Integrated Design and Manufacturing Modeling of Performance and Variability for Screen Printed Resistors in LTCC Circuit Technology

by

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B.S., Mechanical Engineering
Massachusetts Institute of Technology, 1995

Submitted to the Department of Mechanical Engineering and the System Design and Management Program in Partial Fulfillment of the Requirements for the Degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

and

MASTER OF SCIENCE (SYSTEM DESIGN AND MANAGEMENT PROGRAM)

at the

Massachusetts Institute of Technology
February 1997

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APR 16 1997
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Abstract

The principles of simultaneous engineering has become the means to develop high quality products through the integration of design and manufacturing domains. Besides higher product quality, the benefits of integrated product development include faster time to market and reduced costs. A modeling based approach to simultaneously design a product and its production process is presented here. Physical based models are combined with statistical analysis to predict product performance and errors. The influence of system inputs from product design specifications, process variables and material properties is examined based upon a sensitivity analysis of the output error. Thus, a designer is provided with the ability of determining major error contributors in the process. The modeling information is used to develop an interactive worksheet tool that reduces the time and the number of design iterations necessary to find robust design alternatives. Furthermore, in-line process control changes are mathematically deployed to reduce overall system variation. A method of choosing which noise errors to be measured as well as which process variables to be controlled based upon the measurements is discussed. Finally, the tool is utilized to estimate the amount of error reduction from such in-line process control changes in different case scenarios. The overall methodology allows simultaneous engineering of the product design steps and the manufacturing processes to increase quality.

Thesis Supervisor: Kevin N. Otto
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Acknowledgments

First of all, I would like to express my gratitude to Professor Kevin Otto who made all this work possible for me. Through his guidance and support, we were able to develop the concepts presented in this thesis which he more than deserves credit for. I also would like to praise his exemplary style with his students that fosters creativity and new ideas.

Secondly, I would like to mention the people at the System Design and Management Program for their contributions to my education here. It was a great experience for me to participate in this new program at its earliest phase. Thanks to the members of Team SDM for their friendship and help at all times.

The students at the Engineering Design Research Laboratory also deserve credit in this thesis for their academic and intellectual contributions.

Finally, many thanks to my family and friends, here and at home.
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Chapter 1

Introduction

1.1 Scope of Thesis

Today many manufacturing firms strive to develop high quality products faster and better than ever to remain competitive in their markets. The need for shorter development times force engineering teams to consider alternative methods to execute design activities. The concept of simultaneous engineering has revolutionized the traditional design process which involved product designers to work independently without the manufacturing engineers. Today, the sequential, over-the-wall product development methods of the past are being replaced by Design for Manufacture (DFM) techniques which integrate the design and manufacturing steps managed by simultaneous engineering teams. The result is often higher quality products which successfully meet the customer requirements. This is achieved by bringing in the production expertise at the early stages of the development process.

Another advantage of simultaneous engineering can be observed from a more organizational perspective. A simultaneous engineering team involves cross-functional expertise that comes from different engineering and management disciplines.
Alternatively, the traditional teams are generally formed in a hierarchical structure which clearly defines roles and responsibilities. The latter is usually more consistent with an emphasis on the individual as opposed to a group. The hierarchical method of organizing the design process makes it very hard to rapidly change product attributes. In most cases, the process has to be started all over in the case of redesign efforts. The simultaneous engineering eliminates specialization and barriers among different functional groups allowing them to transfer know-how for optimal product development.

Yet the approaches used in concurrent engineering often have difficulty with products and processes that are complex and require more than group synergy to evaluate feasibility. The coupling effect of design and manufacturing integration tends to increase the time to bring in the first design (Eppinger et al., 1994). This phenomenon usually depends on the iterative nature of the design process. The overall concurrent design process is still faster than the traditional one that needs many more iterations after the first design is completed. Nevertheless, the number of design iterations and the iteration time are still desired to be reduced to minimize the time from concept to product being delivered off the manufacturing system.

To make the best out of the iteration process, engineering modeling can be used as a means to support simultaneous decision making (Otto and Ho, 1996). The engineering model may involve several submodels which characterize each step of the manufacturing process affecting the quality of the product. Once such a model is developed, the designer can evaluate the feasibility of a design based on the results obtained from the model. Such
a virtual design concept is a very effective tool to reduce the number of design iterations as well as the time to execute them.

