays. For example, hiring more workers early on to offset the delay required for them to become experienced. About 5% from the SQM responses have shown effective learning from the game play, by noticing the effects of delays and, therefore, they have reactively performed with consideration of delays.

Such findings suggest severe limitations in the participants' awareness of delays in the models' dynamics. As noted in studies such as Sterman (1989), Senge (1991), Paich & Sterman (1993), and Keating et al. (1999), delays play an important role in the dynamics of complex systems. Failure to acknowledge such delays is detrimental to the effectiveness of the manager's decisions and interventions. The findings show consistent performance by participants in both models, and that their awareness of delays is insufficient in terms of effectively managing complex systems. For instance, only half of the participants were aware of the impacts of delays, most of whom had anticipated such delays in their strategies, but only 9% (with 4% being proactive and 5% being reactive) of all the participants had taken action according to such effects. This finding supports the conclusion of aforementioned studies by showing managers'

difficulty to understand complex systems, in terms of their acknowledgement and awareness of delays.

Figure 2 Acknowledgement of Time Pressure in SQM Microworld

Level 1: Overall Acknowledgement of Time Pressure

Level 2: Timing of Acknowledgement
■ In Strategy ☐ Only in Reflection part

Level 3: Actions with respect to Time Pressure
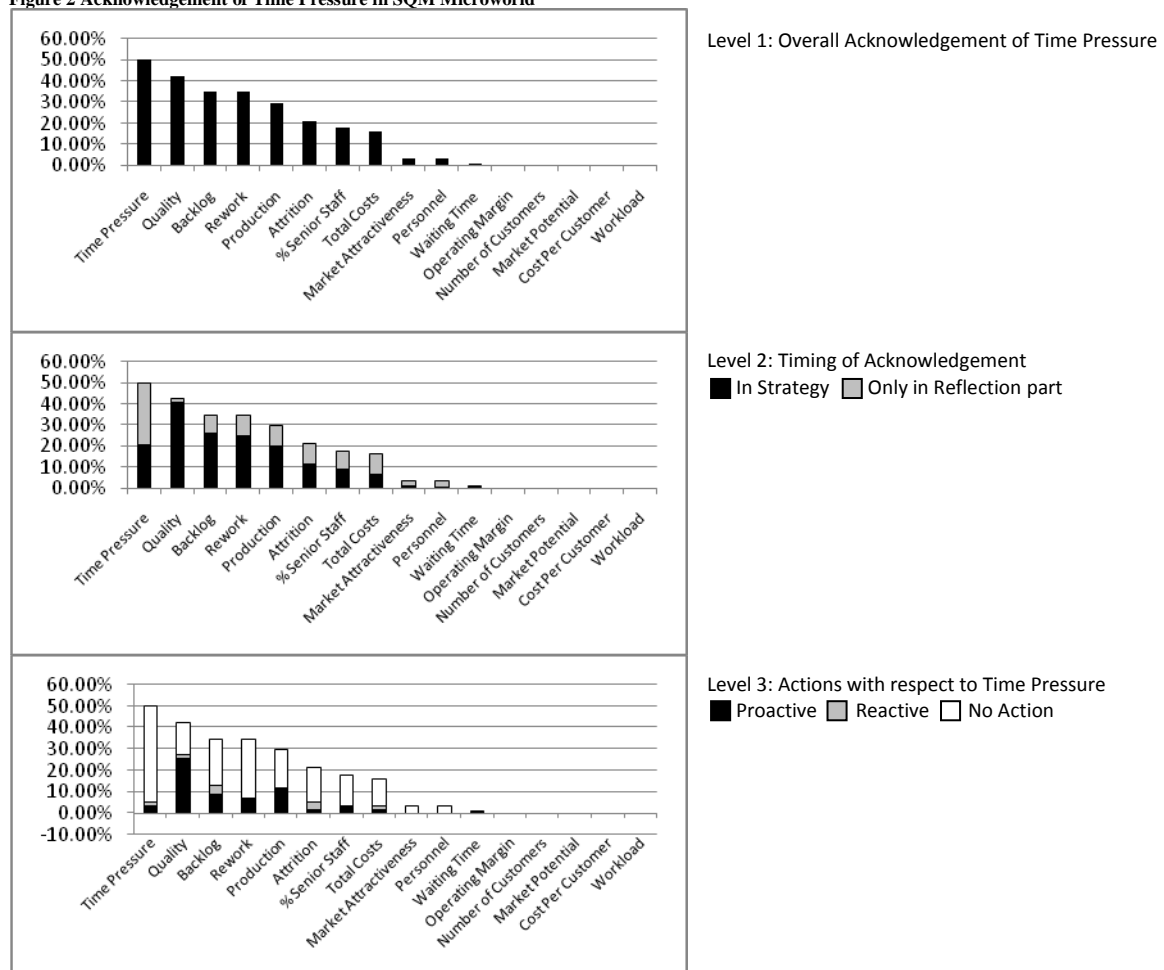■ Proactive ▨ Reactive ☐ No Action

