Development of a system for the prediction of screen printed halftone densities.

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Abstract.

The majority of the scanning and film production for the screen printing process has tended to use standard lithographic calibration curves. These calibrations do not suit the graphic screen printing process, particularly at higher screen rulings, where mid tone and highlight dot loss is common. A comprehensive set of press experiments were used to establish the effect of the primary press parameters on halftone reproduction. These experiments produced vast amounts of data which was difficult to interpolate for different press conditions. In order to combine the results a software tool was developed for the prediction of halftone densities for the graphic screen printing process such that the film positives can be produced to extend the tonal range on the process. This paper describes the formulation of the algorithms and process models used to combine the experimental data, validation studies of the software algorithms and finally the development of software package which can used to improve quality and reduce down time. The concept developed can be applied to any printing process for which sufficient data is available.

1. Introduction.

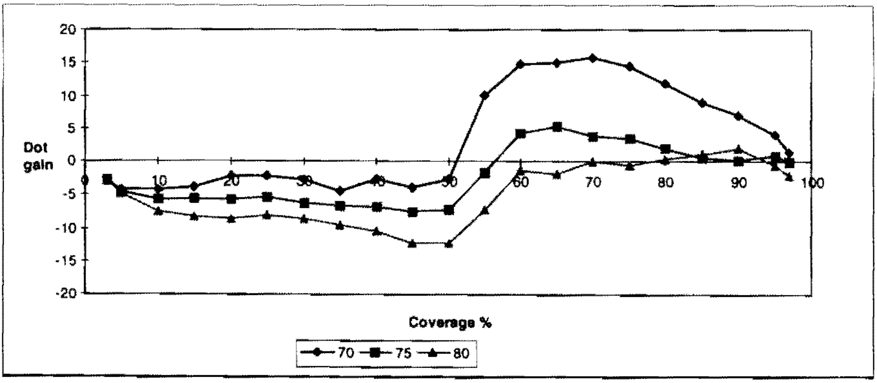
The screen printing process can produce a wide variety of printed halftone densities, changes of ink, substrate, stencil and press settings can vary the dot gain by up to 40%, from dot loss to substantial dot gain, ref [1, 2 & 3] . As the industry targets higher screen rulings and improved colour agreement with the other print processes a system for accurately predicting the tonal reproduction becomes increasingly important. This paper describes the methodology employed in developing a system to provide accurate predictions of halftone densities. The system offers the following advantages :-

1. Prediction of the effect of changes in operating practices, supplier or uncommon jobs on halftone printing without costly print trials.
2. Setting of operational tolerances, such that process control is applied to the most important factors and the press operates in its most stable regime.

3. An off press educational tool for press operators.
4. The development of this tool has also raised awareness of the need for industry to compensate halftone separations for screen printing press parameters and improve process control on the presses.

The large number of parameters which are known to affect the printed halftone density required the investigations to be carried out in a controlled and logical manner. The initial experimental method chosen to accomplish this task utilised orthogonal arrays which allowed a wide range of parameters to be investigated quickly, and a ranking of dominance to be obtained. Having found the dominant parameters and interactions these can then be investigated in a series of smaller orthogonal array or full factorial experiments.

The objective of these experiments was to obtain an understanding of the process physics involved in screen printing. A typical example of the experimental data obtained from the trials is shown in *Figure 1(a)*, which is the average tone gain curves for 3 squeegee angles. However these show characteristics tone gain curves which are also a function of the press type, ink type etc. In order to eliminate the need to develop unique curves for each set of experimental conditions, the influence of the parameter is best considered in terms of its effect on the tonal gain curve by calculating the difference between each of these curves, *Figure 1(b)*.



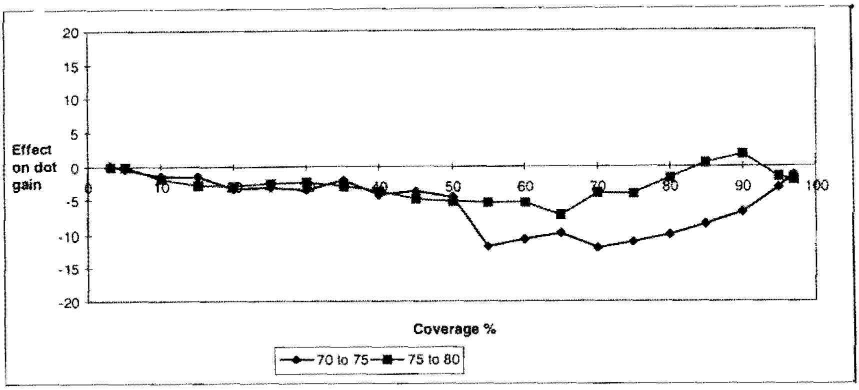


Figure 1 : (a) The effect of squeegee angle on halftone ink transfer & (b) the difference between each of the levels set.