The idea of process simulation tools to evaluate design concepts has more applications than solely evaluating design concepts. One major use proposed in this thesis is the use of process models to predict the quality of the product in terms of meeting specification limits. It is introduced in this thesis that engineering models can be used as quality control tools before and during a manufacturing process. It will be shown that effective use of virtual design tools leads to more robust design while reducing development times significantly.

1.2 Essential Simultaneous Engineering Techniques

The increasing requirement of time responsiveness of companies to changing market conditions has caused the generation of many simultaneous engineering methods. Some of these methods have created deep interest in many industries. Rover was able to bring their Land Rover Discovery model into market in 18 months rather than 48-63 months for similar European products. AT&T reported a more than 10% reduction in their part counts and an improvement of one hundred times for VLSI circuits in surface defects. Computer Aided Engineering (CAE) and Computer Aided Design (CAD) methods rather than physical testing provided huge savings for Ford.

Clausing (1993) presented a total quality development approach to product design including robust design. Dr. Clausing pioneered the concept of Quality Function Deployment (QFD) in the United States, implemented at Xerox Company. QFD method,
initially developed in the late 1960s and early 1970s in Japan, is a structured planning tool of simultaneous engineering which can be used to include product attributes based upon customer needs.

Hauser and Clausing (1988) built a translation matrix between the customer requirements and the detailed control of design activities using the QFD concept. This matrix, which is well known as the House of Quality, involved six basic elements: a prioritized customer requirements list, an engineering characteristic list, a correlation matrix of engineering characteristics, an engineering-customer requirements correlation matrix, a customer preference chart, and a technical and cost assessment of allocated resources. Figure 1.1 shows the structure of House of Quality matrix.

![House of Quality structure](image)

**Figure 1.1:** House of Quality structure
Furthermore, Design for Manufacture (DFM) and Design for Assembly (DFA) methods have helped design to be recognized as the initial step of manufacturing. These two methods allowed the establishment of a manufacturing system that permitted the flexibility and the adaptability to modify the design during each step of product development. Boothroyd and Dewhurst (1991) developed time study methods to minimize cost of assembly in a manufacturing system. A set of DFM and DFA guidelines were developed for manufacturing. Some basic guidelines, stated by various authors, can be listed as follows:

- Minimize number of parts.
- Develop a modular design.
- Minimize part variations.
- Design multi-functional parts.
- Design parts that are easy to manufacture.
- Eliminate separate fasteners.
- Design for top-down assembly.
- Minimize part handling.
- Avoid flexible components.

These guidelines provided a baseline for simultaneous engineering. Nevertheless, without the coherent work of an experienced and talented design team, these methods can hardly result in high-quality, low-cost, and easy-to-manufacture products. They must also be applied considering the influence on the market and the customer. If the optimal design and manufacturing configuration does not meet certain customer needs, the next
best option should be developed and this process should be iterated until all the requirements are met.

1.3 Systems Modeling of Variation

Statistical analysis and the concept of random variables has been the most recognized tools used to quantify variability in a system. The application of statistics to design and manufacturing problems can help teams evaluate their designs and processes. A systematic statistical analysis of variation of a product performance can be used to detect sources of error formation. By reducing variation in a system, the product quality can be improved.

Taguchi (1986) introduced the concept of off-line quality control, to make product design changes that make a product more robust. His methods are designed to identify the problems in a product development process at its early stages. The concept of orthogonal arrays for designing the minimum number of experiments is widely used in many industries. Taguchi's Design of Experiments helps designers to select the best design option with minimum Signal-to-Noise ratio, an unbiased measure of variance.

Besides Taguchi methods, there are other variability control techniques that are commonly used. On-line quality control involves placing sensors in the manufacturing work-in-progress stream, and making adjustments to the equipment operating points in response to measured variation. Total Quality Management (Mizuno, 1988) approaches are used in industrial practice to ensure communication and agreement among the different groups in a development team. Statistical process control (Messina, 1987) is used to
monitor system outputs to rapidly detect errors that are signaled by systematic changes in the flow of the production operations.

