

A constraint-net approach to the resolution of conflicts in a product with multi-technology requirements

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Abstract

Whilst many procedures exist to support the systematic development of a product, it is often difficult to create an environment in which the early stages of the design are resolved. This can particularly happen when the product design is based upon a wide range of technologies and the expert members of the design team are drawn from many disciplines. The constraint resolution approach allows the requirements to be formed into rules and their combined truth established. Within such an environment an investigation has been undertaken to determine the possibility of establishing clusters of rules relating to individual technical aspects of the design requirements, which are then formed into networks that can be solved interactively within the constraint modelling environment. This paper draws upon the experience of designing a disposable cell counting device for medical applications and illustrates its adaptation to other applications through the use of the derived constraint-net.

Keyword: Constraint nets, rule clusters, multidisciplinary design collaboration, constraints

1. Introduction

Design problems can be considered to fall into three main categories; those that are sequence dominate those that are dependent on event decisions and those that are holistic. The sequential problems are handled through the application of normal design procedures that advance the design progressively from a needs analysis, through concept and embodiment to that of prototyping and manufacture (Pahl and Beitz, 1996). This type of design activity covers the majority of industrial development where products are based upon a continuous refinement process that can be handled by a simple design and management process.

Event dependent problems require key activities and skills to be identified in order that these 'events' can be resolved within an overall sequential design process. The problem is required to be partitioned into sub-problems that are resolved or combined about decision points. Here designing can occur in a normal procedural manner with decisions made at the defined decision points and then implemented. In such an approach the organisation and activities of designing are reviewed or adapted as the process advances. If conflicts arise they need to be resolved before the process can continue (thus providing stage-gates in the process). Normally further work can only proceed if a common direction is agreed and carried out.

In some creative problems however all aspects of the design need to be considered together. If a sequential or decision based approach is applied, the design activity is continuously halted and events or decisions revisited as other aspects of the problem fail to be met the different aspects of the problem or these different aspects give rise to unforeseen conflicts in the overall solution. It is here that a more holistic approach is required together with a structure that can be managed. When products that incorporate a number of different technologies are under development it is often difficult to determine which aspect needs to be resolved first or even which technology will eventually dominate the solution. In the consideration of a hand-held drill, for example, is it the ergonomics of operation or the conversion of power into the drilling forces that should be considered first? In truth both are significant in the creation of a workable solution and no successful solution can be achieved if either of these two aspects fail. If the ergonomics is good but the drilling forces are poor or the drilling forces are very effective but the operator cannot use it, then neither provides a

useable product. Simply both must be appropriate, successful and effective. It is in this class of product development that the linear systematic approach to design development is seen to fail. The initial concentration on the resolution of one aspect, before another, is seen to present difficulties that results in the possibility of extensive reworking through the requirement to iterate repeatedly through a number of design activities until all aspects are either successfully achieved or the different technological issues are seen to be in conflict (and no solution is achievable).

In such design problems a more holistic approach needs to be taken where the influence of each technical aspects needs to be considered independently and their influence upon each other and the overall solution determined. (Cross, 1992) The interdependent aspects of the problem can then be more clearly understood and resolved. In this paper an investigation was undertaken to determine the possibility of establishing clusters of rules relating to individual technical aspects of the product development requirements, which are then formed into networks that can be solved interactively within a constraint modelling environment. Which has resulted in the development of the formalized approach presented in the paper. Here the constraint networks differ from that of conventional networks, as the constraints themselves form the rules the design/ development activity. The remainder of the paper is organized as follows: section 2 reviews relevant literature to this research. Section 3 introduces the approach being employed. Section 4, presents a design employing the approach and section 5 discusses and concludes the work.

2. Related literature

The following section presents the previous and contemporary research relating the problem shown in this paper.

2.1 Constraint-based approaches

The importance of constraints has previously been discussed in prominent design theories, such as Pahl and Bietz (1996) and Cross (1989). The core element of the design process is the recognition, formulation, satisfaction and optimal solution of the constraints, which are constantly added, removed and modified (Lin and Chen, 2002). In the conceptual stages of the design process, function is of prime importance. These approaches have used constraint-based techniques to illicit and manipulate knowledge

about the design concept (Mullineux et al., 2005). This has then been used to aid the design process for a variety of domains and design task. The constraint-based approaches aid the designer in the development and configuration of a design and provide the possibility of finding the best quantitative solution and feasible designs (Wilhelms, 2006) through the comparison of alternative schemes (Sullivan, 2002). When considering the design embodiment activities, constraint-based approaches have generally been employed to analyse both products and processes (Thurston and Johnston, 1996). The knowledge of the constraints that bound the limits of a system, allow the designer to develop strategies to define the existing functional performance of the design (Matthews et al., 2007).

