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Research paper

Managing Complex Production System Variables

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Abstract

Managing a large number of production variables' information is a complex task. So far, little is available to assist production managers to manage and visualise variables' information in such a way that these valuable variables information could be used to support strategic decision making. This research has sought to address this problem by developing a software tool that offers a database, and visualisation function, which shows the inter-relationships of the production variables. The tool was developed based on the Connectance Concept, and has a built-in evaluation module using the Analytic Hierarchy Process to facilitate decision analysis. This paper describes the structure of the software tool and its features. The results of testing and application of the tool in companies are presented. This paper concludes by discussing the implications of this research for managers, and identifying directions for future research.

Key words: *Connectance Concept, Decision Support, Manufacturing Strategy, and Operations Management*

1. INTRODUCTION

Do you know what are the variables that influence the performance of your work centres or factory operations? Do you know how these variables are interrelated and how linked to your operations performance? The answers to these questions can have a dramatic effect on your operations strategies and also on the bottom line performance. A review of the literature shows that little is available in existing research to assist managers in mapping and managing production variables information in such a way that these valuable information could be used to support managerial decision making. Existing tool such as the fishbone diagram has been widely applied by managers to study the cause and effect relationships of a problem situation, usually for a small problem within a clear boundary. However, for modelling of complex cause effect relationships of a production system, the fishbone diagram may not be suitable. Managing production variable information is difficult because the relationships among variables are complex, and the 'impact' of a variable is likely to be cross functional. For example, insurance requirement has an impact on the production cost but this variable is likely to be under the control of the personnel department. Thus, given such a complex nature, how could managers model, maintain, and visualise the variable relationships? Also, how could they focus their analysis when the model of the variable became too complex? Clearly, if a tool were to be able to support the modelling of the complex variable relationships in a production system, it needs to have the following capabilities:

a) Visualisation – Graphic user interface functions to enable managers to visualise the linkages among variables.
b) Documentation – Database functions to store the complex variables' interrelationships, and support to categorise variables according to different management functions.

In 1984, late Professor John Burbidge advocated the use of the connectance concept for modelling of production system variables. Burbidge argued that through experience, managers learn the principles which govern the relationships between variables. When driving a car, one learns, for example, that turning the steering wheel in a clockwise direction will cause the car to move to the right, and that pressing the brake will make the vehicle stop. In the same way, by learning something of the effects of changes in input variables on the induced direction of change in output variables, managers can learn how to steer a production system towards achievement of the aims. The working principle of the connectance concept is as follows:

'Providing one does not attempt to specify relationships in quantitative terms, it is possible to make statements about system variable connectance, which are always true, but may not be relevant in all production situations' [1].

Using the connectance concept, Burbidge built a Connectance Model of production variables and intended to use the model for the design of new production systems [2], that was to find the input and system variables required in order to achieve a given combination of output variable requirements. While not necessarily agreeing with Burbidge's assertion that relationships are always true, we believe that the principle of connectance concept could be used to model a complex production system variable. The developed model could then be used by managers to study how a given direction of change in one variable will induce a particular direction of change in any related variables.

The connectance concept, although itself simple, results in large complex models when applied to real production situations. These models are difficult and time consuming to generate manually. Furthermore they are difficult to manipulate manually, and this makes analysis tedious. In order to address these shortcomings we have developed a computerised tool which facilitates the building of production variables' model. Fig 1. compares the functions of the software tool and the Burbidge Connectance Model.

This paper describes the development and testing of a decision support software tool, we called it **T**ool for **A**ction **P**lan **S**election (TAPS) to assist manager in mapping and model production variables' relationships.

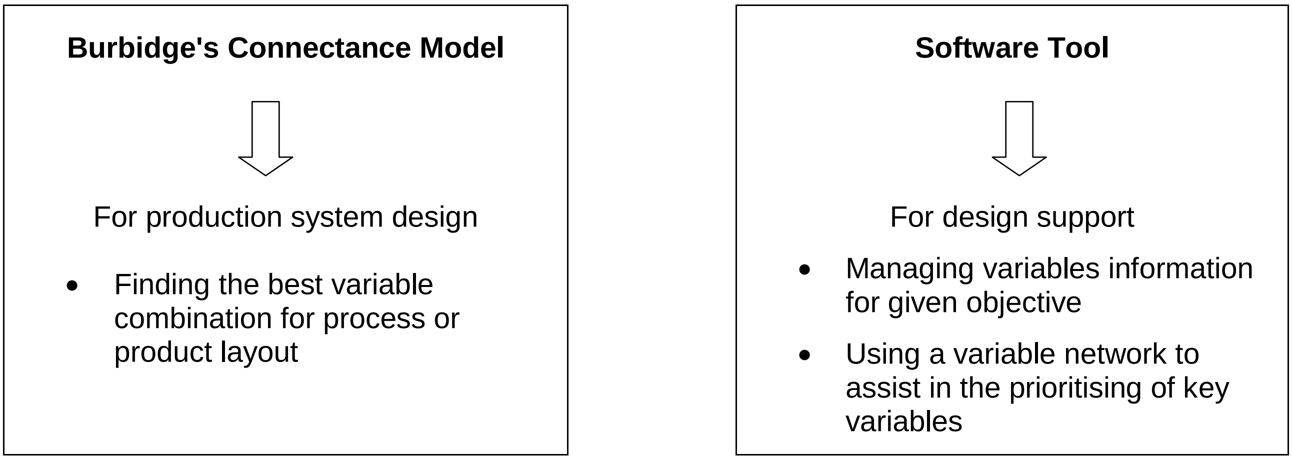

Figure 1. Comparing the Functions of the Software Tool and the Burbidge Connectance Model

The remaining of the paper are organised as follows. The next section explains the structure of TAPS and its features. Then, the results of testing and application of TAPS in companies are presented. This paper concludes by discussing the implications of this research for managers, and identifying directions for future research.

2. TOOL FOR ACTION PLAN SELECTION (TAPS)

The tool is implemented under the Microsoft Windows operating system using Microsoft's Visual Basic 6.0 programming language. TAPS has three main modules: a) database; b) analysis; and c) graphic user interface (Fig 2.).

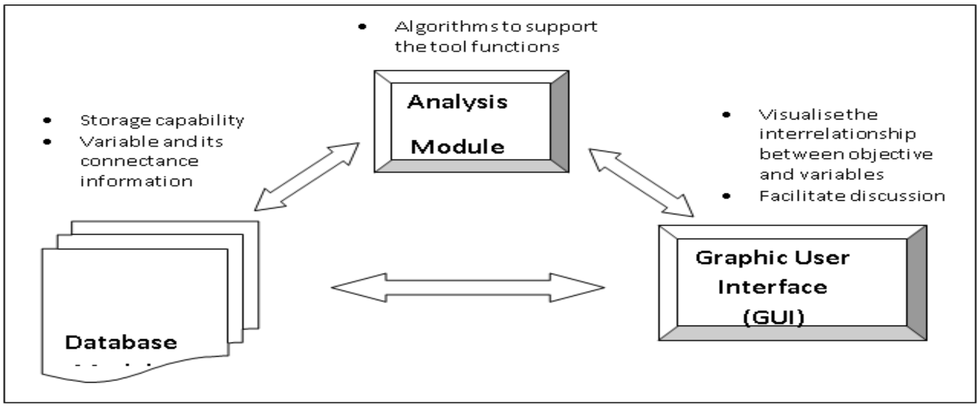

Figure 2. Structure of the Prototype Tool

2.1 **Database Module**

The database module stores the variable information and is based on the original data sheet format as in Burbige's connectance model. There is one record for each variable (Fig 3.), which stores the variable information such as code, name, definitions and its connectance variables. The database module serves as input to the subsequent modules.To reiterate, the aim of developing the prototype tool is not to build a 'computerised' Burbidge's Connectance Model. The objective is to adopt Burbidge's connectance concept as the main engine for the tool.