The basic metric in all of these thoughts is the variability of the product output, represented by variance,

\[
\sigma^2(\tilde{d}) = \int_N \left( f(\tilde{d}, \tilde{n}) - \bar{y} \right)^2 pdf(\tilde{n}) d\tilde{n} \quad \text{(1.1)}
\]

where \( \tilde{d} \) is a product design configuration, and \( \tilde{n} \) is a random state of manufacturing error noises.

In the discrete case, variance is a measure of how a number of individual observations vary about their average. For \( n \) observations, \( x_i \), in a sample space \( X \) with each having a probability, \( \rho_i \), of outcome, the variance can be defined as

\[
V(X) = \sum_{i=1}^{n} [x_i - E(X)]^2 \rho_i \quad \text{(1.2)}
\]

where

\[
E(X) = \sum_{i=1}^{n} x_i \rho_i \quad \text{(1.3)}
\]

\( E(X) \) is called the expected value of the random variable, \( X \).

For an experimental analysis, the expected value of a random variable becomes the average of the individual observations. In that case, the variance can be defined in the following form.

\[
V(X) = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1} \quad \text{(1.4)}
\]
The standard deviation, or standard error, $\sigma$, is simply the square root of the variance. In many applications, $3\sigma$, is used as an acceptable region for product variability. A set of measurements with a $3\sigma$ range means that roughly 99.7% of the individual measurements will fall within $\pm3\sigma$, about the average.

There has been much work to design products that are robust to manufacturing and other errors. Peplinski et al (1996) have developed design methods to explore regions of a design space which are robust. Their Robust Concept Exploration Method was based on a multiobjective decision model that used mathematical programming to determine the values of design variables to achieve a robust design. This method, which was initially developed to generate top-level design specifications, was later applied to manufacturing process design as well. Thus, it was possible to create approximate response surfaces to identify robust regions of a production operation.

Taken one step further, researchers developed the concept of reducing the variation below levels that can be achieved by off-line Taguchi methods. This can be achieved by feeding back real time information on several control variables in a manufacturing system. Otto and Antonsson (1993) introduced the concept of tuning adjustments, and presented design phase models of in-line process control variables that downstream manufacturing systems have to increase quality. Basically, on-line adjustment variables are introduced into the variance equation, and must be internally selected in response to the observed noise variations. The model becomes
\[ \sigma^2(\tilde{d}) = \int \min_i \left( f(\tilde{d}, \tilde{n}, i) - \bar{y} \right)^2 pdf(\tilde{n}) d\tilde{n} \] (1.5)

where \( \tilde{r} \) is now a vector of on-line process control variables, and optimized inside the noise integration for each value of noise observed. This modeling permits a true understanding of the expected variation, and permits product/process design trade-offs (Otto, 1994).

The concept of tuning parameters in design was previously used in case studies. Finch and Ward (1996) implemented the concept into their predicate logic interval mathematics for design. Kazmer et al (1996) implemented the concept in simulation for injection molded parts. A linearized extension of (1.5) was also used to control variability for the LTCC circuit resistors in the context of this thesis.

1.4 Product Design and Manufacturing Case: LTCC Circuits

1.4.1 Multichip Module Technologies

Multichip Module (MCM) is a structure consisting of two or more integrated circuits electrically connected to a common circuit base and interconnected by conductors in that base. The conductors in the base are usually patterned in multiple layers separated by a suitable insulating dielectric material, with vias for interconnections between layers.

Three types of MCM structures exist based on interconnection technologies:

1- MCM-L: These are the modules that use copper conductors on plastic laminate-based dielectrics. Advanced forms of printed wiring board (PWB) technologies are used to form the interconnections in these modules.
2- MCM-C: These modules are constructed on cofired ceramic substrates using screen printing technologies to form the resistor and conductor patterns. This method is also called thick film technology.

3- MCM-D: These are the modules whose interconnections are formed by the thin film deposition of metals on deposited dielectrics, which may be polymers or inorganic dielectrics.