The use of constraints has also enabled users to overcome the fundamental limitations of analysis with purely mathematical approaches. Employing constraint knowledge has given the designer the possibility of modelling the history and topology of the features, as well as modelling the constraints applied to objects. Constraints provide declarative descriptions of important requirements relating to approaches for: planning, scheduling and as an analysis tool. Constraint approaches have proven successful for the production of process plans for manufacture (Ding et al., 2005) and assembly of components (Rajan and Nof, 1996). It has also been successfully employed for collision free motion planning for robots and manipulators that are employed in modern production lines (Gaber and Lin, 2002). The constraints give the user knowledge of the acceptable manufacturing sequence. In the case of motion planning they offer knowledge of what is obtainable from the robot or manipulator. As with process planning constraint-based approaches have proven successful for a variety of scheduling problems, such as batch and job shop work (Li and McMahon, 2007). The constraints in scheduling give the knowledge of the manufacture sequence, as with process planning, and the inclusion of further constraints relating resource allocation, time bounds and manufacturing safety, allows the engineer to understanding the wider issues of the manufacturing problem.

In providing manufacturing support, a diverse range of problems have recently been addressed by employing constraint-based approaches to assist and solve manufacturing issues, for example this can allow the engineer to investigate capability and capacity envelopes of processing equipment (Matthews et al., 2006). Knowledge

of the constraints can assist the production engineer to find good manufacturing set-ups and processing conditioning (Krishma and Rao, 2006), They aid engineer in the over-constrained area, of plant layout for processing equipment (Kopcke et al., 2006), or space saving ways of packaging product (Shen et al., 2005). For human machine interaction with machines within an industrial environment, constraints-based approaches are being employed to simulate the human operation of processing equipment (Mitchell et al., 2007) to aid designers and manufacturers in the conformance to new legalisation.

2.2 Constraint networks and graphs

A constraint-network is an assembly of constraints that are interconnected by virtue of sharing variables (Lin and Chen, 2002). Constraint networks are useful tools and have been employed in a variety of engineering applications. Hashemian and Gu (1996) employ constraint networks to model the downstream aspects of the design process (product maintenance, recycling and disposal), so that such information can be employed effectively during the embodiment design activity. The developed constraint-based system takes functional requirements of a product and other concerns about its potential life cycle and models them as constraints. Munlin (Munlin, 2001) developed an approach based on constraint relationship graphs, to maintain dependency and allowable motions for 3D manipulation and assembly in virtual environments. Deng et al (2000) proposed a generic constraint-based functional design verification model. The verification is achieved by identifying the input and outputs design variables, and employing a variable dependency graph (network), to allow the user to propagate and check the variables against the constraints. Ah-Soon and Tombre (2001) developed a method for recognizing architectural symbols, based on the description of the model through a set of constraints on geometrical features, and on propagating the features extracted from a drawing through a network of constraints. The constraint network approach offered the authors the possibility to incrementally building and updating the model, if new symbols were required. In the area of microprocessor design, Ozturk et al (2006) demonstrated that it was possible to use a constraint network based formulation for the problem of code parallelization for chips. They showed the approach was effective as it outperformed all other parallelization schemes tested in their experiments. There is also a large body of research that has concentrated on the algorithms employed to check the feasibility of

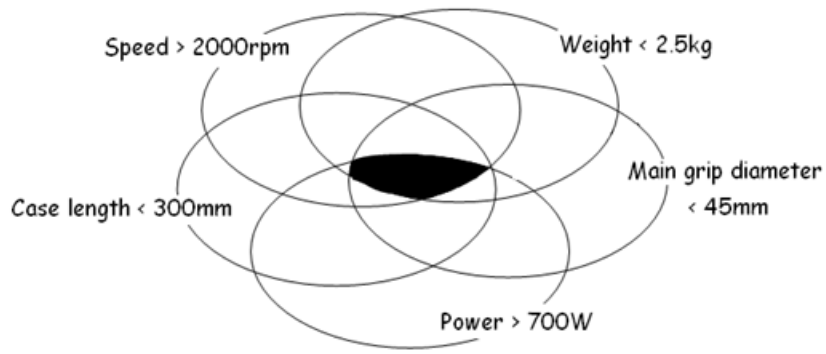
the derived constraint networks such as Baget and Laborie (2006) and Detcher (2003) being two examples.

2.3 Literature overview

Across design and manufacturing and the emphasis of much of the reviewed constraint-based research is directed towards the constraint-resolution techniques and their specific algorithms. However as constraint techniques are fundamentally based upon problem solving techniques, there is a need to select the solution approach to represent the form of the problem being addressed. Whilst some problems have clearly defined objectives through a tight specification, other may be vague and rely upon the finding of a ‘satisfactory’ solution that meet a range of possible needs. In extreme conditions the design may not be the goal but solely a means for using a resource, facility or set of skills. The objective may be to create a new market or change the way a commodity is viewed or distributed. There is thus still much scope for research into understanding of the nature and form of problem being addressed, before solution approaches can be rationalised.