By the end of the trials the effect of each of the process parameters listed in Table 1 had been obtained. While these provided a great insight into the process, for the results to be beneficial to the screen printing community, there was a need to develop a means of combining them to enable the prediction of ink transfer. Thus a predictive software package was developed as a tool for the screen printing industry. The initial step in this procedure was to formulate a generic model which could be used to describe the effect of many changes on a process using an experimental and theoretical database.

Table 1: Parameters investigated in the experimental trials.

Press speed (cylinder press)	Stencil quality (all ink types).
Squeegee speed (Flatbed press)	Screen ruling.
Snap off gap.	Ink thinning (all ink types)
Squeegee angle.	Mesh Tension.
Peel off angle (Flatbed press)	Dwell time.
Ink type.	Squeegee elastic properties.
Mesh Ruling.	Squeegee geometry.

2. Process model formulation.

2.1 A Generic process model.

The printed density prediction is based on a cumulative effect model where the total change in ink transfer may be calculated from the sum of the effect of the individual parameters and the sum of the effect of the interactions, i.e:

$$Total effect = \sum_{1}^{n} parameters + \sum_{1}^{m} interactions \quad (1)$$

where n is the total number of parameters changed which show no interaction (strictly, this is specified as only a small or an unknown interaction) and m is the number of parameters changed which have at least one major interaction with another parameter. An interaction exists between two parameters (A & B) when a change in the value A when B is set at one level produces a different effect to that experienced when B is set at another level. An example of this may be in the way that one ink reacts to a change in stencil type compared to another, *Figure 2*.

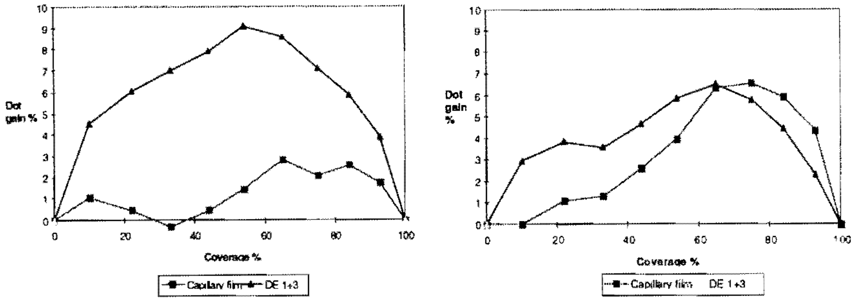


Figure 2: An example of an interaction between two parameters as shown by the difference that changing stencil type has on two ink types.

This cumulative effect model has a number of advantages over a model which considers all the parameters as a complex interacting system. It always allows a solution to be obtained, without excessive computation associated with multi recursive or neural network techniques and it allows new parameters and interactions to be included without a fundamental change to the solution structure or a complete new set of experimental trials to be carried out. If more information needs to be added to the database, such as a new squeegee design or ink type, then it may be added package database easily. The parameters for which the interaction is known, either from print trials or numerical models, are shown in *Table 2*.

Table 2 : Parameters which have been found to have a considerable interaction.

Ink type	Stencil type
Squeegee design	Print speed
Ink type	Ink thinning

The predictions carried out by the model are all relative to a specified fingerprint curve i.e the dot gain obtained under a specified set of conditions, i.e the press fingerprint It does not calculate the halftone reproduction expected under a given set of press conditions, instead it concentrates on the change in halftone reproduction when a press condition is changed from the standard specified operating conditions.

2.2 The database structure and interpolation.

The program database is split into main 3 areas which represent common variables, flat bed printing and cylinder press printing. In addition each press type is split into three sub areas which corresponds to the 3 primary ink types. This choice was made as the experimental print trials had found, that above all, the ink type, and hence rheology, is the dominant factor in determining the ink transfer, *Figure 3*.

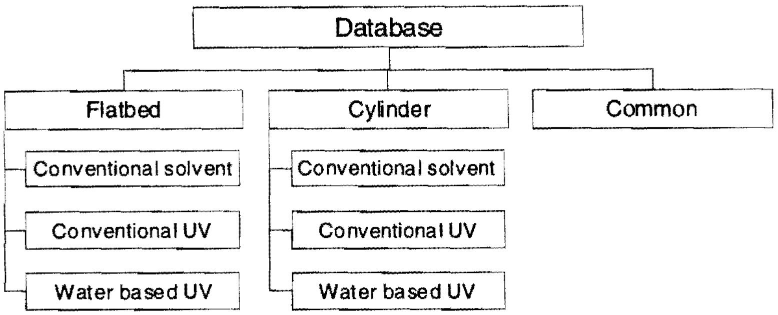


Figure 3: The database structure employed in the model.

