Seminar Notes On ‘Measuring Complex Systems’.

Abstract: Manufacturing processes and supply chains show all the characteristics of complex systems. The focus of this research area is on those aspects of complexity that can be measured. Theory suggests that an appropriate metric is the average rate at which the supply chain or manufacturing process generates information i.e. the entropy of the process. This is called its Operational complexity. Theory also predicts that operational complexity shows itself through the formation of queues – these can be of either products or information. The important point is that the system’s performance is capable of being directly measured by observing the dynamic behaviour of these queues and their causes.

However complexity is neither good not bad. For example mass customisation involves deliberately expanding the complexity of the product range to offer customers greater variety. The key is to be able to do this without raising prices. Therefore one can differentiate between ‘good’ complexity – complexity the market will pay for and ‘bad’ complexity that merely involves additional cost. This is the balance a successful mass customisation strategy achieves. One important dimension is the ability to schedule effectively. Here too the notion of information generation is central. The schedule embodies a quantity of information – the more complex the plant or supply chain the more information contained. A system that follows the schedule generates no further information. Therefore observing how much additional information the system generates is a measure of its performance against the schedule.

Observations made within factories and, more recently, on supply chain have confirmed the validity of the approach and the utility of the measures.

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Measuring Complex Systems

Introduction

Although over long periods businesses must adapt to changing markets their efficient day to day running is essential to their cost effectiveness. Yet even day to day running may mean that a system may exhibit unnecessary complex behaviour which has to be dealt with. By taking a relatively short time slice a system is accessible to analysis and its complexity can be measured in terms of its 'entropy'. Measuring entropy gives an indication of variety and connectedness and even the element of surprise that is in the system. Entropy is a measure of the rate at which coded information is transmitted and can be made an appropriate generic measure across a whole process.

The Nature of Information Transition

We use the following definition of information transmission:

$I(E) = \log_2 (1/p)$ where I is the information content of some event E and p is the probability. (Claude Shannon)

We should explain how this formula comes about.

Information is transmitted using some sort of coding (e.g. language) and the sender and the receiver have to agree implicitly or explicitly what the code is. The code conveys information in chunks (data) from which meaning or information is deduced. Since information is carried in chunks there is often a gap between the knowledge that the transmitter wishes to transmit and the receiver wishes to receive. It's like a 'potential difference' between the sender and the receiver's knowledge and some words or letters convey more information than others. The formula above is a measure of the informational content of some particular chunk of data. Rarely used words or letters carry more information than frequently used ones, so informational content is the inverse of probability and hence the term 1/p where p is the probability. Since computers use the binary system of '0s and '1s, the basic unit has a probability of 1/2 (either 0 or 1) and since the possibilities of arrangement are then to the power of 2, $\log_2$ makes it easy to count the length of the binary chain. Thus one 'bit' of information is derived from the fact that .

$$I = \log_2 (1/p) = \log_2 (1/{\scriptstyle 1/2}) = \log_2 2 = 1.$$

Consequently 'bits' of information would derive from the fact that $\log_2 4 = 2$ bits, $\log_2 8 = 3$ bits and so on. Since, for example, 8 is written in binary as 1000 or 3 +1 the log is approximately one digit less than the length of the chain. The formula is a measure of the amount of information that's carried in the event (word or letter) but over time it also gives the rate at which the receiver is receiving the knowledge.

When we talk about complexity we talk about 'variety' and 'uncertainty' and 'connectedness'. We have variety in our '1s and '0s and we have uncertainty because the receiver doesn't know what the transmitter is going to send until a message is completed and that depends on its connectedness. Some events are irreducible as far as their informational content is concerned which means we have to hear the whole word or sentence before the meaning is conveyed.

Suppose we look at the basic units of words i.e. letters. Little used letters carry more information than frequently used ones. 'X' is the least used letter of the alphabet and has enormous potential as a carrier of information. If we said 'We can't tell you the name of a company but that the first letter of it is 'X'' then you would have a pretty good idea that it was Xerox. Such an approach is also the way that secret codes are broken. If the encoder has simply used different numbers or letters in place of the correct ones, then by merely counting up the frequency with which they occur it is possible to work out which letters they represent. Things out of the ordinary always convey more information. If we see a milk bottle left on a doorstep it conveys an enormous amount of information. This is why we have 1/ probability p in our formula. The rarer the event the more informational content it has.