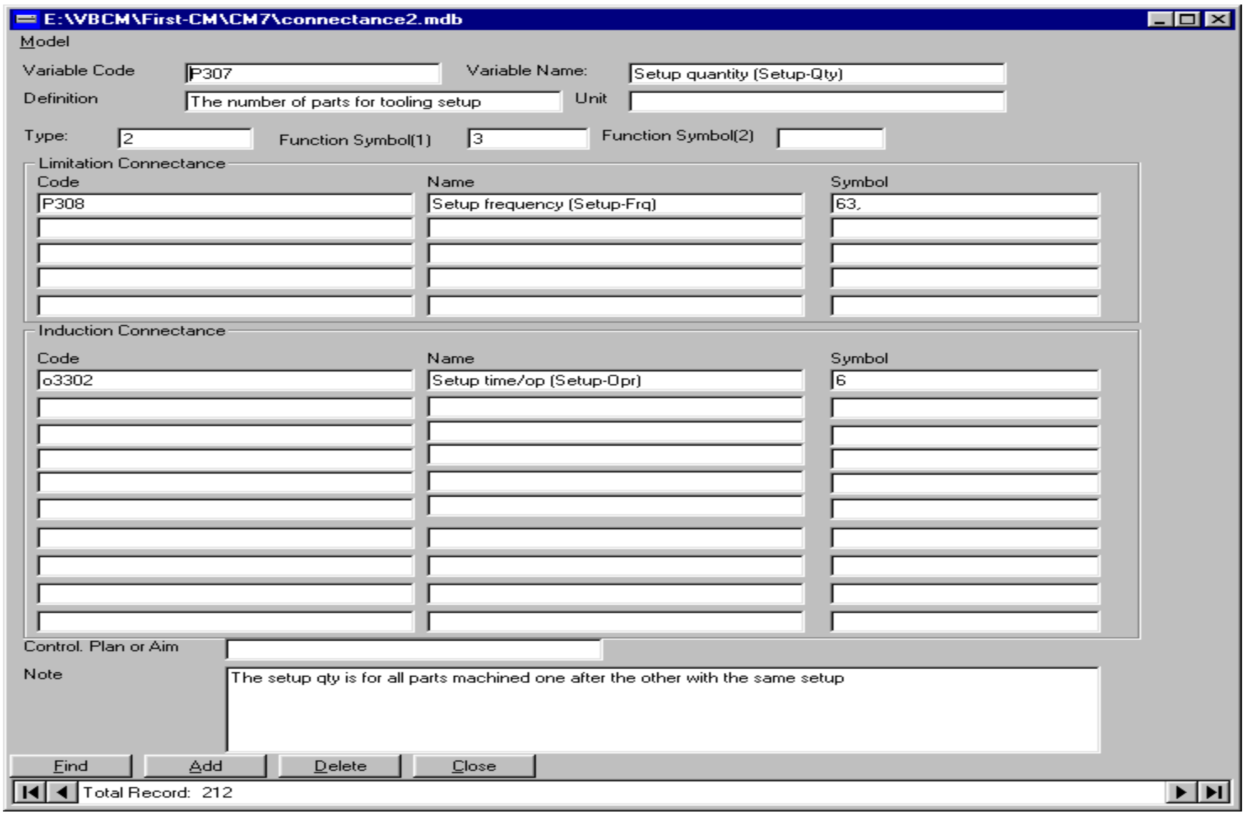

Figure 3. Variable Record Table

Since Burbidge's connectance database comprises the most 'comprehensive' production variable information, it is then useful to take Burbidge's database as the main reference. In so doing, some of the information in the Burbidge variable record table needs to be simplified, in order to enable it to be captured more easily in the prototype tool. For example, the connectance information between variable is captured by the symbol column on the record table (Fig 3.), rather than to Burbidge's graphical display of arrows and symbols.

Considering the potential by vast number of variables and the complexity of their connectance, a linear list data structure is used for the database. For a given variable, the connectance information is stored as pointers. Fig 4. illustrates an example of the connectance network for Var 1. In the network, Var 1 has a connectance with Var 2, Var 3 and Var 4; Var 3 has a connectance with Var 4; and Var 4 has connectance with a Var n. Fig 5. shows how the variables information is captured in the database. First, a record table for Var 1 is established and the connectance information of Var 2, Var 3 and Var 4 is stored as pointers. The process then continues for Var 2, followed by Var 3, Var 4 and Var n. In each sequence, the connectance information is stored as a pointer. To accommodate the building of a large production variable model, each variable database is allocated 10 pointers.