The extrapolation and interpolation is linear in nature throughout the model. Other interpolation routines, such as quadratic and spline fitting, were found to be highly sensitive to the numerical values of both the required parameter and the reference values. When the parameter has a continuous numerical value, such as production speed or mesh tension, the package uses the parameter's gradient from the parameter database to interpolate and extrapolate the effect of a parameter on halftone reproduction. Consider *Figure 4*, which shows the effect of changing mesh tension on halftone reproduction at one tonal value where capital letters represent the reference values and small letters the user values.

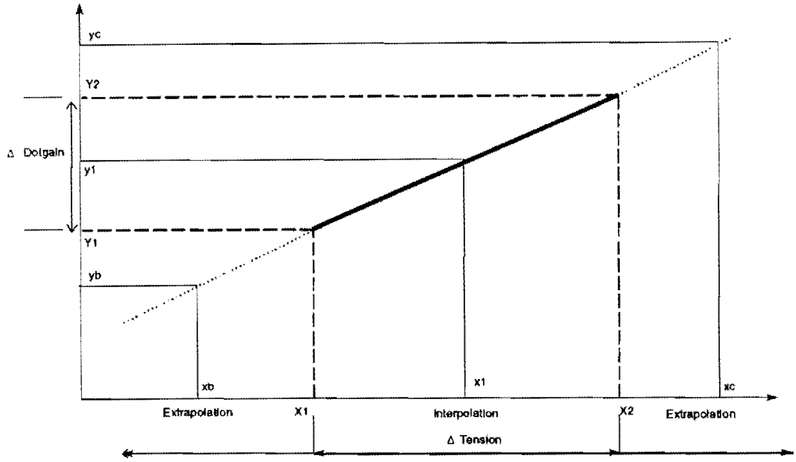


Figure 4: The linear interpolation and extrapolation used to determine a change in a continuously variable parameter.

The dotgain ,y_a, at any interpolated tension, x_a, may be given by:

$$y_a = \frac{\Delta dotgain}{\Delta tension}.(x_a - X1) + Y1$$

Similarly the dot gain in the extrapolated regions (x_b, y_b and x_c, y_c) may be calculated by:

$$y_c = \frac{\Delta dotgain}{\Delta tension}.(x_c - X2) \qquad and \qquad y_b = \frac{\Delta dotgain}{\Delta tension}.(x_b - X1) + Y1$$

Where the experimental data allows more than two levels to be used, a correct interval is found and the appropriate linear interpolation is carried out. When a parameters' "value" is available at only discrete settings, such as squeegee type or stencil type, it is not possible to predict a change in dot gain due to the gradient of the curve, since the ordinate is not continuous, and therefore a gradient cannot exist. In this situation the net change in dot gain when moving from one setting to another is used, *Figure 5*.

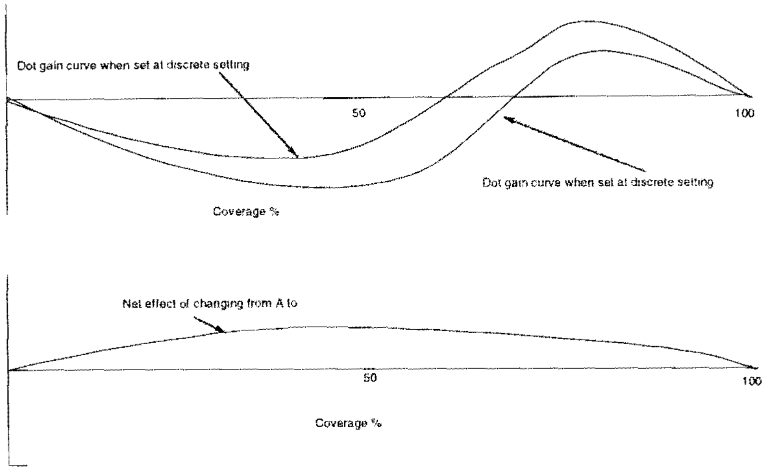


Figure 5: The method used to establish the difference in dot gain when the parameter is available only at discrete settings.

Interactions are dealt with in a similar manner to the non interacting parameters, only that the interpolation is carried out in two directions. When one of the parameters is available only at discrete values the interpolation and extrapolation is a mixture of the gradient and the net effect described above.