Suppose we look at the information transmitted by the word 'queue' in terms of its letters. The second least common letter of the alphabet is 'q'. The letter 'q' has a probability of .0054 and has an informational content of about 7 bits (high information content). The second letter 'u' always follows 'q' and has an informational content of zero because it's totally expected and it could be dropped in transmission. The following 'e' has about three bits of information and the 'ue' on the end again has practically no information content. So the total content of the word is about 10 bits of information which gives an average information generation per letter of 2 bits. This is known as the 'entropy' and is a measure of the generation of information by a source. For a number of subtle reasons 'entropy' appears to be a more fundamental notion than 'information content'. We can use this notion for any transmitting event which as a whole gives us information. The quantity given indicates rarity or variety in the event and is therefore a measure of the rate of information generation.

This notion of entropy can be related to horse racing. If the betting system is fair and the odds can be seen as a measure of information generation then there is an 'entropy' quantity which, plus a punter's winnings is a constant. It thus turns out that the lower the entropy the higher the punter's winnings (presumably because the bookie's information is low?), the higher the entropy the lower the winnings. In a fair betting system the mathematics will tell us what we all know intuitively; that it's better to bet on a two horse race rather than a ten horse one. Another example of the use of this notion, quite close to the idea of entropy per letter is the number of questions a person needs to ask, given certain mathematical restrictions, to validate a piece of information. For example suppose we are asked to think of a number between 1 and 8. If we remember that $\log_2 8 = 3$, this tells us that we can find out the answer with certainty if we ask three questions. Suppose the number thought of is one. The questions are: 'is it greater or less than four?' (less), 'is it greater or less than two?' (less), 'is it two or one? (one). Again this emphasises the point that information is a 'potential difference' between what a listener needs to know and what he's got. So this strange notion of entropy as information generation appears very fundamental and crops up in a number of areas.

Manufacturing and Supply chains

Manufacturing process and supply chains show the characteristics of complex systems such as variety, surprise and connectedness. The entropy is a measure of how much information we need to get out of a system in order to understand it. In that sense it is a measure of variety and is linked to Ashby's 'law of requisite variety' and the more variety there is in a system the more information we have to extract from it in order to understand it. Because the mathematics uses probabilities it can deal with surprises. In fact, Gerry first became interested in complexity theory when he realised that surprises were not the factory work force ganging up against him but the result of systemic problems.

Entropy of course deals with linked events and must be seen in the context of a whole system, but for any system where variety affects the dynamics if we set out to develop a mathematical model of measurement for variety we end up with the entropy principle. So this means we can 'pull over' information theory to help us with manufacturing problems and there are some unexpected insights when making the analogy. Coding for example, is analogous the information about a process contained within the finished product or more explicitly, when a message is sent, about production or about supply, it is encoded, then transmitted and finally decoded. The 'channel capacity' will be an important limiting factor in the transmission, and information theory in general also suggests limits to the kind of things that can be deduced about a system.

The first useful conclusion is that the index for entropy is also additive. In a way this is tautological because when we actually do the mathematics, a requirement for things to be measurable is that they must be additive. But it means that if we have a source of entropy here and another source there, then they can be added or subtracted.

The second conclusion is rather more startling in that entropy as a property of variety is therefore independent of the actual system being measured. And what that means in practical terms is that we can start adding entropy from different sources. In a supply chain if we start looking at the entropy transmitted by information generation and the entropy generated by materials transmission, the two are linked. We get a demand from the customer and a supply from the supplier. We need the two for a complete picture of the operation. We need to look at the performance in terms of the information transmission as well as the material transmission. This gives a basis for making comparisons because variety is involved and it doesn't matter what variety it actually is.

A third interesting conclusion is that entropy has a fractal structure; it is a relative measure which means that whatever level of resolution we examine in a complex system we always derive the same recursive structure using the formula. It has the practical consequence that we cannot simply re-run an information or material transfer event and it's also easy to make the mistake of coming up with two sets of statistics which are not comparable because one has been obtained at one level of resolution and the other at another. Indeed, one of the practical difficulties in a study is making sure that we are always measuring to the same level of resolution.