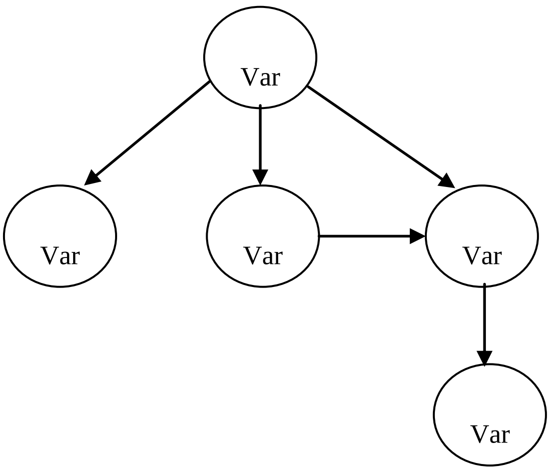

Figure 4. Network Diagram for Var 1

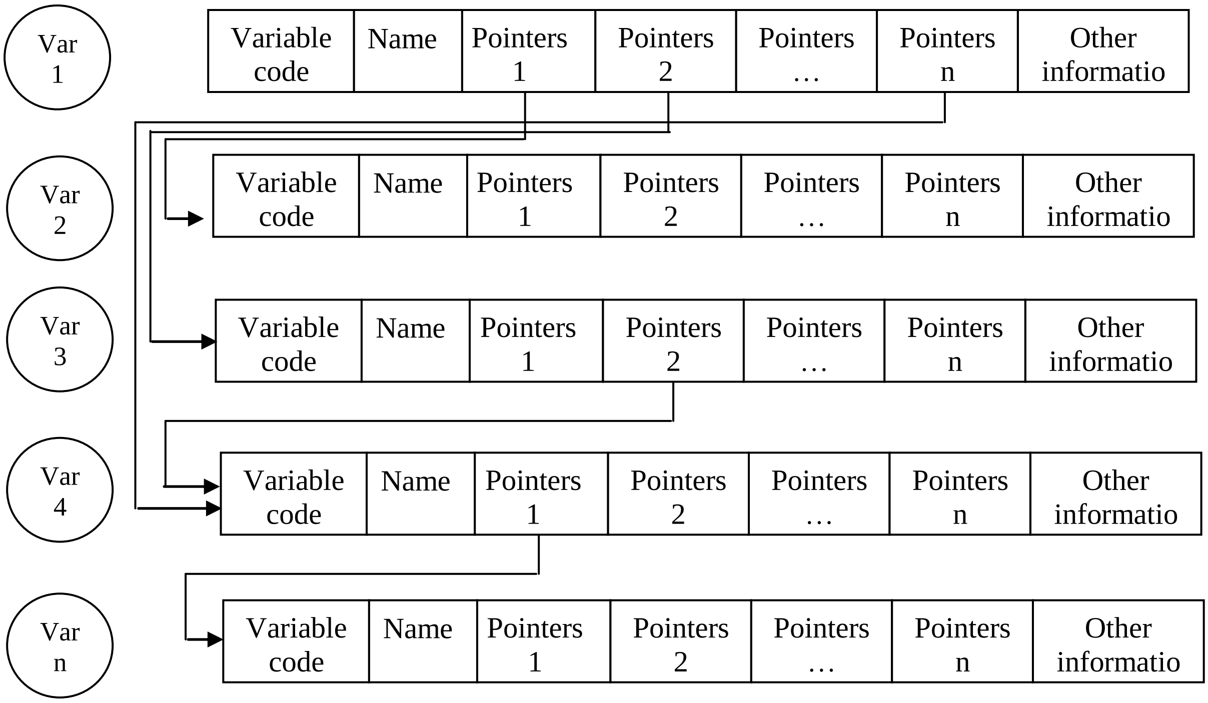

Figure 5. Database Structure for Var Network 1

2.2 **Analysis Module**

The analysis module contains algorithms for accessing the database information and arranges the variable and its connectance variables information in a network diagram. The analysis consists of two main functions: Trace-Down Analysis and Trace-Up Analysis (Fig 6.). A Trace-Down Analysis function is an analysis to determine the effect of a given direction of change in one production system variable on other variables on the network. A Trace-Up Analysis function, however, starts with a desired direction of change in a variable and works back to find which other variables have to be changed in value and in which direction.

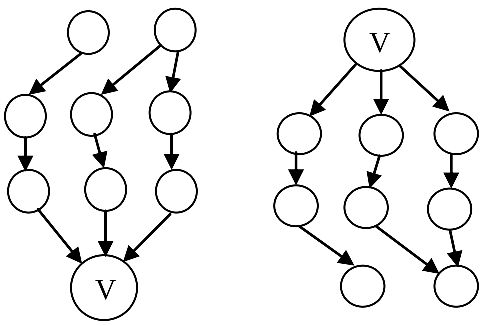

Figure 6. Trace-up and Trace Down Network for Variable A

Example of a trace-up algorithm can be briefly described as follows:

1. Selects a specific variable, interactively from the user interface or directly from the database
2. Initialises a new connectance model with the selected variable.
3. Sets the selected variable as the current variable.
4. Search all parent (connetance) variables of the current variable, and stores all unknown parent variables to the new connectance model in the data array.
5. Moves the index of the current variable to the next datum in the array.
6. If the current index is less than or equal to the total of the variables in the updated connectance model, repeat from 4. Else, the procedure ends.

2.3 **Graphic User Interface (GUI)**

The graphic user interface module serves to display the computerised model and contains functions to allow the managers to manipulate the model interactively.

In the network display the variable is displayed as a node with edges (lines) linking it to other nodes with which it has a connectance. Thus, a variable's connectance network is made up of nodes and relations.A network display for the variable 'setup time per operation' (o3302) in the Trace Up Analysis is shown in Fig 7.

The variable and its connectance information was extracted from the Burbidge Connectance Model [2]). The variable being studied (o3302) is located at the bottom of the network with its immediate connectance at the top. The relationship of the connectance is represented by the direction of the arrow, and the induced variation is given by the sign above the arrow. For example, the arrow from variable 'pre-setting tooling on work centre' (IS205) is pointing to variable 'setup time per operations' (o3302) with a (-) sign above the arrow. This indicate a negative induction: pre-setting tools on a work centre can reduce the setup operations time.

In the network display, connectances that have 'first order' [2] relationships are displayed on the first row. This is followed by the 'second order' or indirect connectances. For example, variables (IS205; IP203; IS309; IP307; IS213; IS204 and IP202) have first order connectance, they are variables that have a direct knock-on effect on variable (o3302). Variables (IP308 and IS302) have second order or indirect connectance to variable (03302) but they were first order connectance to variable (IP307). Thus, nodes at the higher levels in the network hierarchy have only indirect impact on the variables at the bottom of the hierarchy.

The tool is designed to be user friendly, thus enabling users to update or search the variables database easily. By linking to the database, the tool traces and displays the variable's connectance network in hierarchy form. Other graphic interactivity features in the tool are sketching and node editing functions (size, colour, move, rename etc.) which enable the user to modify the network hierarchy display. The modified connectance network can then be transferred into a new database. In other words, the tool allows the user to build a new connectance database from scratch and modify existing variables' connectance from a database.

3. TRIALING THE PROTOTYPE TOOL

Having developed the TAPS tool, a series of tests was carried out to evaluate the programme quality and robustness. These tests are described as below.

3.1. Connectance Accuracy

The first test was performed to evaluate its connectance accuracy. Before this, the variables' information from Burbidge's connectance model was input into the database. A comparison was performed to compare the output of the prototype tool on the 'Capacity-Work Centre' (o3208) variable with a diagram produced by Professor Burbidge [1]. The results showed that the prototype tool yielded a more comprehensive connectance network for the 'Capacity-Work Centre' variable. A manual check on the database [2] proved that the connectance network generated by the prototype tool was valid.

3.2. Operability

This test was carried out in a practice session which introduced a group of 44 Masters students to the prototype tool. A short exercise on model building and database management design lasted 60 minutes. The students were given a step by step guidebook on the prototype tool and asked to produce the model and database and hand it in to the researcher. The test showed that the students faced no difficulties in following the manual instructions for building the model and no errors or bugs on the prototype tool were reported.