2.3 Modelling the role of squeegee.

One of the more tasking aspects of developing the model was creating an algorithm which would model the role of the squeegee in ink transfer. The role of squeegee is to push the ink through the mesh to the substrate and it is often used to control the density of the print through the application of increased pressure to the squeegee . There is however an interaction between the squeegee geometry, squeegee material, squeegee angle and squeegee pressure, *Figure 6.* As the squeegee is generally based around a compliant polyurethane product, an increase in the load applied to the squeegee results in squeegee deformation and bending with a subsequent change in squeegee - mesh contact angle. The degree to which the squeegee deforms and bends is a function of the squeegee material and geometry. Long thin squeegees are more likely to undergo distortion while shorter thicker squeegees are less likely to distort.

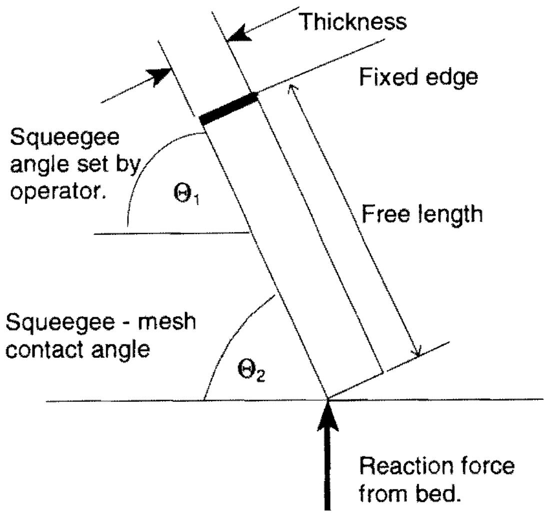


Figure 6: A schematic of the parameters which influence the squeegee's behaviour under load.

In the initial trials the squeegee parameter interactions were eliminated so the squeegee angle and pressure could be considered as a discrete parameters by mounting a rigid (4 mm thick) steel section behind the squeegee. Increases in squeegee load therefore resulted in squeegee tip distortion, with the contact angle being equal to the angle set at the top of the squeegee. The squeegee angle was found to be a dominant factor in determining ink transfer, with ink deposit increasing as the squeegee angle moved closer to the horizontal. This investigation also found that the ink transfer would be approximately equal if the ratio of squeegee pressure to squeegee material elastic modulus was constant. i.e a squeegee of modulus x subject to a load y would perform ins a similar manner to a squeegee of modulus 2x subjected to a load of 2 y.

However, as most screen printers do not use a steel reinforced squeegee, in order to be of practical use a relationship between the applied conditions at the squeegee holder and the resultant detailed conditions at the squeegee tip had to be established. As the squeegee is a well defined mechanical system, it was feasible to use an extensive series of numerical finite element simulations to obtain the relationship for all types of squeegee and all operating conditions. This was far quicker and enabled a more comprehensive investigation than in this relationship had been established experimentally.

The algorithm which ties the interaction between the squeegee parameters and the contact angle makes use of a database created from over 600 finite element models of squeegees subjected to bending. Each model consisted of 144 (168 for the steel backed squeegees) 8 noded elastic elements with the element density being focused on the tip of the squeegee. The geometry, loading and constraints considered are given in *Table 3*, where the tri layer squeegees represent a 90 shore centre sandwiched between the relevant material. Analysis of the finite element models found that the action of the load on the squeegee results in squeegee distortion by two mechanisms; squeegee bending around the point of contact with the holder and localised tip deformation at the point of contact with the substrate, *Figure 7*. Tip deformation is dominant at low squeegee length thickness ratios and at squeegee angles of incidence closer to the vertical while bending is dominant at high squeegee length / thickness ratios and shallower angles of attack. As the squeegee contact angle was found to be a dominant factor in determining ink transfer, then a method for determining the change in contact angle as a result of bending was required.