The fourth conclusion is also very interesting and that is that entropy has an 'emergent' property when applied to hierarchies. If we apply the formula to a hierarchy we get two terms; one which is a systems term and the other which is a detail term and we can never get rid of the system term. This means that whatever level of the hierarchy we apply the formula we have a term which is only applicable to the system and not to the detail. We can thus see that we are dealing with many of the observed characteristics of complex systems.

The real problem as observers is to decide what kind of coding is taking place. It depends on defining discrete states of a system in terms of certain categories over a continuous time span and this is very subjective. One person can come up with one set of states that he or she thinks is significant and another will come up with another set.

Neither is right or wrong but they depend on the particular aspect of the system being observed. They are interest and observer relative. So probably no agreed coding and no agreed endpoint - you never know whether a sufficient number of states have been observed (may be long cycles) and of course the system being observed may not be stationary (significant evolutionary rate).

And the last point is the strength of the connections. There's no prior knowledge of linkages. But these problems are familiar to anybody whose ever done a simulation. In fact part of the job is often dictated by the package because it tells us what kind of states we can have and what we can't. There's also a trade off between the information and its accuracy. The more data we collect, the less clear the significance of each bit becomes. We are trying to balance the amount of information we pull out with how accurately we can measure it, so different observers must agree a level of 'granularity'. Finally we have to identify a significant variable in a particular state and observe it at least twice before we can measure something over time. This last says something about the limits of measurement.

But one breakthrough that came in terms of what to look at when defining states came with the concept of 'queuing'. If we look at input/output systems, adverse complexity gives rise to 'queues'. This provides us with something to look at and an up-front categorisation. If we look at a production process we have different opportunities for queuing: the raw materials at the input end from the supplier, goods in transit, processing and assembly, finished product to client etc. Building a schedule involves assembling information which can only be implemented when all the information has been gathered together - so it involves queuing itself. The longer it takes the more the situation is liable to change and the less useful the schedule becomes. So queues have to be dealt with to make performance more efficient. In fact the only queue people want is money in the bank account but even this is an obstacle because although it may generate interest if it is money owed, the supplier will incur a debt which the manufacturer will have to subsequently pay for and this will re-appear in the price to the manufacturer.

Concentrating on queues allows us to ignore linkage or connectedness. In fact a peculiar mathematical property of networks in which there are queues is that they behave as if linkages don't exist. The discovery of queues also provide a direct link to costs and enables us to make some prediction about how a system ought to behave. High entropy in the supply chain gives longer lead times and less predictable processes. The ' bottleneck' may well be where the highest entropy exists so reducing entropy increases effective capacity. If we have a system that has a high degree of randomness there are periods in which resources are lying idle. If we have a good flow in which the arrival rate is predictable then we can close the gaps so the process becomes more efficient and create additional capacity. Its the same on the M25. When they put up speed indicators and ask people not to change lanes, the result is constant flow and even though the speed limit is lower the traffic moves more efficiently because the gaps are being filled and the additional capacity that it creates means that all the cars will get to their destinations on average, faster.

Ironing Out The Wrinkles

Making the system more predictable increases capacity. There are basically two approaches to ironing out complexity in manufacturing in order to increases predictive ability over a certain time period: one is to simplify the operation by the removal of process components rather than products and the other is to try to control it. If we take products out we do not simplify to the same extent. These has important consequences for customisation (tailoring products for particular clients). We can counteract the demand for more products by taking processes out and every process we take out will have a much bigger effect than every product we put in. We do not say that complexity per se is a bad thing and it may be the only source of survival if the market is demanding a lot of variety. But we need to home in on unnecessary complexity, and reduction in process problems will often enable an increase in the number of products. It also helps to delay differentiating a process until piloting a product has reached its final stages. Entropy gives a measure of several of the characteristics of complexity and allows for emergence, variety, connectedness and uncertainty. In general the smoothness of the input/output flow and whether different parts of the process are measurable is an indication that complex behaviour taking place. Any factory manager can relate to these issues. Simplifying a process is a 'one off' cost whereas attempting to control is ongoing and although we can never get complete predictability we aim for a grey area in which the system is quasi-stable and can be measured in the way we have described. In talking of prediction we are talking about a probabilistic average behaviour. We also have been careful not to define what is meant by 'information' and are using the notion in a very specific context. What counts as information in a general sense is, like 'knowledge', still hotly debated and we have only tried to give a quantitative definition of its transmission.