3. Research approach

The constraint resolution approach to product development is thus based upon these fundamental concepts of problem solving. In simple terms the problem is specified by a collection of objectives, defined in terms of problem rules, which need to be true if the problem is to be solved. These rules can specify all aspects of the problem from mathematical relationship, parametrics of geometry, including manufacture and economics, to even a ‘wish’ list. If we considered the power drill example described earlier, the design constraints relating to power and ergonomics can be represented by the Venn diagram (figure 1) where the goal is to find a workable solution that satisfies all the imposed constraints. This solution is then represented by the intersection of all the individual constraint fields.



A workable solution lies at the intersection of all the individual constraints

Figure 1. Constraint rules illustrated as sets

3.1 Research environment and general resolution

For the purpose of investigation a constraint-based environment has been employed, SWORDS (Mullineux, 2001). To investigate the effects of and to resolve the constraints the constraint modeller uses penalty functions; the squares of constraint relations are effectively added into the objective function to reduce the problem to one of unconstrained optimization. If there are n variables x_1, x_2, \dots, x_n involved in m constraints. These are denoted as follows.

$$F_j(x_1, x_2, \dots, x_n) = 0 \quad \text{for } 1 < j < m \quad (1)$$

Inequality constraints can be handled within equality constraints using a “ramp” function. For example take the constraint:

$$x + y < z \quad (2)$$

can be represented by:

$$\text{ramp}(x + y - z) = 0 \quad (3)$$

where,

$$\begin{aligned} \text{ramp}(u) &= u \quad \text{if } u \geq 0 \\ &0 \quad \text{if } u < 0 \end{aligned}$$

An objective function is then formed by taking the sum of the squares of these constraints as shown.

$$F(x_1, x_2, \dots, x_n) = f_1^2 + f_2^2 + \dots + f_m^2. \quad (4)$$

During resolution, the expression for each constraint rule (within a function) is evaluated and the sum of their squares is found. If this is already zero, then each constraint expression represents a true state. If the sum is non-zero then resolution commences. This involves varying a subset of the design parameters specified by the user in a search for a zero state. The sum is regarded as a function of these variables and a numerical technique is applied to search for values of the parameters, which minimize the sum (Mullineux, 2001). If a minimum of zero can be found then the constraints are fully satisfied. If not, then the minimum represents some form of best compromise for a set of constraints, which are in conflict. It is possible at this stage to identify those constraints that are not satisfied and, where appropriate, investigate whether relaxing less important constraints can enable an overall solution to be determined.

3.2 Network generation

Once the design team has specified the design requirements for the product, they are formulated into the constraint rules for the network. These rules take the form of equalities and inequalities. All variables related to each requirement are also formulated against each constraint rule. An investigation can be then undertaken to form clusters of rules that related to individual technical aspects of the problem being addressed. Each cluster being the constraint rule(s) and its respective variables. These can then be assembled into a network that could be solved interactively within the constraint modelling environment. The resolution of these individual clusters, thus forms the conjunction of the sub-problems and hence together provide the total proposition of all of the rules that must be true. In general terms they can be seen to form a complete network in which every rule is considered to be influenced by changes in every design variable (cf. Figure 2).

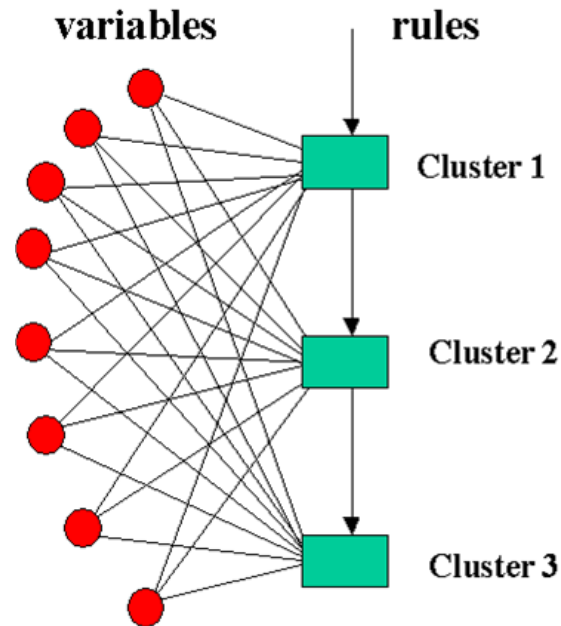


Figure 2. Constraint network

However within this class of problem the network may be simplified or ‘unravalled’ to form a network in which the variables have the minimum of interaction with more than one cluster. This is achieved by studying the occurrence of the individual design variables in each cluster of rules or by the studying of the sensitivity of each variable upon the total truth of the network. Variables used within only one cluster can then be handled as though ‘owned’ by that cluster, whilst those used within two or more clusters must be ‘shared’ and the value made common between the various clusters. The resulting structure allows the problem to be divided up and handled by solving the individual clusters, with ‘shared’ variables being reflected across the net to ensure that they are maintained at a common value in each sub-problem. This approach has been formalised into 5 phases:

1. Design requirements
2. Rule and network generation
3. Network clustering
4. Solution evaluation
5. Design and manufacture

This approach is presented graphically in the flowchart figure 3.

