Modeling and measuring the interaction between experience and the quality of information

Andy Belyavin & Chris Ryder
QinetiQ Ltd
Motivation

- Analysis of the effectiveness of information concepts is central to the development of NEC in the UK and NCW in the US
- Two aspects to system performance: time to perform and quality of output
- Much analysis of processes focuses on time to perform but quality of output is as important
- Quality of decision making has been the subject of experimental and modelling study for many decades
- Affected by data, decision-maker attributes, and environmental factors
- Difficult to assess for all processes and procedures within a C2 system
- Ideally need some approach that encapsulates these factors and can be used for engineering a system
Study aims and assumptions

- Two elements to quality of decisions: information quality and decision-maker’s capability
- High level aim was to develop metrics that could capture information quality and the interaction with decision-makers’ attributes such as experience
- The cognitive activity of interpreting information can be represented as fitting a model to a set of data
- If the model parameters are known the only source of variability in the model output is the information input
- If the model parameters are acquired through a process such as experience there are two sources of variability in the model output – information quality and the variability of the parameter estimates
- Two widely used measures of information content:
  - Shannon’s information (entropy)
  - Fisher’s Information
Shannon’s entropy

- Data and information are different although often treated as the same
- Data are part of the physical domain and measured in bits; information is in the cognitive domain and is measured in models of the current and future state of the world
- Shannon’s entropy is strictly a measure of optimal coding for messages and therefore of data
- Has no concern about the meaning of a message – information content
- Interested in the quantity of data measured in number of bits
- Provides a measure of data flow given assumptions about the pattern of data elements in the stream
Fisher’s Information

- Fisher’s Information measures the amount of information data provides about a set of model parameters
- Expressed in terms of the precision of these estimates provided by the data
- Derived from the Maximum Likelihood estimation procedure
- Can be viewed as a measure of the quality of the model in terms of describing the data
- Can be extended to describing the information content of the model
- Decided to use Shannon’s entropy as a measure of data flow and Fisher’s Information as a measure of information content
- Basic measures are not commensurate
- Have used the approach of Cedilnik and Košmelj to bring them onto a common scale
Mathematical definition of the measures

- Shannon’s entropy $e_p$ is defined by the equation on the right.
  \[ e_p = E[-\log(p)] = -\sum p_i \log_2(p_i) \]
  \[ e_p = \log_2 n \]

- Fisher’s Information $I$ is based on the estimate of the variances of a set of $k$ parameters $\theta$.
  \[ I = \frac{1}{2} \log_2 \left( \prod_{i=1}^{k} \left( b_i - a_i \right)^2 \right) \frac{1}{\det(\text{Var}(\theta))} - 1.79k \]
Example data flow

- Consider a sample of data that might be coming into the system
- Series of pairs of numbers – a sample shown on the right
- Considered from the point of view of Shannon’s entropy the information content is the length of the message
- The message comprises 20 numbers reported as a maximum of three decimal digits
- The length of the message is a maximum of 20 x 7 bits = 140 bits
- That is the data content……..

(1.0, 1.0)  
(2.0, 1.7)  
(3.0, 3.3)  
(4.0, 4.1)  
(5.0, 4.9)  
(6.0, 5.5)  
(7.0, 7.2)  
(8.0, 8.3)  
(9.0, 8.9)  
(10.0, 9.9)
Develop context and model (1)

- Suppose this sequence of pairs of numbers records the advance of an entity with time.
- Extra information: we can estimate the average speed.
Develop context and model (2)

- Suppose this sequence of pairs of numbers records the advance of an entity with time
- Extra information: we can estimate the average speed
- A model we are applying to the data
- Speed is not exact as data has noise
- Extra information can be estimated using Fisher’s information
- Using basic assumptions the information added is 5.46
Suppose this sequence of pairs of numbers records the advance of an entity with time.
Extra information: we can estimate the average speed.
A model we are applying to the data.
Speed is not exact as data has noise.
Extra information can be estimated using Fisher’s information.
Using basic assumptions the information added is 5.46.
We can estimate the position at 15 and 18.
Following same logic, further information added is 9.48.
Suppose the underlying observations are twice as variable
Using basic assumptions the information added is 4.66
We can estimate the position at 15 and 18
Following same logic further information is 7.88
Fisher and good and bad models

- Previous example was developed using the “true” model
- What happens if inappropriate model is applied?
- Appropriate model fit is shown in the upper graph
- Inappropriate model shown on the lower graph
- The estimates of Fisher’s information for the “slopes” in the two cases are:
  - 11.46
  - 2.04
- If we used this for prediction the added information would be small for the inappropriate model
Metrics, models and data