It is often an advantage in a manufacturing process to chop it into a number of flexible operations as there is usually a relation between size of operation and the complexity problems encountered. There is a further peculiarity in that the amount of effort we have to make in observation goes up exponentially with the amount of linkage. If we had units in a system without links we would just have just random events. But if we link events together in twos the number of observations we have to make is squared and for three linked events cubed and so on. If we increases linkages we quickly pass into the realms of observational impossibility because the length of time necessary will be grater than the time to implement some remedy. So whether it makes complete sense or not it the only way to deal with the problems may be to break the operation up into small chunks. But before we do we have to ask ourselves whether or not we are breaking an important linkage and there seems to be no a priori way in which we can know this. It's simply guesswork. Mathematical models often tell us no more than we already know, except in a more formal manner but taking measurements and adjusting the model enables us to find out about the complex system as a whole. Again, there is no assumption that a transmitter and the receiver have to reach the same level of knowledge and this is a general limitation in getting information out of a complex system. We may either fail to obtain sufficient information because we stop measuring just when something new is about to pop up or we fail to explore the system at the most significant level. It is one of those awkward problems of 'granularity' that often by increasing the quantity of information obtained the overall defining characteristics are lost.

The aim of the project was to understand the problems encountered in a manufacturing process and to ask the question; 'what is fundamental to the way that this organisation runs itself that gives rise to its chronic problems?' We looked at the whole process in terms of design and operation. The focus was on the shop floor in terms of layout and product process; how to design a facility and how to schedule it. The work on entropy and information theory seemed to fit this bill.

The Entropy Concept

Entropy is one of those things that people don't have a natural intuition for. We understand concepts in physics like heat and weight and momentum and kinetic energy but entropy remains a bit fuzzy. In this case we have attempted to define it in terms of the degree of complexity and the information that needs to be obtained from a system. In terms of a supply chain, if we can observe entropy and measure it directly we can then build simulations and sample the simulations and then tune the simulation so that the entropy in it is the same as we got from the actual observation. We can consider scheduling in terms of machines and process and we can compare different group input requirements

People in factories will say things like: 'how do I know where everything is?' If the customer phones up and says 'where is my order in the system', we need to know and we need to know what to do next. And then the question arises as to how far into the future can we predict what we ought to be doing given the state of our facility now? We can think of the machines on the shop floor as generators of information rather than say, bashers of metal. We know that a product has been through a particular process because the stages are embedded in its current state. Machines embed information in this way, but also are continually generating new information. The controller or scheduler of that facility needs to know such information to answer questions about its performance and therefore has to monitor it, but he also has to know the status of the shop floor in order to plan the transition to the next step. Theoretically we should be able to answer questions by looking at the schedule which purports to tell us what state every resource on the shop floor should be in up until the horizon of the schedule (ten minutes or a day or a week etc.). However a schedule may not give us accurate information because:

(a) Customers change their mind about what they want
(b) They want the product adapted.
(c) They want it in a short lead time etc. etc.

And the schedule may be subject to constant changes in demand because operators don't show up or the machine breaks down or suppliers deliver the wrong thing or the wrong quantity or quality. All of these things generate extra information that the scheduler has to manage.

So entropy is the complexity or the expected amount of information that you need to know about the state of the facility. If we are operating a high entropy facility (i.e. need a lot of information to know the state of it) and it's generating information at a very high rate we need to keep getting information out of the facility in order to compare its state with the schedule and update it. The customers and suppliers will be deriving schedule changes as well. In high entropy facilities particularly those managed by computer based information systems, where there are different job lots the schedule may contain a lot of information that is specific to each job. The more things that vary like lot size, production rate and time of day, the more information has to be put into the schedule. The schedule may be difficult to construct because of constraints or options but is made even more difficult if the system is generating its own information and therefore having low predictability. Engineering job shops have these characteristics. There are many different routes through the facility, lots of queues building up, lots of discretionary schedule amendment. All these make it a high entropy facility- we need a lot of information to know its current state. Put a job into the job shop, for example, and we usually don't know when its going to come out or where.