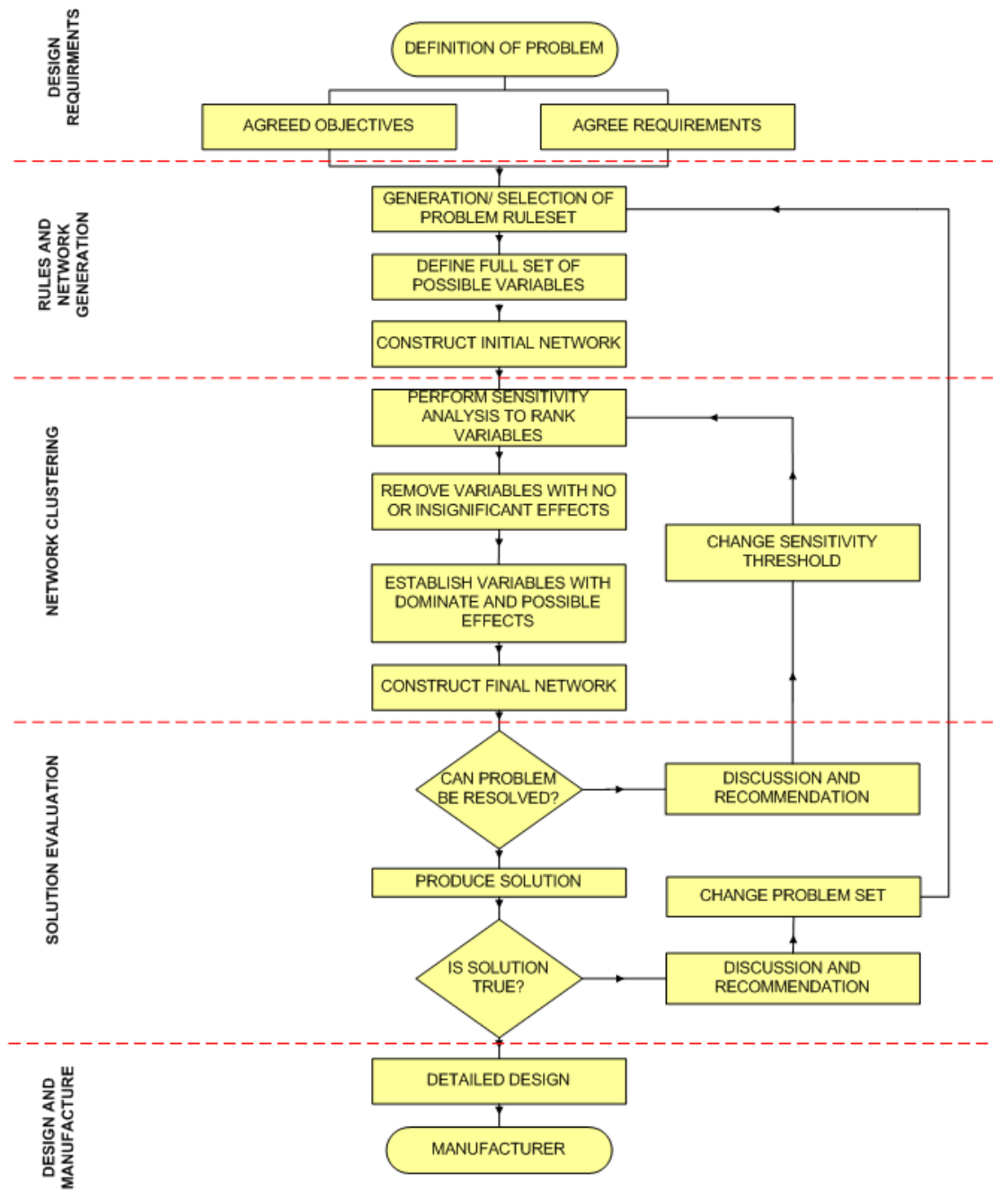


Figure 3. Approach flowchart

The principle of this approach (cf. figure 3) has been demonstrated through the following case study based upon a real design problem.

4. Product case study

This paper draws upon the experience of designing a disposable cell counting device for medical applications and illustrates its adaptation to other applications through the use of the derived constraint-net.

4.1 The product

In a recent study of methods for the automation of the analysis techniques of medical samples a new approach was proposed. Here the diluted sample had previously been prepared and fixed upon a slide for manual scanning and analysis upon a microscope. The new approach was simplified by the process of marking the cells to be counted with the appropriate antibodies. These were then laid upon a membrane for automatic scanning and counting by an optical recognition system. Other objectives of this new approach was to simplify the requirements of sample preparation (by removing the highly skilled laboratory activities involved in slide preparation) and to ensure that contamination of the sample or the operator could not occur and so allow the sample preparation to be performed outside of a sterile environment. These would allow the method to be much more portable and be undertaken outside of the clinical environment of a hospital.