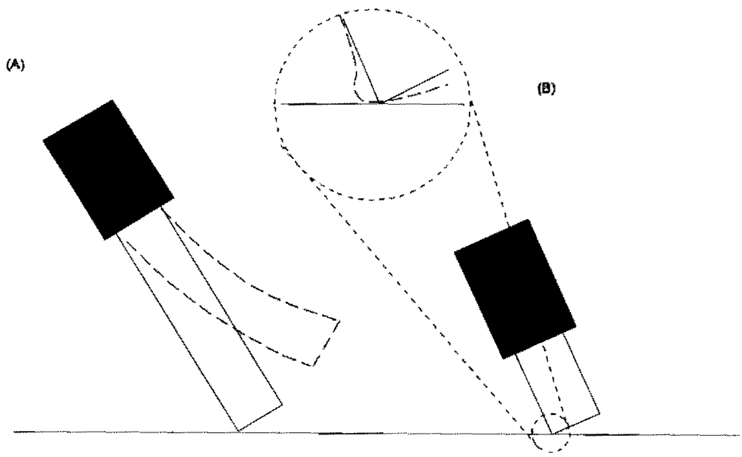


Figure 7: The two extreme forms of squeegee distortion under the action of a vertical load.

A flowchart outline of the algorithm used is shown in *Figure 8* and is discussed below. If any parameter relating to the squeegee is changed then the effect of this change is then calculated as the effect of the change in angle between the "new" and "old" contact angle. If the squeegee distortion is dominated by squeegee bending then the relevant contact angle is calculated by interpolating between the correct data points in the database array. If the squeegee is dominated by tip deformation (i.e it is stiff) then the contact angle is assumed to be equal to the set squeegee angle.

Table 3 : The details of parameters investigated in the squeegee modelling investigation.

Parameter	Systems considered.
Squeegee free length.	30 an 50 mm
Squeegee thickness.	5, 7 and 10 mm.
Set squeegee angle.	60, 65, 70 and 75 degrees from the horizontal.
Squeegee material / design.	65 Shore, 75 shore, 90 shore, 65 shore tri layer, 75 shore tri layer and 65, 75 and 90 shore squeegees with steel backs.
Squeegee load.	50 N/m to 400 N/m in 50 N/m steps.

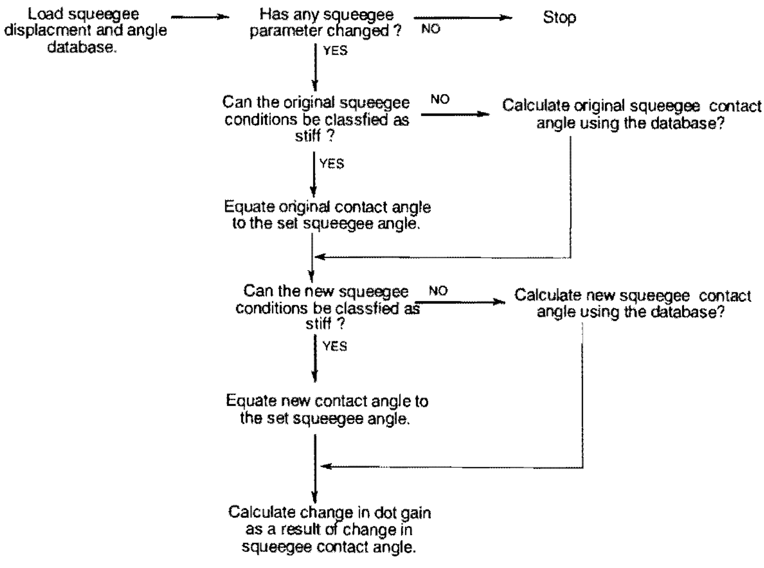


Figure 8 : A simplified flowchart of the method used to model the squeegee parameter interactions.

The squeegee parameter database consists of arrays which hold the contact angle and displacement of the squeegee tip for every load, angle, length, thickness and length in the range considered. Implementing this algorithm into the overall model required a routine which interpolates in 4 dimensional space. This is carried out using a biasing technique which weights the four parameter coefficients around the specified point based on the inverse square of the distance from the point.

This algorithm described to calculate the interaction between the squeegee parameters only considers the effect of changes on the squeegee contact angle. While this has been found to be a dominant process variable, it is also known that changes in the squeegee tip deformation can also have an effect on the ink transfer. Generally for a squeegee which is dominated by tip deformation, an increase in load applied to the squeegee, results in an increase in the level of tip deformation and a subsequent increase in the ink transfer. A system which defines a squeegee as "stiff" when deformation is dominant therefore neglects this component of the ink transfer. In practice the definition of a stiff squeegee is made by considering the change in the squeegee - mesh contact angle upon the action of load. If this decreases then squeegee has bent and can be classified as compliant and if it increases it is classified as "stiff"

3. Experimental confirmation of the model.

As with any process model, it is essential that the model is validated by experiment. To achieve this an experiment was carried where a fingerprint tonal reproduction curve was obtained under a set of known press conditions. Changes were made to the press settings and the tonal reproduction curves were measured. The results of this validation experiment are shown in *Figure 9a to 9e*, where the conditions were changed according to *Table 4*. As the ink rheology is a dominant factor a fingerprint curve was obtained for each of the ink types considered.