MCM-C technology is the next phase of traditional hybrid circuit technology where screen printed conductors are used to provide the signal interconnections. One early application of this cofired MCM-C structure, with over 30 ceramic layers, was for mainframe IBM 390/9000 high performance computers (Kumar and Tummala, 1991). In this technology, the glass ceramic dielectrics used originally in ink form were later made into tapes. Simultaneous firing of all the layers was then possible at the lower temperatures used in original hybrid circuit technology. This process called “low temperature cofired ceramic” or LTCC technology.

New developments of thick film screen printing emulsions and wires allow fine conductor lines to be patterned on LTCC dielectrics, while at the same time new LTCC dielectrics have been developed with dielectric constants as low as those of the organic dielectrics used in MCM-D. In these ways, performance will soon approach that of MCM-D but at much lower cost.
1.4.2 LTCC Technology

The driving force in the recent developments in the LTCC technology is the combination of high conductivity metals with thick film processing. High Temperature Cofired Ceramic (HTCC) packaging has been common for a few decades. This technique originally allowed increased circuit density, reduced number of interconnects, and shorter conductor lengths. The concept of using “green tape”, unfired sheets of dielectric tape formed from a slurry of alumina powder, glass and other organics, was also introduced with HTCC. However, the conductor materials used to make HTCC circuits bear low conductivity. The LTCC technology allows the use of higher conductivity materials such as gold, silver, and copper that can be fired at lower temperatures. The use of higher conductivity materials is advantageous since higher conductivity results in higher processing speeds.

LTCC circuit production involves a number of sequential operations. These steps are shown illustratively in Figure 1.2.
**Figure 1.2**: Operation flow diagram of LTCC circuit manufacturing.

These steps can be described in more detail as follows:

- Cut the ceramic tape from the roll into desired sizes.
- Drill or punch interconnection vias in the tape for desired circuit design.
- Fill the vias with conductor ink.
- Screen print conductor patterns on the tape.
- Screen print resistors on the desired layers.
- Cut cavities in the layers to allow for packaging features and external device attachment.
- Collate and stack the multiple layers to form a laminate.
- Laminate the layers together.
- Cut the unbaked laminate into the approximate final dimensions.
- Burn-out and fire the laminate.
• Trim the laminate to the final size.

Screen printing, as discussed in the Chapter 2, is used to deposit the components in the form of wet paste on to the ceramic tape also called substrate. A squeegee forces the wet paste through the openings of a screen with the desired circuit design. In this process, there are a number of key variables; the squeegee speed, hardness of the squeegee, angle of attack and snap-off distance. Some other parameters are the screen mesh size, the screen wire diameter, emulsion characteristics and the paste material viscosity. Screen printing machines can be either manual or fed automatically. In both cases, the control of variability to obtain desired component geometry is essential.

After screen printing, a drying process is applied to the components when the material properties of the paste change to desired levels through the removal of organic solvents. Typically, drying occurs at 85°C - 150°C for five to ten minutes in a continuous belt dryer. During the drying process, the circuit attains the required fine line definition. Then the circuit is fired using a conventional furnace equipment. The rate of heating determines how rapidly and how completely the organics are removed from the components. The cooling rate is also important as it can cause thermal cracking. A typical completed LTCC circuit is shown in Figure 1.3.
Figure 1.3: A typical LTCC circuit

The most recent LTCC research initiatives have intended to study the characteristics of resistor screen printing on internal layers of a LTCC circuit (Ho, 1995). The placement of resistors not only on the surface layers but also on the inner layers provides further flexibility to the designers to build compact circuits. However, due to the unavailability of laser trimming for the inner resistors, a better understanding of the technology is essential to produce resistors within specification limits. The focus of performance modeling in this thesis will be on resistance performance of LTCC circuits.

1.5 Thesis Overview

Following this first chapter, Chapter 2 describes the model developed for the LTCC circuit resistors. In three steps, from the screen printing of the resistors to the final
cofiring process, the product and process variables are related such that an integrated resistance model based upon multiple inputs is generated.

In Chapter 3, this integrated model is used to create a user-friendly computer tool to evaluate design considerations. It is described how this tool can be exploited to select a robust design among many design alternatives, also considering the manufacturing constraints in the system.