4.2 Design requirements

After extensive investigations of the requirements, the needs of the users and the cost implications, it was decided that a solution would be sought that was based upon a disposable device. Here fluid would be metered into a chamber in the disposable device and passed through to lay the cells upon a membrane for analysis. Upon completion of the test the cells would remain upon the membrane and the fluid passed into a holding reservoir built into the device. A number of requirements were thus set for the overall design of the device, as follows:

- a. The device should be compatible with a normal microscope in order that, at any time, the device can be removed from the automatic analysis equipment and mounted upon a microscope for manual comparison and verification.
- b. The region above and below the membrane must be optically clear so as to not distort or reduce the optical images.
- c. The membrane must be sufficiently flat as to lie within the depth of field of the microscope and the analysis instrumentation.
- d. The porosity of the membrane must be sufficient to allow the fluids through whilst capturing and presenting the cells desired for analysis.
- e. The membrane viewing area must be sufficient to allow a specified minimum number of cells to be observed to provide a valid test.

- f. The instrument should operate on the minimum number of scanning lines or ‘tiles’ necessary to comply with the necessary scanning area and specified cell numbers.
- g. The reservoir size should be appropriate to allow the maximum volume of fluid to be contained or processing stopped if minimum number of cells is not achieved.
- h. The size and volume of material in the device should also be minimized to provide a cheap and readily disposable item (and to discourage attempts to reuse).

Some of these requirements are seen to relate or control the overall size of the device, some influence the complexity of the analysis instrument (in terms of the numbers of rows and columns of images that need to be taken), others limit the range of image interpretation that can be achieved optically whilst others determine the range of cells and quality of the tests that can be performed.

4.3 Rules and network generation

In order to resolve these individual and conflicting requirements an approach was adopted that was based upon a constraint network. Here the three main aspects of the network were defined and resolved by separate constraint resolution functions.

The first simply defined the reservoir space that would be available to receive the tested fluids. These chambers were designed to sit one at the end and the other below the base of the device. These were thus described parametrically by their width (A_w , B_w), breadth (A_b , B_b) and depth (A_d , B_d). The rule thus defining the available volume (V) was given by the following:

$$\text{RULE}((A_w * A_b * A_d) + (B_w * B_b * B_d) - V);$$

Within the constraint resolver all rules are declared to be true when the RULE equates to zero. Within the network structure any values can be set for a combination of variables and the remainder resolved to create a true state. Additionally all reservoir parameters were set with inequality rules that ensured that a solution would be found with all dimensions that were themselves real.

The next constraint function was set to determine the relationships that would occur between the cells and the filtering membrane. The membrane was described parametrically by its length (D_w) and breadth (D_d), together with the selected cell diameter (J_d). The maximum number of cells in the viewing region of the device (r_{nnc}) was given by the number of cells down the length (r_{ncw}) and across the breadth (r_{ncb}). This was resolved by the following cluster of rules:

$$\begin{aligned} & \text{RULE}(D_w - (J_d * r_{ncw})); \\ & \text{RULE}(D_d - (J_d * r_{ncb})); \\ & \text{RULE}((r_{ncw} * r_{ncb}) - r_{nnc}); \end{aligned}$$

To these were added the probable cell density (pc) on the membrane and the density of the cells in the fluid (pv) in order to calculate likely number of cells (r_{nlc}) and the volume of fluid required (vv). The cell analysis function was thus completed by the addition of two further rules :

$$\begin{aligned} & \text{RULE}((pc * r_{nnc}) - r_{nlc}); \\ & \text{RULE}(r_{nlc} - (pv * vv)); \end{aligned}$$

The volume determined by this function could then be compared with that provided in the reservoir volume calculated in the first function to give the proportion of volume filled (vp) or ,when operating in the opposite direction, to specify the dimensions of the reservoir required.

The final function was set to define the length of optical scanning (I_w) and the breadth (W_b) to ensure that the required number of images could be scanned (r_{nns}), by the calculation of the number of cells in the length (r_{nsw}) and the breadth (r_{nsb}). These rules together ensured that a minimum number of cells would exist within the image region to ensure that a reliable analysis could be undertaken.

$$\begin{aligned} & \text{RULE}(D_w - (I_w * r_{nsw})); \\ & \text{RULE}(D_d - (I_b * r_{nsb})); \\ & \text{RULE}((r_{nsw} * r_{nsb}) - r_{nns}); \end{aligned}$$

Together these rules provided the constraints that were incorporated in various forms of the constraint net described in the following section.