Table 4 : Press conditions used for model confirmation.

Experiment	Press Conditions.
Fingerprint curve for water based UV ink	Mesh Tension 15N, capillary film, 75 shore squeegee, squeegee angle 75 degree from the horizontal, 100 lpi image, squeegee 50 x 10 mm & print speed of 1500 cph.
1	As water based UV fingerprint but with squeegee replaced with a 90 shore steel backed squeegee and an increase in speed to 2500 cph
2	As water based UV fingerprint but with squeegee moved 5 degrees away to the horizontal, ink thinned by 7% and the speed increased to 2000 cph.
Fingerprint curve for conventional UV ink.	As Fingerprint for water based UV but using conventional UV cured ink and an increase in squeegee load of 30%.
3	As conventional UV fingerprint but with ink

	thinned by 5%, matt substrate, speed reduced to 500 cph and load increase of 10% on a 65 shore squeegee.
4	As conventional UV fingerprint but with squeegee moved 5 degrees away from the horizontal and an increase in load of 40% on a 90 shore squeegee.
5	As conventional UV fingerprint but with squeegee moved 5 degrees closer to horizontal and a gloss vinyl substrate.

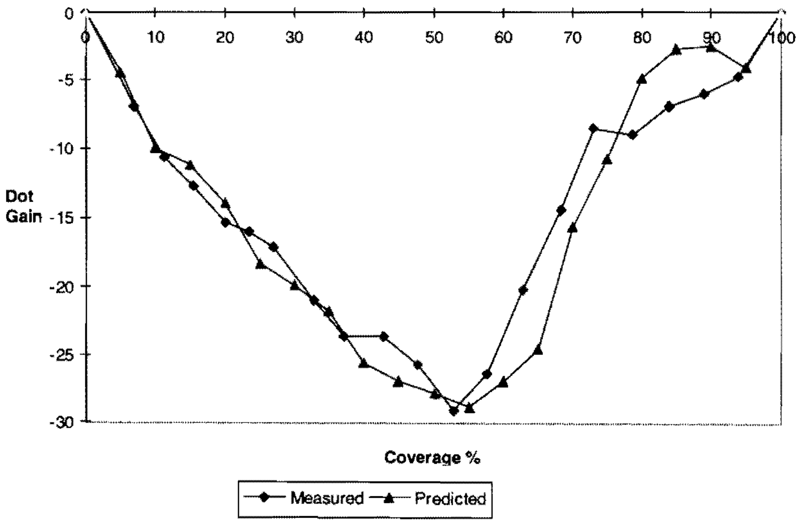


Figure 9a: Experiment 1

The squeegee load was defined as the load reaction load measured when the squeegee arm was placed stationary in the centre of the screen above top dead centre on the cylinder. The load was a fixed displacement type, set using a threaded screw , and was measured using load cells mounted on the linear bearings.

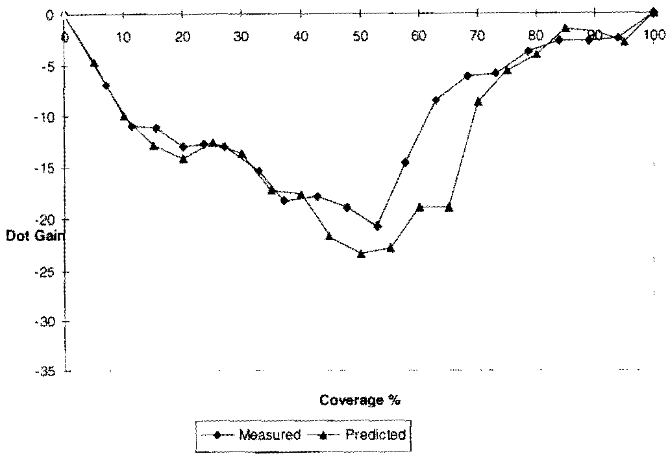


Figure 9b : Experiment 2.