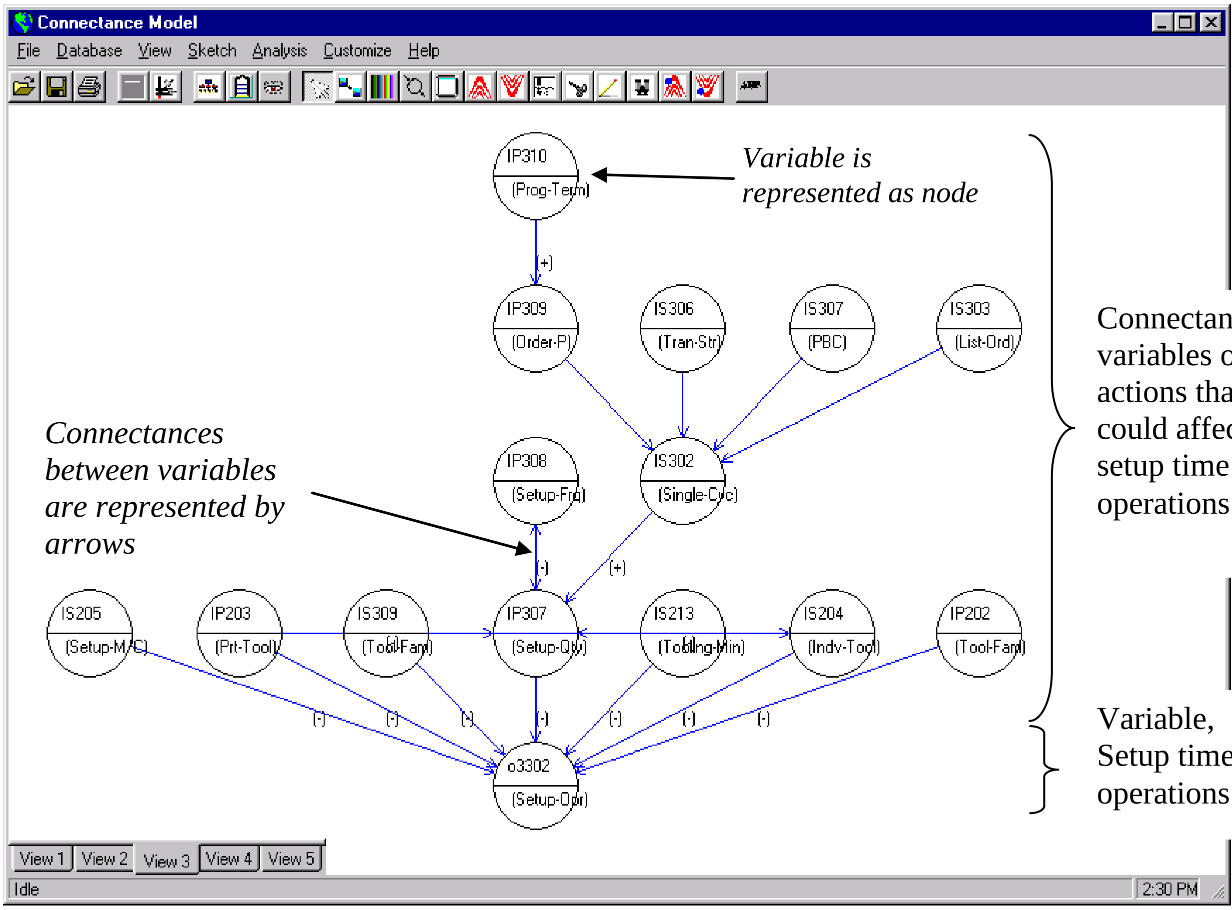

Figure 7. Sample of Variable's Connectance Network from the Prototype Tool

3.3. **Trial with Industrialists**

Having established accuracy of the connectance and operability of the prototype tool, a series of case studies with industrialists was conducted to study its validity: that is the extent to which the prototype tool is appropriate to the task in hand. In this case, the 'task in hand' refers to the capability of the prototype tool to assist managers in building a variable model and supporting managerial decision making. In total, case studies were conducted with 13 companies in UK. In each case, the meeting typically involved a presentation of the research project, a demonstration of the prototype tool, and a feedback and discussion session. Managers were encouraged to have an 'hand-on' experience, using the tool to develop production variable models. Variable information in Burbidge's database was used for reference. The feedback from the cases was positive (see Appendix A for a summary of the case results). The results are further explained below:

General Validity of the Tool:

All the managers felt that the prototype tool was capable of showing variable connectance graphically and captured the information in a database. The interviewees felt that the connectance variable network was useful in managing and understanding variable cause effect relationships. All interviewees agreed that the database function in the prototype tool was well designed. The database was supported with features that enabled the variable information to be updated and customised to the current operating environment.

User Interface Validity:

As the industrialists were the target users of the prototype tool, their feedback on this aspect is very important. All managers felt that the prototype tool was well designed and the graphical display of the variable information was easy to understand and interpret. A manager in Company 13 commented that "*The tool appears to be very reliant on smart development of the initial network and capable to replay information back from multiple view points. This is very powerful for training of manufacturing business, and for checking a manager's thought processes"(sic*).

However, some concerns were raised pertaining to the structuring and management of the variables' information, for example:

a) The connectance network for some variables could be very large and complicated. For example, variable 'total production cost' (o6825) from Burbidge's connectance model has 196 connectance variables in the network. This makes it very difficult for the user to visualise and to analyse the variable relationships.
b) The tool had little information on the characteristics of the variables or the connectance relationships. This makes it difficult for the user to single out variables for further study.
c) Another shortcoming of the original Burbidge model is the aggregation of variables. Some of the output variables (objectives) such as 'Flexibility' have an aggregation of more than 10 variables. This makes it difficult for the user to analyse and group the variable relationships.

Applications:

All managers felt that the prototype tool could be applied to a wide range of applications beside its function for managing variables' relationships. A manager in Company 6 pointed out that the prototype tool could assist managers in framing a problem situation through the building of a variable model which frees managers from the implicit or hidden assumptions that they may be constrained by, and surfaces new insights into the problem.

From the discussions, the prototype tool was also identified as useful for:

a) production knowledge management (Companies 5 & 6);
b) training or teaching aids in production management (Companies 2 & 11);
c) modelling process and output measures for performance measurement (Company 13).

In some of the cases (Companies 11 & 13), the managers felt that there is a lack of decision making capability in the prototype tool. They felt that a decision support function for assessment and prioritisaiton of the identified key variables would be useful.

4. ENHANCEMENT TO THE PROTOTYPE TOOL

The case studies' results indicated that the prototype tool was feasible to serve its task as a tool for building and managing variables' cause-effect relationships. However, some shortcomings of the prototype tool and the Burbidge connectance model were identified. In order to address these shortcomings, the following modifications and changes were made to the prototype tool:

4.1. **Filter Function**

Shortcomings (a & b), were addressed by enhancing the tool with a filter function on the variable record sheet. Two types of filter information were added to the record sheet, which relates to the variable and its connectance. Filter information on variables would enable managers to single out the variables that they were looking for. Filter information on connectance would enable managers to decide on the connectance information that they would like to focus on. These changes were incorporated in both the database and analysis modules of the prototype tool.

An example of the enhanced variable record sheet is shown in Fig 8. Three types of filters were used to relate to the variable information:

- *Function* – for classifying the variables according to the production management functions.

- Examples of management functions are production planning, purchasing, product design, production control etc.
- *Level* – for classifying the variables according to the management control level. Examples of management control levels are plant, cell, work centre etc.
- *Ctrl/UnCtrl* – there are two types of variables; the controllable and the uncontrollable. The controllable refers to a variable that a manager can control and assign a value to; the uncontrollable refers to a variable whose value is imposed by the 'environment' where a manager has little or no control. Examples of uncontrollable variables include safety laws, minimum wages etc.

Three types of filter information were applied to the connectance between variables, in addition to the existing induction information above:

- *Time Factor*– refers to the time taken for the connectance variable to have an impact on the variable being studied. The filter categories were immediate, medium or long. For example, factory capacity could be increased immediately by working overtime, could be increased in the medium term by putting on an extra shift, or in the long term by acquiring an extra plant.
- *Cost* – refers to the cost of changing the connectance variable. The filter categories were low, medium and high.
- *Strength* – refers to the strength of impact of the connectance variable on the variable being studied. The filter categories were low, medium and high.