4.5 Network clustering

Within an interdisciplinary project the design may depend upon a number of individual skills and expertise working upon a number of individually designed, but related, elements. As within the medical device example, they were brought together to design and implement the analysis chambers that met the needs of the medical requirement, optical performance and geometric form to allow the constraints of the device to be automatically scanned and analysed.

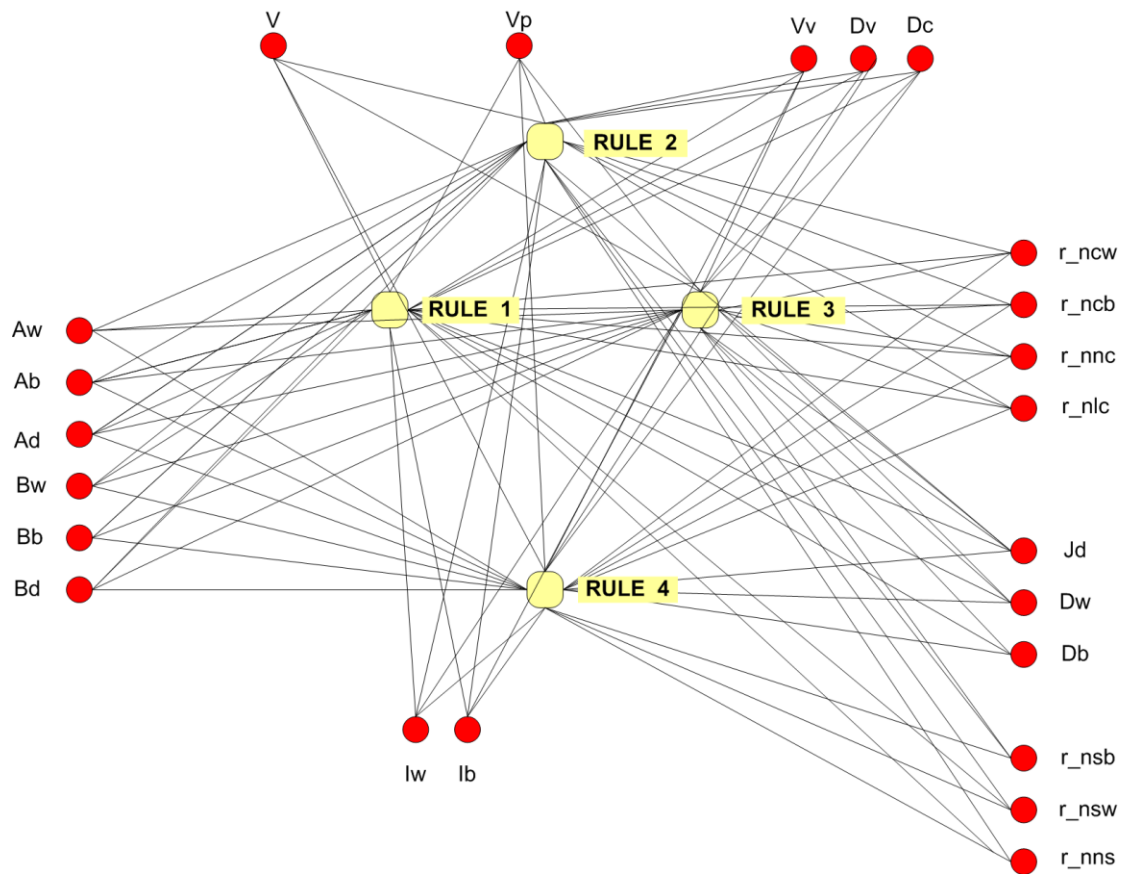


Figure 4. The complete network of interdependencies

Here a cluster of rules was assembled, as shown in Figure 4, which within RULE 4 cluster was to establish the size of the viewing area and the number of separate images that needed to be taken to cover the chosen analysis region. This cluster was in turn related to a separate cluster (RULE 3) that estimated the number of impurities in a given volume were necessary to perform a reliable test. As it was intended that the whole sample remained within the device after testing these rule clusters were additionally related to RULE 1 cluster that defined the available volume of the device and then to one (RULE 2) to check that the scanning and optics was sufficient to

calculates the volume of the reservoir 'V' from the chosen six parameter set (extending from 'Aw' to 'Bd' in the diagram). As the constraint rule structure, incorporated in the SWORDS modelling environment, applies direct search techniques to find a correct values for the variables from the equations given to specify the volume, then by 'fixing' or 'freeing' these variables during the search different objectives can be set and different combinations of parameters found that give a true solution. If all the variables are fixed except 'V' then the volume will be obtained from the geometry of the reservoir. Conversely if the required volume has been calculated then 'V' is known and fixed and one or more geometry parameters can be freed and the changes in these parameters will be made that will maintain the desired volume. Thus, as shown in figure 6, with the volume (V_p) set the truth of the volume in the reservoir (V) and the volume necessary for the analysis (v_v) are determined. The constraint network then proceeds to manipulate the reservoir parameters to make the RULE1 cluster true. Similarly the parameters controlling the cell analysis (in RULE3 cluster) and then the optical scanning parameters (in RULE4) are manipulated until all rule clusters are true. In addition to ensuring that each rule set is true, the search ensures that each parameter does not exceed the maximum set, in order to ensure that, for example, the reservoir will fit within the space of the microscope viewing platform.