Figure 2 presents an overall level of acknowledgement of key variables from participants under the SQM environment. The first level of categorisation showed a 50% overall acknowledgement of Time Pressure as a key variable. Such acknowledgement is further categorised at level 2 according to the timing of their acknowledgement. As shown in figure 2, only 20% of the acknowledgements (of time pressure) are made before game play, with 30% of the acknowledgements made after. Finally, at level 3, the acknowledgement of time pressure as key variable are further categorised according to actions carried out explicitly with respect to time pressure (the three categories of 'proactive', 'reactive', and 'no action', as for the analysis of delays discussed above). The actions of participants who have acknowledged time pressure as a key variable show a distribution of 3% in 'proactive', 2% in 'reactive', and 45% in 'no action'.

In summary, the results suggest that 20% of all responses were intuitively aware of time pressure as a key variable in SQM before game play. That is, the idea of using time pressure as a performance indicator is based on their own mental models. 30% of all responses, which have acknowledged the use of time pressure only in their post-game reflections, may have acquired such ideas from the learning process during the decision task. That is, they have not naturally or intuitively been aware of the influence of such a key variable until the update of their mental

models during game play. From the third level of categorisation, results suggest that only a small proportion of participants have put the information from time pressure to use in their decision task.

One major revelation from the results is both the importance of time pressure (qualitative in nature) as a key influencer of performance as well as the awareness of such importance are not commonly acknowledged by decision makers. As seen in figure 2, the awareness of time pressure and other key variables in the SQM Microworld are compared. At level 1, time pressure turns out to be the most popular performance indicator as identified by the subjects out of all the nominated variables followed by 'quality', 'backlog' and 'rework'. However, if we consider the popularity of these variables as key indicators in the participants' mental models BEFORE participating in SQM, we should consider the results from level 2, with respect to the timing of acknowledgements. Focusing on acknowledgements in strategies (before game play), it is apparent that the most popular key variable is 'quality', followed by 'backlog' and 'rework'. Time pressure's popularity as a key indicator sits at forth equal with 'production'. Such pattern suggests not only that most of the overall acknowledgement of time pressure as a key variable stemmed from experiencing the decision-task (that most of the awareness was show AFTER game play), but also the fact that such experience raised the awareness of time pressure at an overwhelming rate which casts a shadow over the original top choices (quality, backlog, and rework), suggesting the significance of time pressure in the SQM environment, and how the decision-task resulted in 'learning' in the form of increase in acknowledgement.

While such 'learning' may be considered as a positive outcome of the decision task, the utilisation of this new 'knowledge' is highly questionable. This is suggested by the third level of categorisation, where only 10% of the participants who are aware of time pressure (5% out of 50%) actually acted proactively or reactively upon that . Surprisingly, 90% of the 'enlightened' ones simply blamed the time pressure for their problems.

Updates of Mental Models through Repetition

For this aspect of analysis, the results from 'Validity of Mental Models' are broken down into results from the first round and second round of game play. Results from the two rounds are compared in order to identify any improvements which may suggest valid updates of mental models through repetition, and thus, learning effects. The results are summarised in table 2.

Table 2 Analysis Results for Updates of Mental Models Through Repetition

Total Responses			Correct Value	Initial	Correctly Portrayed General Trend	Correct BoT Shape identified
258	Round (129 responses)	1	28.29%		12.79%	1.55%
	Round (129 responses)	2	27.52%		19.38%	0.78%

16

As shown in table 2, similarly low percentages of correct plotting of initial profit value is seen in both rounds of simulation. No improvements in this aspect can be attributed to the experience and the learning gained in the first round.

For the perception of the 'general trend', the results show an improvement in performance between the two rounds. While this may be due to learning effects from the first round of simulation (Vogel et al., 2006), such improvements may also be attributed to the combined effect of the participants' general tendency to predict positive performances, and the better actual performance achieved in the second round by most participants.

Finally, for the shape of the profit curve, the performance in the second round turned out to be worse than the first round. If this in fact is due to the learning effect, one has to be concerned about what is being learnt.

Summary

This study investigated three aspects of decision-makers' learning and mental models: (1) the validity of the decision-makers' mental models, (2) their awareness of dynamics and key variables in complex systems, and (3) updates of mental models through repetition of decision tasks. Our results suggest that while the comprehension of the dynamics in decision tasks is critical to the success of interventions, the participants' mental models are, however, inadequate for understanding such dynamics. This is shown by the participants' proposed interventions and their lack of awareness in the criticality of key dynamics underlying complex systems.