Having developed the filter functions, a built-in function called 'Filter Customisation' was also developed. This function allows the user to customise the filter types and categories on the record table. Thus, the filter function will allow the user to sort out and focus on high impact variables upon getting an overall view of the situation. So, for example, they might concentrate on those variables having an immediate effect, or those which cost little to change.

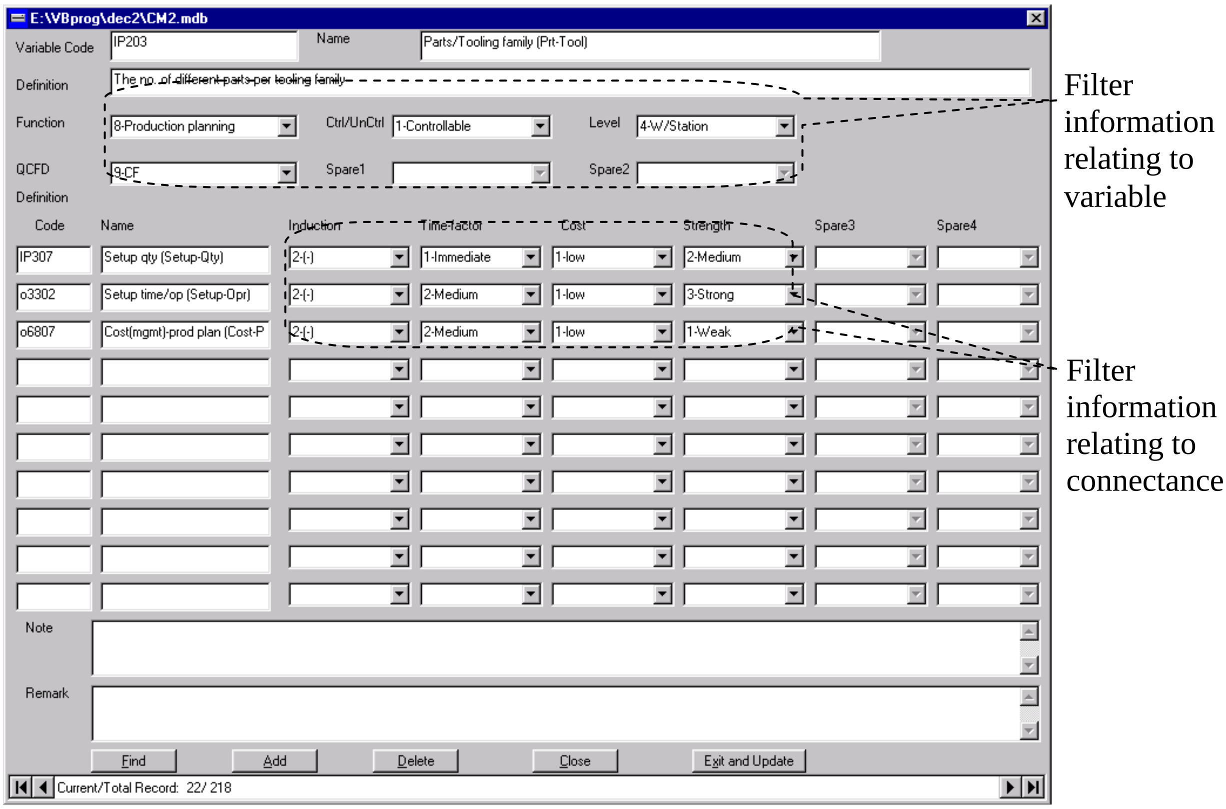

Figure 8. Sample of Variable Record Sheet in the Prototype Tool

4.2. **Evaluation Module**

In order to allow managers to perform an evaluation process to prioritise variables for further decision analysis, it is desirable for the prototype tool to have an evaluation module. Analytic Hierarchy Process (AHP), a Multi-Attribute Decision Making (MADM) method developed by Saaty in 1987 was added to the prototype tool. The advantage of AHP is its capability to elicit judgements and scale them uniquely using a valid procedure that measures the consistency of these scale values [4]. Fig 9. shows the structure of the prototype tool with an additional evaluation module.

The built-in AHP function is based on the procedures and eigen vector calculation methods proposed by Saaty [4]. For those selected variables, a pair-wise comparison between two variables v_i and v_j (i=1,2…, n) can be quantified by users as a matrix A = $[a_{ij}]$ which denotes the importance of v_i over v_j. An approximation of the priority vector for the selected variables can then be computed according to the AHP method as follows.

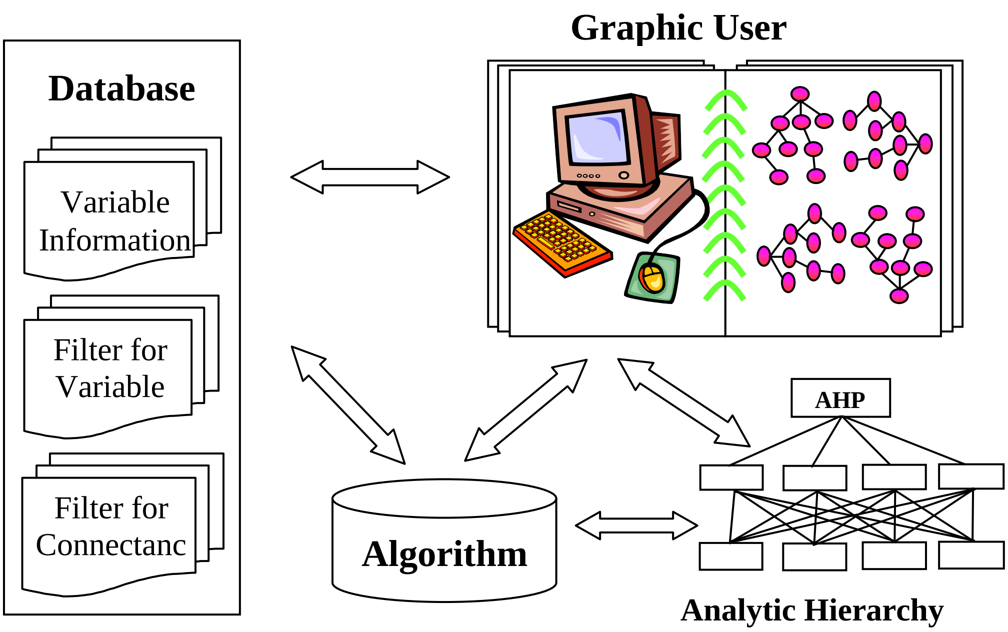

Figure 9. Structure of the Prototype Tool (With Evaluation Module)

A normalised matrix of **A** by a row vector of the sum of its columns can be given as

$$\mathbf{B} = [b_{ij}] = \left[\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \right] \qquad (1)$$

Then an approximation of the priority vector can be given as

$$\mathbf{x} = [x_i] = \left[\frac{1}{n} \sum_{j=1}^{n} b_{ij} \right] \qquad (2)$$

which provides the priority of those alternative variables. Since the pair-wise comparison is arbitrary, the computation of the consistency ration c_r is also provided. The consistency ratio is a scalar value indicating the consistency of a pair-wise comparison