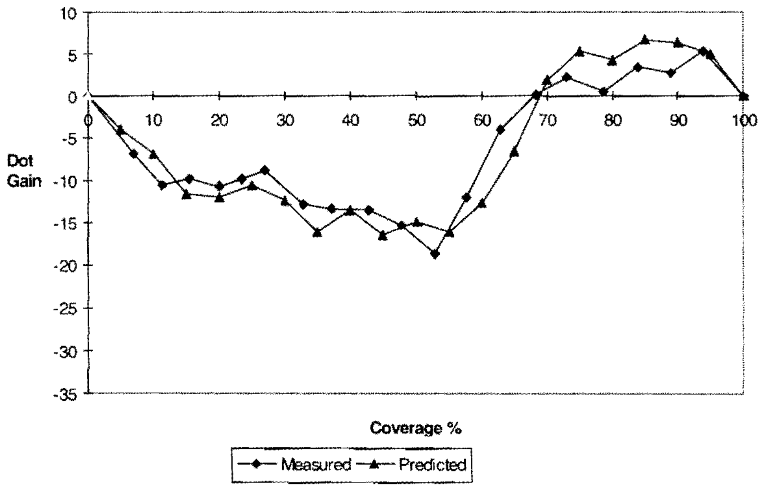


Figure 9c : Experiment 3

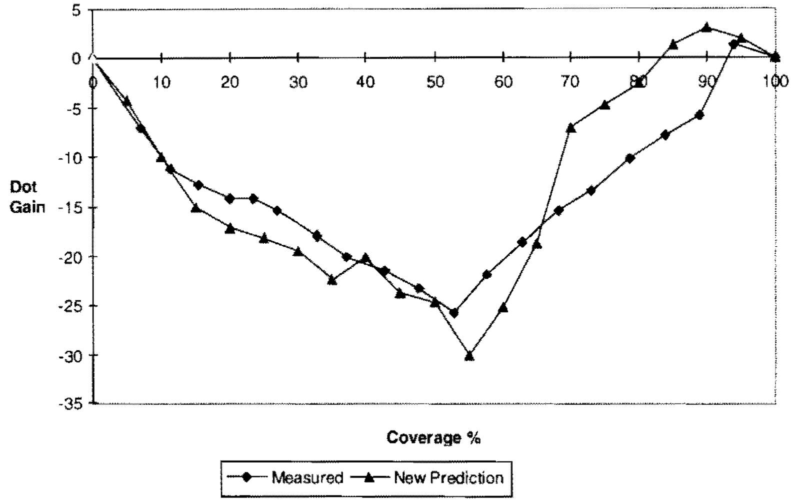


Figure 9d: Experiment 4

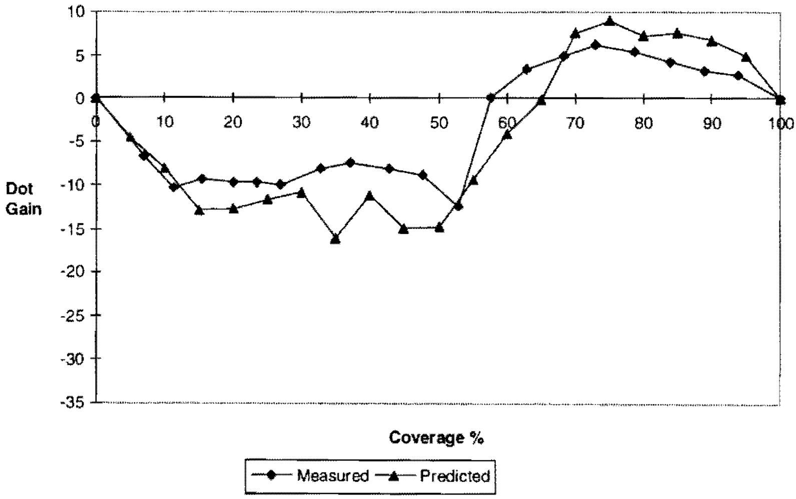


Figure 9e: Experiment 5

Examination of *Figure 9a, 9b and 9c* show good agreement between the measured and predicted tone gain curves. The clearest deviation between these plots lies in *Figure 9b* where there is up to 10% difference in the 50% to 70% coverage level. This deviation is similar to that which exists between the tone gain curve for a square and elliptical dot. As the experimental data was based on elliptical dots, it is likely that this these anomaly may be cured by the production of an accurate method for converting between the dot shapes for all screen rulings. The good agreement observed in experiment 3 (*Figure 9c*) highlights that the validity of the cumulative effect model as a number of changes were made to the operating of the press, yet the overall effect on the dot gain remains sound.

The predictions for experiments 4 and 5 show a greater deviation, *Figures 9d & 9e*, although at worst these are at a maximum of 8%. The deficiencies mentioned in the squeegee model where increases in load on a squeegee deemed stiff does not increase the ink transfer may be the source of the problems in experiment 4. The gloss vinyl substrate used in experiment 5 is approximately twice the thickness of the paper substrates. As the squeegee pressure setting system employed utilised a fixed displacement squeegee any change in this displacement results in a change in load. As the primary discrepancies lie in the highlight region where the loss is over estimated, the discrepancy may be related to the actual squeegee force being underestimated. While these latter predictions are not as accurate, both the predictions gave the correct direction of the change in dot gain relative to the fingerprint dot gain curve. Thus, while not giving the press operator an absolute number with which to compensate the operation of the press, it points them in the right direction.