In Chapter 4, an optimization method to reduce variability is shown based on tuning parameters concept in product design. The mathematical foundation of the tuning parameters to reduce systematic variation is described. Then, the benefits of this concept is discussed with an application to the LTCC system.

Finally, in Chapter 5, conclusions and recommendations are presented.
Chapter 2

LTCC Resistance Model

The first step to model the behavior of a screen printed resistor is to calculate the dimensions of its wet geometry after the printing operation. Subsequently, a model of the drying process should be considered to relate the wet geometry to the dry geometry. Once the dry geometry is obtained, the resistance value of the resistor can be found by a physical relationship among the resistance, the dimensions and the post-fired material properties.

2.1 Screen Printing Process

The screen printing process is widely used to place electronic components onto a substrate. This stage of an electronic circuit manufacturing strongly affects the performance of the end product. The physics involved with the screen printing of components such as resistors and conductor lines require more complex models than the ones for simple solder screen printing. In solder screen printing, the geometry is the main performance measure. However, in the case of component screen printing, the physical performance of the component (e.g. resistance, conductivity) is the major output variable to be controlled. Thus, it is necessary to take into account the changes in the material and
processing parameters in addition to the geometrical dimensions of the component to predict outcome.

In the wet geometry modeling, the thickness is the most sensitive dimension to the screen printing process. The other two dimensions of a resistor, the length and the width can be assumed to be either normally distributed parameters or determined by other simple models. Thus, the following section will only focus on calculating the wet thickness.

A study of the screen printing was conducted in order to find a physical model of the process (Owczarek and Howland, 1990). In this study, interrupted printing tests were used to provide information on the flow pattern in the paste during the deposition process. The squeegee fronts were approximated by a wedge due to their deformation during printing. It was found that the region that extends from the leading edge of the deformed squeegee tip to the beginning of the deformation region had the highest impact on the flow.

Based on this flow model that will be used in the following sections, it was possible to calculate the wet thickness of deposited paste. This is achieved in three steps. The first step involves the derivation of a simple equation for the wet thickness of deposited paste. In the following two steps, the two major variables for the wet thickness equation will be determined from screen printing characteristics. These variables are the equivalent passage thickness and the paste flow speed under the squeegee.
2.1.1 *Wet Thickness of Deposited Paste*

The wet thickness of the resistor, \( t_w \), is directly a function of the screen printing parameters. Figure 2.1 shows the screen printing dynamic geometry and the associated variables.

![Diagram of screen printing process](image)

**Figure 2.1:** Equivalent fluid dynamic behavior during screen printing.

The thickness \( t_w \) is greater than \( t_n \) (where \( t_n \) is the equivalent passage thickness) because of the higher pressure formation ahead of the squeegee during paste flow under the squeegee. The mass continuity equation for the paste flow in a period of time, \( \Delta t \), per unit squeegee width requires

\[
V_w(\Delta t)(t_w - t_n + t_r) = V_p(\Delta t)t_n
\]

(2.1)

where \( V_w \) is the squeegee transitional speed, \( V_p \) is the resistor paste flow speed, and \( t_r \) represents the thickness of the paste residue left on the screen.

(2.1) can be rewritten as
\[ t_w = t_n \left( 1 + \frac{V_p}{V_{sq}} \right) - t_r \]  \hspace{1cm} (2.2)

In this equality, it is possible to obtain the values for the squeegee speed and the residual paste thickness from in-line production measurements. The other two variables depend on further process and product characteristics. Therefore, physical models to determine the two variables are described in the next two sections.

### 2.1.2 Equivalent Passage Thickness

The equivalent passage thickness, \( t_n \), can be calculated from subtracting the volume of the screen wires and the volume displaced by the squeegee from the volume of the screen filled with paste, and adding the equivalent open area thickness in case screen does not contact the substrate. Figure 2.2 shows the screen geometry and the other variables associated with the calculation of the equivalent passage thickness.