- Examples displayed in previous slides illustrate three key points:
  - We can construct a methodology for measuring effect of information transactions
  - The metrics are sensitive to data quality and model quality
  - They demand an understanding of how models are acquired
- Simple example deals with a model constructed from data gathered as part of the information flow
- For data fusion the model will have been constructed prior to system use
- To apply the previous logic we need to know the quality of the model
- In addition we will have to handle variability in the data to which we apply predictive models
Approach to testing the metrics in a model

- Selected a model with a repetitive decision that had been modelled
- Based on the DECIDE task developed under an earlier programme
- The task was developed under the guidance of Neville Moray at Surrey University
- Original form comprised a single-person task with multiple information sources
- The aim was to deduce when troops should be sent through hostile territory to achieve the largest number sent with minimum casualties
- The task was taken as the basis for a model of a headquarters with four streams of information and a simple decision to make
- Permits an overall measure of effectiveness through task score
- Can manipulate information use and study overall effect
Basic building blocks in the HQ model

- Information processing behaviours
  - Gather data
  - Process and fuse information
  - Decide
  - Order action
- Communication and co-operation (teamwork behaviours)
- Representation of the impact of decisions by closing the loop using a pseudo-military task
- Use original information pattern from DECIDE task
- Abstract data observation and interpretation as flows between cells in a notional HQ
Organisational structures
Problems to be represented in the metrics as applied to the model

- Quality of decision-making procedure in information terms – reflecting training and experience
- Impact of timeliness on decisions
- Impact of unreliable information sources
- Impact of inappropriate models
Decisions in the DECIDE task

- Originally the DECIDE task was tested with a population of students and the information employed in the two main decisions was characterised.
- It was found that the two key decisions – start sending troops and stop sending troops – appeared to be based on a simple fusion of the four key sources of information about enemy strength.
- The exact form varied from individual to individual but it appeared to be established during the training period.
- If the same approach is to be modelled in the pseudo headquarters the same data fusion process must be modelled.
- Two aspects must be addressed so that Fisher’s Information can be calculated:
  - Precision of the fusion model.
  - Variability of the data employed in the fusion.
Acquisition of the data fusion models

- In the development of the statistics of the data fusion model it was assumed that the model was based on experience of the real system.
- This was represented by gathering data from the simulated task and fitting the fusion model to the observations.
- From the model fits the variance characteristics of the model are described.
- It is assumed that training and experience is represented by a level of exposure to real situations.
- Observations of performance following training indicate a performance curve that follows a $t^{-\frac{1}{2}}$ law where $t$ is the training time.
- The model that assumes exposure will follow the same law statistically.
Timeliness

- The timeliness aspects of information are captured in two components of the model
  - The rate at which enemy strength changes in the simulated world
  - Time delays in the processing of information in the model
Unreliability of information and appropriateness of the model

- In the simulated HQ information sources can become corrupt
- An extra step was inserted in the information processing to check the quality of the source vulnerable to corruption
- Simple linear prediction was used to describe the check
- For the construction of this model it was assumed that effectively unlimited experience would be available for “own sensors”
- Variance of the model therefore assumed to be small
Conditions tested

- Simulations of the HQ model were conducted varying the following conditions
  - Amount of experience of the decision-maker
  - Level of noise on the data for the *training* of the decision-maker
  - Level of noise on the data in the simulated decision making
  - Presence or absence of source corruption
- Effectively trying to measure three aspects of information handling
  - Quality of basic data
  - Quality of models used in decision-making
  - Appropriateness of decision making models
Basic features of demonstration

- Data flows at the same rate under all circumstances
- Noise on the data is used to modify the effective input information according to Shannon’s entropy – assumed that data reported to appropriate precision
- Fisher’s Information is summed from the analysis of potentially corrupt data and from the calculation of fused information
- In general the information added in data fusion is of the same order as the information in the input data
- Quality of training and experience contributes about the same amount as the data gathered from sensors
Effect of noise on performance and ModFI
Effect of training on performance and ModFI
Effect of information delay on performance and ModFI
ModFI as a predictor of performance

\[ \sqrt{\text{Perf}} = 1.63 \times \text{ModFI} + 26.48 \]

\[ R^2 = 0.6085 \]
Overall conclusions

- It is possible to describe transactions in a C2 system using a combination of Shannon’s entropy and Fisher’s Information.
- The information metrics correlate with overall performance in the abstract example used in the study.
- The key to the approach is the description of the models applied in decision-making.
- An essential element is the description of the statistical properties of these models.
- Some of these elements can be estimated through additional simulation.
- It is also important to describe data accuracy and information content in the same terms.