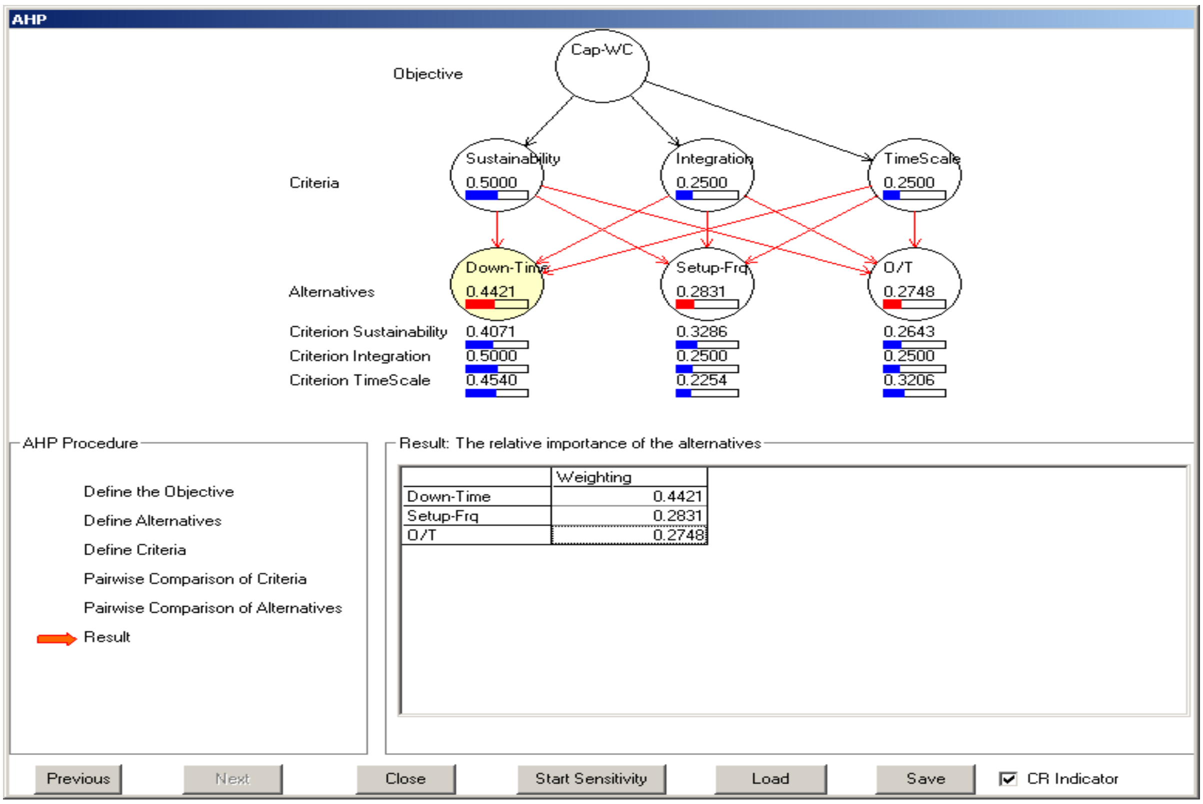

Figure 10. A Dialog Box for AHP Evaluation

and is calculated by

$$c_R = \frac{c_I}{r_I} \qquad (3)$$

where

$$c_I = \frac{1}{n(n-1)} \sum_{i=1}^{n} \left(\frac{\sum_{j=1}^{n} (a_{ij} x_j)}{x_i} \right) - \frac{n}{n-1} \qquad (4)$$

and r_i depends on the order the pair-wise comparison matrix **A**. Generally, if c_r is less or equal 0.1, the pair-wise comparison can be considered as satisfactory.

Based on the AHP principle, the prototype tool evaluation function enabled users to visualise the problem in a hierarchy tree and see the results of their judgement at each stage of the analysis process (Fig 10.). Moreover, the evaluation function allows managers to state all their assumptions and to make subjective weightings explicit. Thus, the built-in evaluation function helps managers to organise their decision making process and provide a record of how they reached the conclusion they did. To allow managers to answer some of the 'what-if' questions pertaining to their decisions, a sensitivity function was also built into the prototype tool.

4.3. **Network Structure**

In order to address the problems of highly aggregated variables on output (objective) variables, a four level network structure was introduced (Fig 11.) to assist managers in building a variable model. The bottom level displays the objective or the focus variable of the analysis. In level two, the objective is broken down into its different dimensions. For example, the objective of "flexibility" could be broken down into four resource dimensions [6]: System, Labour, Process and Control. The purpose of breaking down the objective into its dimensions was to have a more manageable network diagram. In level three, the relevant connectance variables for each resource dimension are displayed. The top level displays the actions that could be taken to address the variables. For example, the connectance variables for labour flexibility could be training and working hours. And one of the actions that could be taken to address working hours issues is overtime.

5. APPLICATION

The advantage of applying the connectance concept is that models can be created that are consistent with the ways in which managers have experienced the world, and can be transformed in order to answer specific queries.