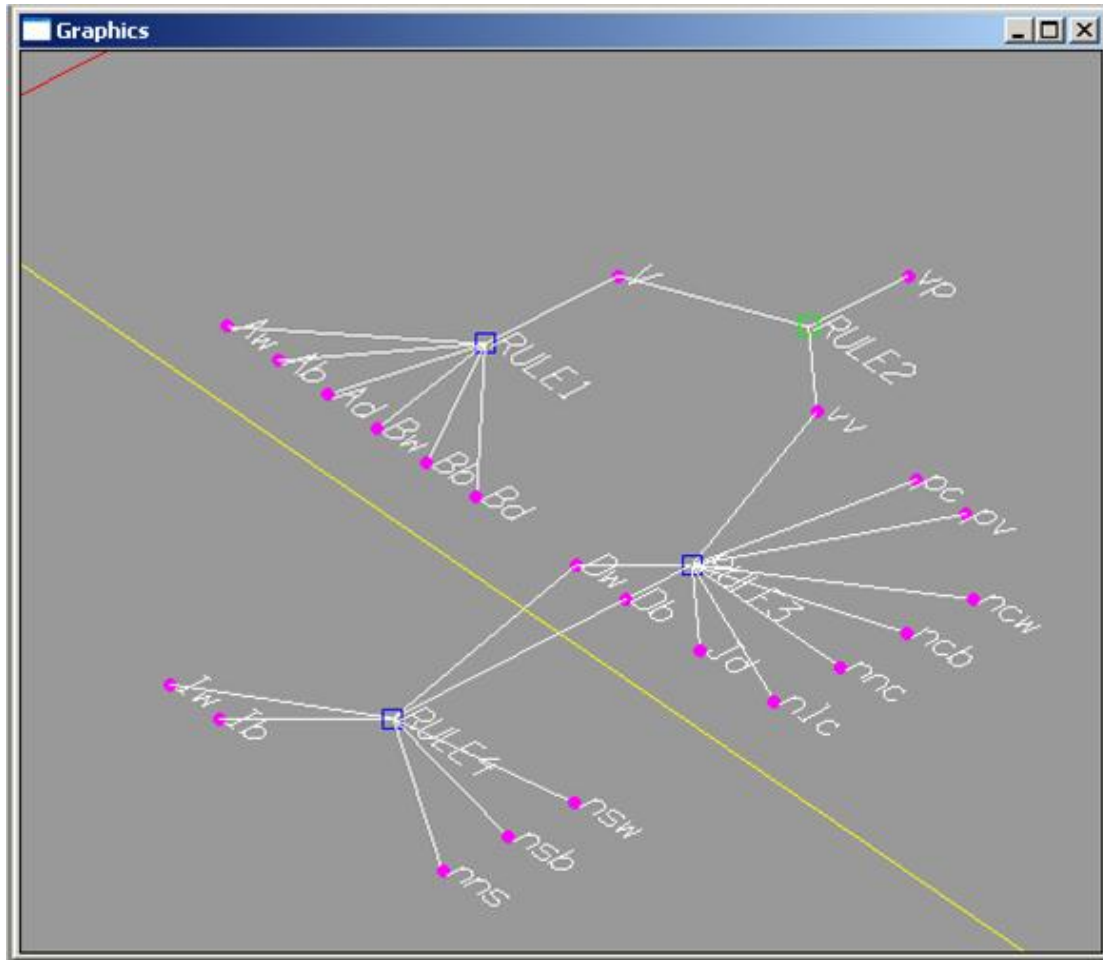


Figure 6. Network of rule clusters and device design.

By selecting various starting parameters in the network (and fixing then) different layouts of the device were investigated. By selecting a single line of cells (by setting I_w to 1) a long single line-scanning device could be considered. The viewing length could be reduced by incorporating multiple line-scanning, with the necessary increase in machine complexity to provide a traversing facility and reversing capability between the lines.

Similarly the width and deformation of the filter membrane was also considered together with the density of cells placed upon it. This was undertaken through experiments conducted with a number of membranes made from different materials, of different thickness and hole densities. From these experiments the optimum size of membrane and cell density was determined.

The preferred number of cells upon the membrane (to give the highest confidence in the analysis) together with the dilution determined the overall volume of the reservoir. The various parameters, determining the sizes of chambers let into the base of the device were then manipulated to allow that size to be achieved without restricting the viewing region or making the device too large.