A low entropy facility is much more predictable because there's much less variety. The schedules contain very little information and very little new information. For example 'Thursday morning do job C'. There's little information necessary because we always do that and we always make 500 items so there's no surprise. It's a fixed sequence comprising one route and one operating condition. If there is any need to deviate it's under agreed conditions or discretion. Researchers who study scheduling through simulation have often compared job shops and 'cell' based layouts (units with specific job specifications) to see what the operating efficiencies are and decide that a job shop ought to be preferred because they have more flexibility or synergy. The assumption is that if something goes wrong we can use the many different machines to fill up the gaps so we might ask the question 'why do manufacturers persist in using cells?' - something the simulation has shown is less efficient? The reason is that, theoretically, if we're doing a simulation all the information that we need to run that facility is there when we need it, but in a real machine shop the information is not there. You have to send someone to get it or look for it on the computer. It's not error free and it is costly to make decisions without sufficient information. We may have to install sophisticated IT equipment to make the information available. If we think about the entropy associated with running a real manufacturing facility we can see why real manufacturers make educated guesses. Applying the concept of entropy and information theory to a manufacturing facility enables us to ask the right questions. So long as we agree on our definition of states we have a measurement which is objective in that any researcher can get, within reasonable error limits, the same measure. it enables a quantitative comparison of system layers and operating practices and we can compare different factories as well as the different layout designs in a particular factory.

But we have to define the states of the system and this brings up the question of meaning. We define the states according to what the data coming from the facility means for the production controller . If we're thinking about the quantity that our machine has produced on a certain day, what kind of tolerance on the target production causes no problem? Is it plus or minus what percent? This defines one of the boundaries. When a facility is not producing what it ought, when does the deviation from schedule production cross into causing a different problem and what do we do about it. It may well be that we define the states for a small customer differently from that of a large customers resulting in different state definitions within a single supply chain. And if operators are understanding the deviations differently this will result in different impacts on the whole operation. So we have to be careful about objectivity when we define the states since they will be defined with respect to the problem. That's where subjectivity comes in.

For each of the states we calculate the probabilities of occurrence of those states. That gives us the pi in the formula previously described. A high level of entropy will require more resources for scheduling and we may need skilled people and computers to monitor the facility. In general increased entropy goes with the number of machines, the number of possible routings and the number of products. The symptoms of high entropy is the occurrence of queues, change of requests etc. So to design a new facility or change an existing one we need to calculate whether this will increase or decrease the entropy (the amount of information we need to know to understand the state of the system). We want to be able to say 'this will increase the entropy or this will decrease it' We can then compare not just alternative design in one factory but compare the layout of different factories. By saying that the facility generates information when it deviates from the schedule we can measure the rate at which it is deviating and consequently how well it is sticking to the schedule in order to talk reliably to customers and suppliers. So our new approach to scheduling is to ask 'what is the optimum horizon?' Looking at scheduling literature it tends to assume that we know all the jobs we want to make and the operating rates of all the machines and can predict. this is unrealistic. We want to answer the question 'how long will the process stick to this schedule?' and therefore 'should I be scheduling for a week or a day?' Nothing in the literature tells us about scheduling 'horizons'. If we push a facility to the limit of its operating capacity things are very likely to go wrong and the less it is likely it will stick to the schedule. We have to build in a bit of leeway in order for the facility to operate reliably.

What is also interesting is to see how a change gets transmitted along the supply chain. If one facility changes its schedule, for example, how does that impact on customers or suppliers? Whilst it may seem simple for say a large food retailer to have a 'buy one get one free' sales drive what is the impact on the supply chain? Richard Wilding has found that this doesn't just double demand but may multiply it by a much larger factor. What's interesting here is that although the big supply chain supermarkets might say 'we can cope' they often do not take into account the impact on small manufacturing enterprises (SMEs) who may not be able to cope with that amount of entropy.