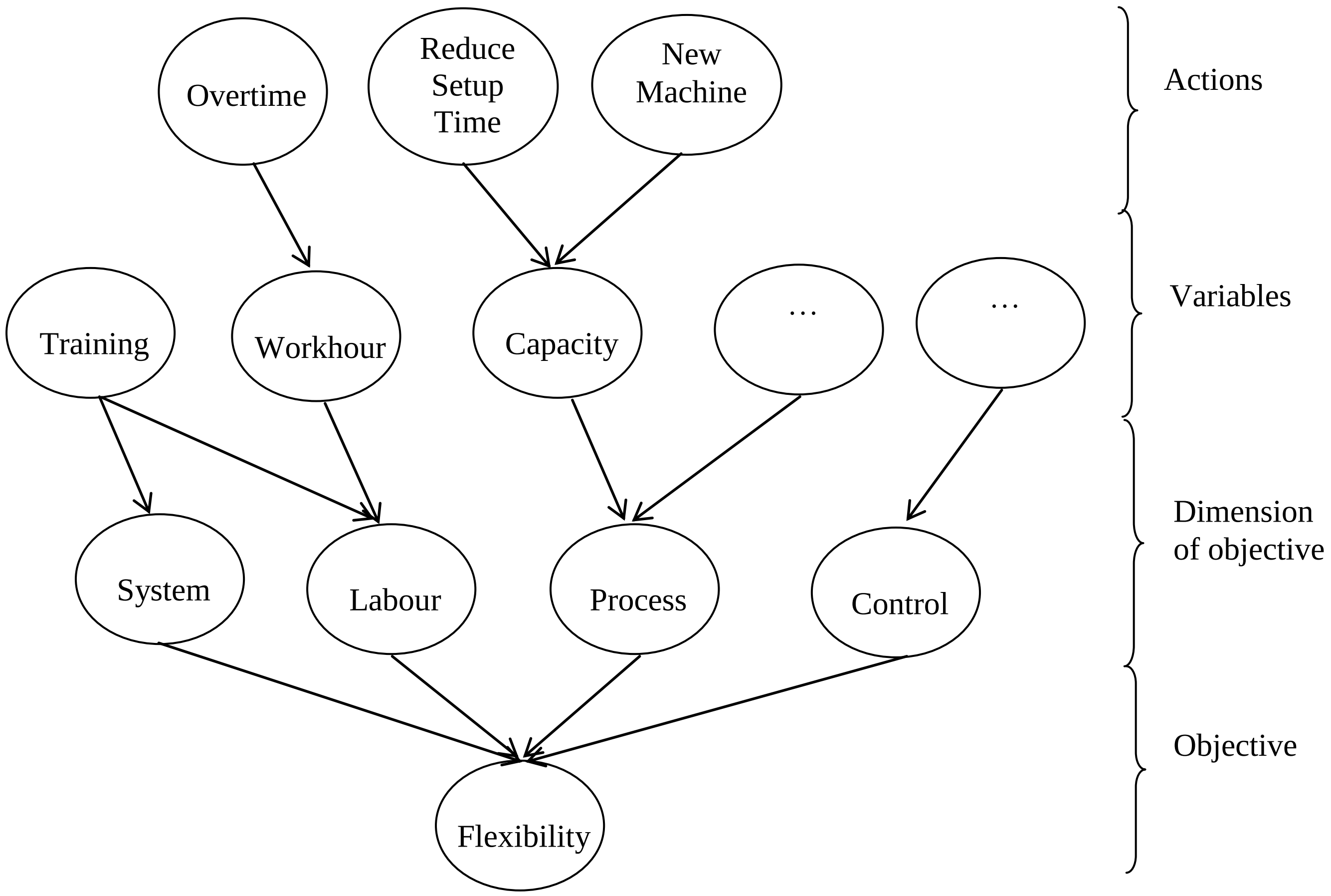

Figure 11. Structure of the Network Diagram for Flexibility

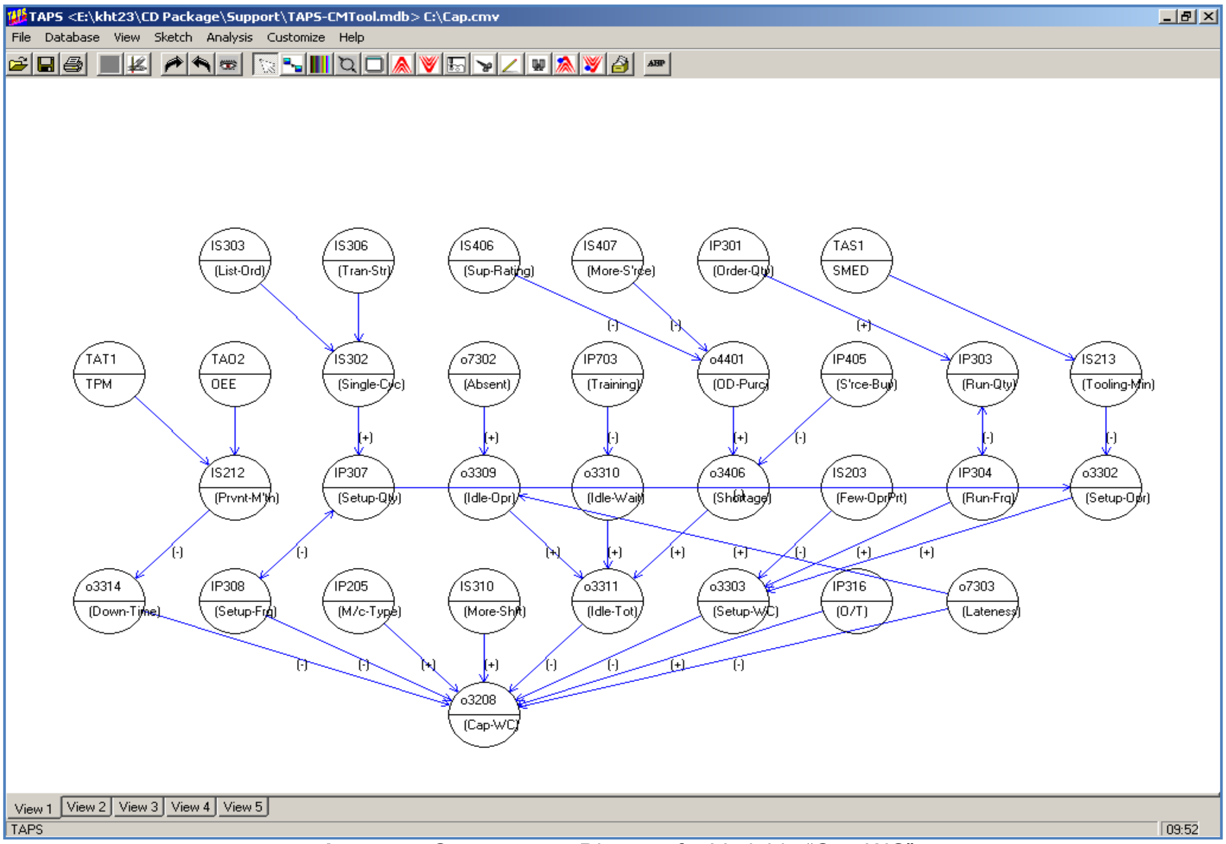

Figure 12. Connectance Diagram for Variable “Cap-WC”

For example, if managers would like to identify the range of action plans to improve capacity utilisation (Cap-WC) on a work centre, they could use the prototype tool to build a ‘Cap-WC’ connectance diagram of production variables based on their experiences (Fig 12.).

The connectance diagram enables managers to represent their knowledge and experience of variable relationships, in a way that can be easily communicated and discussed. Once the variable connectances are understood, the potential actions to achieve a particular objective are revealed. In the example, increasing work centre capacity could be achieved by one or more of the following actions:

- reducing (indicated by a (-) sign) work centre down time (o3314);
- reducing machine set-up frequency (IP308);
- reducing the amount of idle time on work centre (o3311);
- reducing lateness of machine operator (o7303);
- increasing (indicated by a (+) sign) overtime (IP316);
- increasing the number of working shifts (IS310);
- increasing the number of machines (IP205.

Moreover, managers could activate the filter function to assist them in narrowing down the scope of the variable model. For example, they could activate the filter function to focus on those variables that have negative induction with ‘Cap-WC’ (Fig 13.).

The enhanced prototype tool was further testing in five companies in UK, using a process research based on action research methodology [3]. In each case, a number of workshops were organised to assist managers in applying TAPS to address production operations management problems. Further information on these cases can be found at Tan and Platts [3,7].

6. CONCLUSION

Understanding and managing production variables are a key task for industrial managers. This task is essentially complex as it requires an understanding of the relationships among many variables. The relationships between objectives and variables in a given industrial situation are usually not available to managers in the form of scientific laws. Rather, they are discovered, defined, and labelled by the managers who use an implicit understanding of the operating environment to make sense out of them. We have developed a tool that is capable to enable managers to visualise the ‘implicit understanding’ of the variables cause-effect relationships. The use of such a visualisation permits managers to have an overall view of the situation.

This paper has discussed the development and application of TAPS. Through TAPS, a number of shortcomings in the Burbidge Connectance Model were also identified. The shortcomings identified from the cases were further addressed by enhancing the prototype tool with filter functions and an evaluation function based on the AHP decision making process.
Using TAPS managers can build and modify a variable model interactively and store the information in a database for future reference.