4.7 Design and manufacture

This approach process ended in the successful development of the product that met all of the requirements. The developed device allowed all aspects of the cervical smear test to be conducted within a single device, that could be mounted both within the electronic scanning vision device, and also be manually checked when used in a manual microscope. The final device was as shown in figure 7b, with the analysis section shown in the slit in the circular assembly section and the first reservoir chamber situated to the right. The photograph (cf. figure7b) shows the prototype optical scanning device using a vertical scanning system mounted above a set of three-axis linear slides. This allowed all aspects of the scanning to be independently studies, including line length, gap between lines and automatic searching for depth of field. Samples of the cervical cells suspended in liquid fixative were introduced into the device using the syringe shown in part b. The device allows the fluid to spread out over the divergence channels, and then settle on the porous membrane held across the analysis slot. Excess fluid passed through the membrane and into the reservoir while the diagnostic cervical cells were retained on the membrane for imaging.

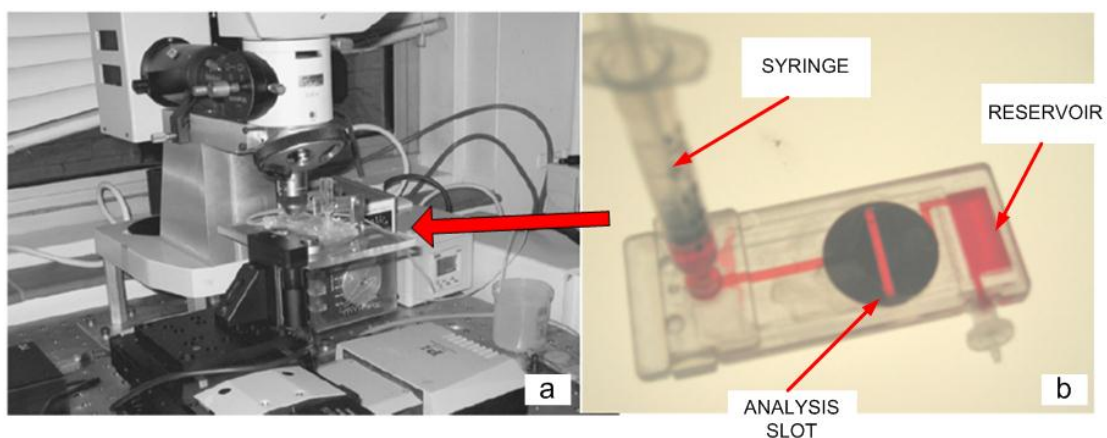


Figure 7. The final product

The study was completed by providing a full and detailed understanding and analysis of the approach that could be used in the design of a commercial system based upon the approach investigated.

5. Conclusions

In the generation of new technological products, such as medical devices complex interactions are found between the technologies being employed, the diverse skills of the design team (spreading from surgeons, through specialist materials scientists and manufacturing engineers, to business partners) as well as technical conflicts within the design of the device itself. Such interactions are seen to greatly increase when the objective is to create a family of products for a wide range of potential applications.

Within such a design team conflicts can often occur as members concentrate upon their individual responsibilities. Here they draw upon the skills and experience of their individual disciplines and can be unaware of potential problems being generated in other areas. It is only when such a conflict is identified by another member that it can be discussed and resolved. An approach based upon constraint networks has thus been investigated to handle such complex interacting design issues. The approach has been successfully demonstrated in the design of a new disposable cell counting device for medical applications that uses antibodies to mark cell that are to be automatically scanned and identified by an optical system.

The main achievements illustrated in this paper were:

- The creation of clusters of constraints to represent individual technical aspects of the problem that included the medical analysis of cells, the optical requirements for cell reading and the engineering of a device that was both disposable and would mount under a standard microscope.
- The formation of individual team members into sub-groups to handle and resolve the issues of the separate clusters.
- The use of a constraint network to investigate and resolve the conflicts arising between different aspects of the problem

- The use of a combined constraint modelling and experimental approach to determine new rules and to resolve them as the investigation advanced.

As discussed in section 2, new directives and regulations affecting the use of industrial processing machines require companies to take greater care and responsibility for the machine operators. Such new legislation, together with an increase in legal responsibility for operator safety, has made it necessary for companies to demonstrate that they have taken all due care in insuring the safety of their machines and manufacturing environment (Mitchell et al., 2007). Simulation using constraint-based human modelling is being used to investigate these interactions between human and machines, the approach demonstrated in this paper is currently being employed to overcome the conflicting requirements for the interaction with the machine, legislation constraints and the ‘natural posture’ of the constraint derived models.

Acknowledgements

The work reported in this paper has been supported by a number of grants for Engineering and Physical Sciences Research Council (EPSRC), Department of Trade and Industry and Department for Environment Food and Rural Affairs and the Food Processing Faraday Knowledge Transfer Network, involving a large number of industrial collaborators. In particular, current research is being undertaken as part of the EPSRC Innovative Manufacturing Research Centre at the University of Bath (reference GR/R67507/01). The authors gratefully express their thanks for the advice and support of all concerned.

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