What is the hidden cost of transmitting entropy? What is the cost of monitoring and control and how can this be included in schedule optimisation? To what extent should we embed flexibility in our operating practices? What is the impact of this on the information we have to transmit and people have to understand? We need an integrated approach to scheduling and system design. Up until recently layouts of factories have tended to be designed on the basis of how far things should move and then the schedulers are given a list of products and jobs and told to produce the best schedules. The scheduler then gives it to the people on the shop floor who have to somehow make it work and although the schedule is apparently optimised many of the facilities don't work for the type or size of the lots. But the reason why people aren't able to stick to the schedule is nobody's fault. The system is imposing constraints that are not in fact workable and the question remains as to how could we come up with realistic schedules? Schedules that will anticipate the changes in products and operating conditions that might occur over the lifetime of the facility. We need to integrate scheduling and system design.

Complexity or entropy may be good or bad. Complexity may enable flexibility but it's only good if the customer will pay for it. Bad entropy is when a facility is not operating well and generating a lot of information which we are paying for. There are good reasons for being complex if we can get other people to pay for it. A manufacturer can hide a lot of entropy in stock. If suppliers are variable and unpredictable or customers keep changing their minds at the last minute then we can accommodate it by keeping stock. It is how a manufacturer often deals with it and is therefore a symptom of high entropy but of course the manufacturer is then paying for the storage. 'Queuing' in general is a sign an attempt to deal with high entropy as are constant schedule revisions. One of the supply chains studied is a good example of entropy transmission. There was a big UK manufacturer of liquid goods who received their bottles from a supplier some 18 miles away. The manufacturer was subjected to a 'buy one get one free' sales drive from the retailer which immediately gave them a lot of complexity. Their manufacturing facility was also not that reliable so they kept sending their supplier updated requests for the number of bottles they thought they would need. The bottle suppliers absorbed the complexity as stock and charged a premium. When the manufacturer got sick of paying it, it decided to integrate the facility and put the bottle manufacturer in the warehouse so the bottles could be put straight through the wall to the bottling facility. But the bottle manufacturer wasn't good at coping with schedule variation and said things like 'sorry we can't change the schedule'. The result was that the complexity was re-imported and had to be absorbed by the liquid goods manufacturer It is a typical case of the transmission of entropy along the supply chain. And it also involves the 'Forrester effect' in that a small change at the consumer end of the chain produces big changes at the raw materials end. Things which generate complexity are, change of requests, unreliable resources, unscheduled changes in machines or operators. IT systems can smooth out the queuing and increase operating flexibility and by doing that we can turn the entropy into better customisation, but usually we have to pay for any entropy other people give us. Complexity is always paid for by someone.

Calculating Entropy

We can calculate the entropy of a facility by the following steps:

(1) Measure variations across flows.

(2) Classify the data according to similar levels of variation (**i**).

(3) Calculate the probabilities (**p**) for similar (scheduled) states of **i**.

(4) Obtain a complexity index by calculating the entropy as:

$$- \sum pij \log_2 pij$$

where **pij** is the probability that the facility **i** is in state **j** summed over all scheduled states (e.g. different products or scheduled maintenance). It is a measure of the expected amount of information you are required to know about the state of the facility.

If this is the structural complexity we can then compare it with the dynamic complexity by calculating an index for unscheduled states ($i^{/}$). This is a measure of the degree to which the facility deviates from the schedule by unscheduled states such as breakdowns and this is an indication of the generation of information by the shop floor. We have also developed measure of decision making complexity which tells us how difficult it is to generate the schedule.

The actual project carried out was on supply chains and involved gathering data on quantity and delivery time at the interface between two organisations as supplier and manufacturer. This included both historical data and that collected over a period of three weeks during which we had the opportunity to discover reasons for deviations from schedule. We assumed that the deviations were bounded in that the system had average behaviour which was consistent over the period of observation so freak one off events from outside the system were not taken account of. We identified relevant documents within the supply chain, and the various stages in which information was transmitted. Quotations from the supplier were often subsequently followed by a number of revised schedules and we looked at discrepancies between the quotation, the rescheduled deliveries and the actual delivery of material. We were then able to compare material and information flow. Previously these two aspects were dealt with by different departments; the material flow by mechanical engineers and the information flow by computer people. We then:

(a) Identified a number of states

(b) Calculated the probability of those states occurring

(c) Used the formula to work out the complexity index.