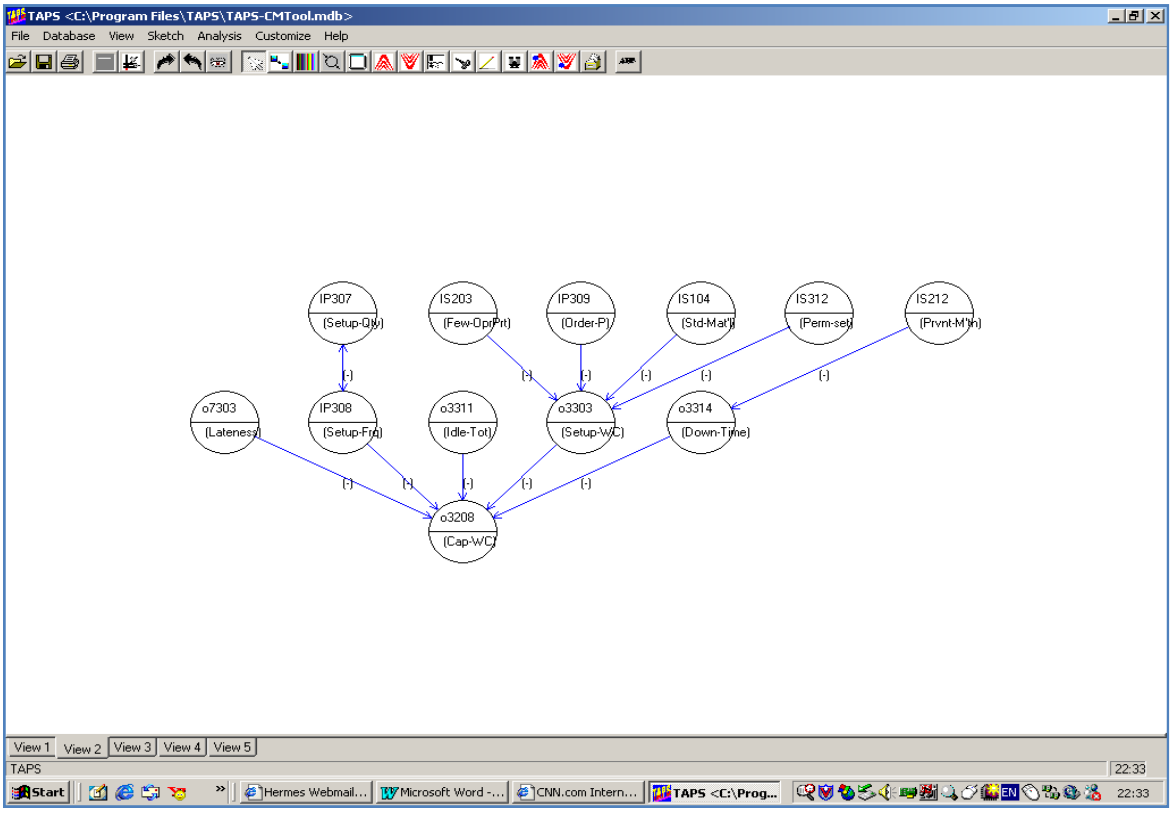

Figure 13. 'Trace-up with Filter' Network for Variable "Cap-WC"

Case study results indicate that TAPS is feasible and provides a structured and reliable method for manager to build and understand the complexity of production variables' relationships. The benefits of the TAPS approach could be summarised as follows:

- Collective understanding – The variable network building process enables everyone to have their knowledge brought into the open and their assumptions challenged. Managers agreed that this process is useful to enhance their understanding of an issue, as well as to facilitate organisational learning.
- Decision support – The built-in filter functions and database enable managers to study variables that have cross-functional relationships. By activating the filter functions, managers could see how the decision make on one variable will effect other functional departments in a firm.
- Facilitate discussion – The variable network helps managers to increase both the depth and breadth of participation in the discussion production management issue. The TAPS approach recognises the importance of assisting the evolution of the managers' ability to deal with the problems confronting them through increasing their understanding of the relevant variables. It provides models of the environment from which a manager can develop insights into the effects of his decisions on progress towards the goals that he wishes to achieve.
- Knowledge Management – The building of a variable network allows information to be passed, assessed and quantified, so that the ideas and beliefs contained within the model can be altered or modified at will.

Results of the case studies showed that the basic structure of this approach seems to be applicable even beyond the manufacturing domain. With TAPS, we are a step closer to provide managers a useful tool for production operations management. We would like to make TAPS available to any bona-fide researcher wishing to replicate or build on our work.

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Appendix A

ANALYSIS OF PROTOTYPE TOOL TRIALING CASES

Company	Interactivity features	Data representation	Perceived weaknesses	Perceived Applications
1	Satisfactory	Large network can be complicated	No	Factory capacity study: To identify action plans for greater capacity performance
2	Satisfactory	Good	Availability of variable information	Factory action plan selection: A common set of process variables to assist managers in action plan selection
3	Satisfactory	Can be confusing for large network	Database maintenance	To complement Hoshin Kanri on the objective deployment process
4	How to focus an analysis?	Good	No	Manufacturing flexibility study: To develop a flexibility model and identify a set of improvement action plans
5	Satisfactory	Can be confusing for large network	Database maintenance	Manufacturing knowledge management tool
6	How to narrow down an analysis?	Aggregation of variables	Database maintenance	Production operations management tool: To assist managers in decision making, and to serve as a production knowledge management tool
7	Satisfactory	Aggregation of variables	No	New product introduction study: To build a variable model and identify the key variables that have impact on new production line
8	Satisfactory	Good	No	Manufacturing quality study: To identify key variables and action plans for quality improvement
9	Satisfactory	Good	Availability of variable information	CNC setup time reduction study: To identify key variables to reduce setup operations in a CNC group machine
10	Satisfactory	Good	Database maintenance	Future aerospace systems study: To identify variables for greater process optimisation and integration
11	Satisfactory	Can be confusing for large network	Tool for decision support?	General manufacturing management tool: Especially for assisting managers in action plans selection process
12	Satisfactory	Good	Database management	Decision support tool for production operations management
13	Satisfactory	Need better network structure	Tool for decision evaluation?	Process variables study: To identify process and output measures for better operations performance evaluation

Upravljanje složenim varijablama u proizvodnom sistemu

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Rezime:

Upravljanje velikom količinom informacija o varijablama u proizvodnji je kompleksan zadatak. Do sada je na raspolaganju manji broj rezultata koji pomažu proizvodnim menadžerima da upravljaju i vizualizuju informacije o varijablama na način da tako značajne informcije čine podršku za donošenje strategijskih odluka. Ovo istraživanje razmatra problem uz primenu softverskog alata koji nudi bazu podataka i vizualizaciju koja pokazuje međusobne veze između proizvodnih varijabli. Ovaj alat je razvijen na osnovu Connectance Concept i sadrži ugrađen modul za ocenjivanje koji koristi AHP proces analize odluka. Članak opisuje strukturu softverskog alata i njegove karakteristike. Rezultati testiranja i primene ovog alata su pokazani na pimeru određenih kompanija. U zaključku članka data je diskusija uticaja ovog istraživanja na menadžere, kao i pravce daljih istraživanja.

Ključne reči: *Connectance Concept, donošenje odluka, proizvodna strategija, operacioni menadžment*