Evidence of the mental models' adaptability is shown in the updates of mental models during and across repeated experiment sessions, as the participants' perceptions of performance and their underlying dynamics change. While it was evicent that the participants 'learn' about system dynamics during the decision tasks, nevertheless such updates in mental models did not lead to improvements in subsequent experiments. Analysis shows that most of the participants use this insight as blame for their poor outcomes, rather than for improving their subsequent strategies. . As such updates of mental models can hardly be attributed as learning.

As a result of these misperceptions, the participants' performance across the two rounds of repeated game-play showed no improvements whatsoever, contrary to the prevalent learning curve theory that 'practice makes perfect'.

Conclusions

This study sheds light on some important aspects in dynamic decision making (DDM), and the short-comings of human decision-makers' ability to manage DDM and to learn from their experience. Our results show that decision-makers' perceptions of the system's dynamics are often (if not always) different from the actual performance. Their ability to interpret feedbacks system are critically limited, and even when given multiple opportunities, improvements in decision-makers performance and awareness are not evident. These finding have important implications for management education and highlight the need for inclusion of systems thinking and dynamics training, in particular for managers and policy makers.

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Appendix A

Sample response

Worksheets

Exercise Two

Aim: To maximise profit over the course of 5 years by altering *ANY COMBINATION* of the three parameters (Net Hiring, Production Goal, and Quality Goal).

A brief description of your proposed strategy:

1-2 Increase net hiring → Remain Quality goal + production.

2-4 Remain increased level of hiring → increase quality goal → remain production

4-5 Remain level of increased hiring → Observe quality goal → increase production (depend upon no. of employees).

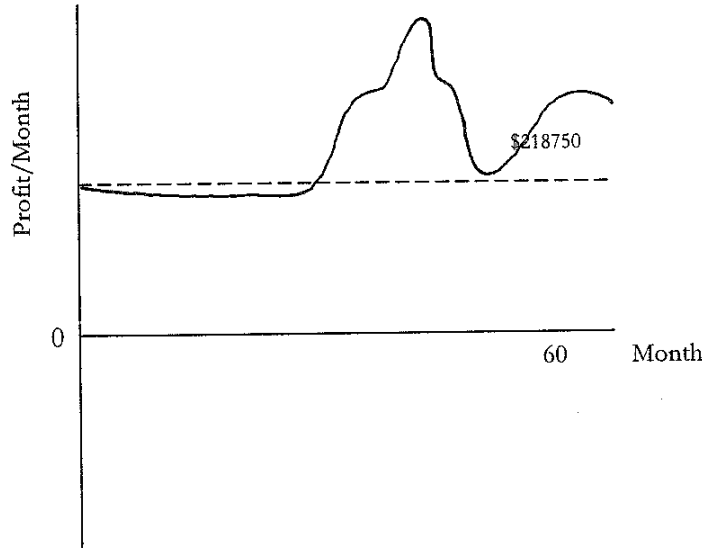Your expected outcome (monthly profit):

Question:

Increase hiring = Increase expenses = lower profit. But if market don't expand, this model might not work!!

$218750

1-2 yrs.

0   60   Month

Profit/Month
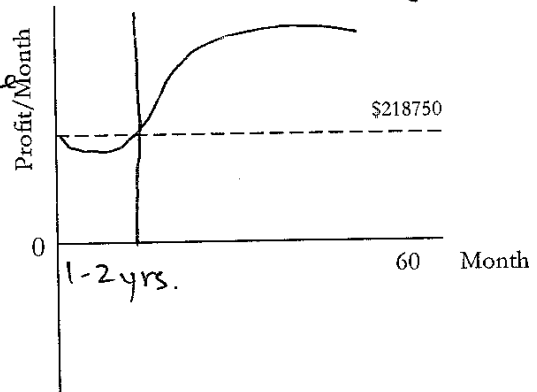
Worksheets

Actual outcome:

Cumulated Profits: ___$ 7, 877, 107___

Are you satisfied with the results? What has happened that would have caused the

success/failure?

The constant increase of staff have a lower than expected
impact in company expense. After the 2 year working
experience, new employee become experienced employee.
So, when I increase the quality goal the employee can take
on the pressure & work effectively while at the same time
being able to reduce backlog per employee. During this
period profit increased tremendously. The profit occurs
when time pressure is too low. Ie. too many staff not
enough work (as the market doesn't expand).
Time pressure causes turnover to increase while at the
same time the number of employee hired decrease due
to lack of work (jobs). When leave > hire, backlog increases.
Therefore the total personnel decreased dramatically while
the new employee are not experienced backlog increase
& rework increased.
If the simulation can be longer than 5 years I believe
reduce the business cycle I've proposed for the 1st 4 years
may bring the profit to a higher level once again. Worksheet - 6