This enabled us to compare different sequences of documents. For example, quotation received date, acknowledgement due date and purchase order due date, progress report and delivery details . By the comparison between the documents we could measure the complexity of the deviation between documents. This enabled us to say what degree of complexity there might be between orders and delivery, between the supplier and the manufacturer and we could see how well the progress report added information to the system. What we found was that the manufacturer itself was causing most of the complexity. Their supplier was absorbing their complexity and charging them a premium for it, although was adhering to delivery promises pretty well. But we did find that the delivery dates did not meet the progress report which tended to be overoptimistic so that its value was questionable. Overall the conclusions were:

- Yes there was a prompt response to request quotes.
- The premium rates were a means of costing the complexity.
- The complexity being generated by the supplier was greater than what they were importing from the manufacturer.
- They tended not to deliver at the right time but tended to deliver the right quantity.

We also looked at finance for the manufacturer. There were a lot of revised invoices and credit notes so a lot of information was going to and fro. Again complexity was transmitted backwards and forwards in terms of late delivery of material and money.

Extending The Work

The entropy / information theory approach could be used to achieve the following goals:

1. Understand how information is moved around in organisations and define a measure of schedule complexity.

2. Structure an organisation to allow discretion on decision making in different sectors(i.e. design a scheduleable facility).

3. Use extended supply chains to see where the complexity is absorbed and what the practices are(e.g. stock, IT etc.).

4. Benchmark complexity by taking a number of organisations in a particular sector and see how they compare.

5. Decide how an organisation might choose its entropy level according to its needs and its people, (e.g. low entropy by limited products, steady schedule or high entropy by being a mass customiser and having flexibility and short lead times).

6. Decide the value of an IT system (sometimes IT systems increase complexity and it is not known whether it is good or bad).

Discussion

The question was asked whether the approach could be used for a service organisation such as a call centre where complexity came from the outside the system and was dealt with by people inside the system. However the research that had been undertaken on how information was processed and complexity of information content was not taken into consideration. In terms of information transmission within a network studies have been made of banks and insurance companies which face the same problems of queuing etc. In fact the cost of the design facility was investigated in the manufacture of lorry trailers and it appeared that the daily information requirement in the design office was higher than that required in the manufacturing operation and that there was some kind of bottleneck there. Interestingly what was discovered was that the designers actually spent less than 50% of their time on design because they were so useful doing other things. Again, we weren't interested in the design itself, but how much resource was being put into it. Any operating facility could be included in the study that's accessible to being defined as a number of states. High entropy is often an indication of high cost but this is not necessarily so. It may be a sign of strength if it enables an organisation to move to a different regime but any complexity has to be dealt with within a normal range and its cost accommodated. We stepped back from the notion of optimisation in terms of human resources and didn't take account of different knowledge classes or bounded rationality. A system can be designed within the context of what the business wants to achieve and human resources are important in this respect. If a schedule is totally predictable people create variation in their workload and enjoy a certain amount of complexity (say around 4 'bits' + or – 2); less is dull more is stressful. It would be nice to measure people as complexity absorbers but it's probably difficult. Whether IT turns out to be value added depends to a large extent on the software writers, but complexity can also be absorbed by training. Entropy is additive but up to a point people often manage to cope with increasing entropy. One company that was looked at was always introducing new products. Management gave up telling operatives exactly what to do and would simply say something like, 'can you make one of these?' The job shop was a very 'noisy' area but although the company wasn't very good at getting out new products on time the addition of extra new products didn't seem to make matters much worse. It may seem strange define complexity in terms of entropy and probability but it was discovered that any development of theory that attempts to take variety into account combined with information transmission theory ends up with an entropy principle.

In all studies it was assumed that a system was essentially stable and that probabilities could be decided over measurable time. Systems with fast changing or adapting dynamics were not considered nor was there any attempt to be prescriptive about the amount of entropy that might be desirable. The system might become more predictable by reducing entropy but that would be no indication of whether the organisation would be more successful. Nevertheless the ability to absorb complexity that comes in from the environment be that a changing market or errant suppliers is obviously an advantage. Some companies such as R.S. Components thrive on taking on complex product and delivery schedules and are able to charge a premium.. There is also a growing number of service organisations who will absorb complexity for other people.

G.H. 29/4/02