This first confirmation experiment shows that successful prediction of screen printing ink transfer is an obtainable goal and that there is considerable scope for a methodology such as this although there are some situations where the predictions are not absolute.

4. Developing the model as a printers tool.

Having formulated a system which could be used to predict the ink transfer there was the further problem of providing industry with an easy to use tool. While the system was flexible, it required the user to make changes in the core of the software code to perform any meaningful analysis, something which would require in depth training and understanding, increase the likely hood of mistakes and be time consuming. With this in mind the final step of the next logical step was the development of a flexible software package interface.

The software was developed for the MS - windows and Mac OS operating environments, and although visual differences are apparent between the packages they function and basis are identical. The user interface in its MS - windows form is shown in *Figure 10.* The value of all the press parameters and the fingerprint curve obtained under the specified conditions are set in a data file which is used the package as the user input. This data file can be created in a standard text editor or by using the separate data file creation software. Within the data file, the value of each press parameter is defined using a keyword, e.g. `mesh_tension=17` defines a mesh tension of 17 N / cm.

The flexibility of the software and the ease with which parameters may be changed presented the problem that while any combination of press parameters could be specified, in extreme cases these parameters would not necessarily be compatible or produce a print in practice. To alleviate this anomaly and to improve of the educational nature of the software it was decided that the software be fitted with some degree of "intelligence". The system employed uses a set of rules which tell the user when a combination of parameters are likely to be incompatible. The rules are built on experience and discussion with printers and suppliers.

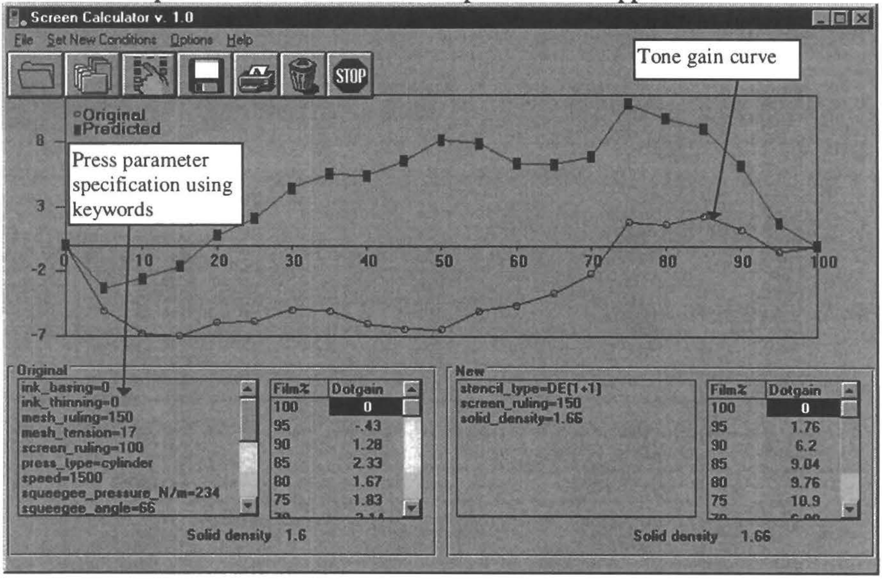


Figure 10: A screen shot of the software operating under the MS- windows operating system.

5. Conclusions.

A process model has been described which has been developed to aid the prediction of halftone densities on ink transfer in the screen printing process. The methodology used in developing the model from a set of experimental results, through to a theoretical process formulation and finally to printers tool has been outlined. This formulation methodology can be used for any process if there is sufficient accurate data available and sufficient understanding of the fundamental process physics.

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References

1. W. Appleton, T.C. Claypole and E.H. Jewell, *"Preliminary findings of the effects of print parameters on dot reproduction in screen printing."* Swansea / Gloscat screen printing project, January, 1995.
2. T.C Claypole, M.F.J. Bohan, E.H Jewell and W. Appleton - *"An analysis of the trials carried out by the UK screen printing colour standards panel"*, Swansea / Gloscat screen printing project, February 1996.
3. W. Appleton, T.C. Claypole & E.H Jewell.- *"An evaluation of the stencil, mesh, ink and substrate interactions in the screen printing process"*, Swansea / Gloscat screen printing project, April 1996.