Based on the volumetric balance, the following relationship can be written:

\[ (t_o - t_r) L^2 = 2DL^2 - \frac{\Pi D^2 L}{\cos \gamma} - \Delta t_{sq} L^2 \]  \hspace{1cm} (2.3)
Figure 2.2: Screen variables of resistor screen printing.

where \( D \) is the screen wire diameter, \( M \) is the screen mesh count per inch, \( \Delta t_{sw} \) is the average squeegee penetration thickness into the screen, and \( t_e \) is the equivalent open area thickness.

(2.3) can be further simplified to

\[
t_o = 2D - \frac{\Pi D^2}{L \cos \gamma} - \Delta t_{sq} + t_e
\]  

(2.4)

Also

\[
\cos \gamma = \frac{1}{\sqrt{1 + (DM)^2}}
\]  

(2.5)

As a result, the equivalent passage thickness can be written as below:

\[
t_o = D \left[ 2 - \frac{\Pi}{2} DM \sqrt{1 + (DM)^2} \right] - \Delta t_{sq} + t_e
\]  

(2.6)
2.1.3 Paste Flow Speed

Finally, the paste flow speed, $V_p$, can be approximated by the power law based on the volumetric flow rate of the paste that is dependent on the flow area and pressure change at the tip of the squeegee. The flow area furthermore depends on screen mesh and wire size, on the deformation of the squeegee, on the magnitude of the vertical force acting on the squeegee, and on the emulsion thickness and the printed area width. Figure 2.3 and Figure 2.4 describe the variables affecting the paste flow speed due to the deformation of the squeegee.

Figure 2.3: Undeformed shape of the squeegee before printing
Figure 2.4: Deformed geometry of the squeegee during printing

The equation for the paste flow speed under the squeegee is defined as:

\[ V_p = \frac{n}{2(2n+1)} \left( \frac{t_w}{r_p} \left( \frac{P_{sq} - P_{um}}{2kW_w} \right) \right) \] (2.7)

where \( P_{sq} \) is the pressure at the leading edge of deformed squeegee, \( P_{um} \) is the atmospheric pressure, \( k \) is a constant at a given temperature, \( W_w \) is the width of the flat portion of deformed squeegee, and \( n \) is the power law exponent. The power law exponent is from a relationship relating shear rate, \( \dot{\gamma} \), with apparent viscosity, \( \eta \), as determined with a Brookfield viscometer. The power law relationship is:

\[ \eta = k \dot{\gamma}^{n-1} \] (2.8)

which must be fit to experimentation to determine \( k \) and \( n \).

The pressure drop under the squeegee can be expressed as:

\[ P_{sq} - P_{um} = \left( \frac{n+1}{n} \right) \left( \frac{V_{w}}{t_w} \right) \left[ 1 - \left( 1 + \frac{X_{w} \tan \alpha}{t_w} \right)^{-n} \right] - 2n \frac{V_{w}}{n+1} \left[ 1 - \left( 1 + \frac{X_{w} \tan \alpha}{t_w} \right)^{n+1} \right] \] (2.9)
where $X_{sq}$ is the distance from squeegee tip to location where squeegee angle of attack changes to its undistorted value, $\alpha$ is the squeegee angle of attack.

Combining (2.8) and (2.9), the following equation can be derived to give the paste flow speed, $V_p$, used in (2.2).

$$\frac{3}{2} \nu \left( 1 - (1 + \varepsilon)^{-n} - \frac{2n}{n+1} \frac{V_p}{V_{sq}} \left[ 1 - (1 + \varepsilon)^{-(1+n)} \right] \right) = \left[ \left( \frac{2n+1}{n+1} \right) \left( 2 \frac{V_p}{V_{sq}} \right)^n \right]$$

(2.10)

where

$$\varepsilon = \frac{X_{sq} \tan(\alpha)}{l_n} \quad (2.11)$$

$$\nu = \frac{X_{sq}}{W_{sq}} \quad (2.12)$$

The screen printing process is a major contributor of variability in LTCC resistor performance. The existence of many input variables to the process and the complex nature of the way that these variables are related to each other increases the cumulative error in the system. Figure 2.5 shows a representation of input variables and their associated independent variability causing errors on the output variables. It will be shown that the intermediate output variables of the screen printing process are consequently the error contributors to the final resistance of LTCC resistors.
2.2 The resistor drying model

Once the resistor is printed, a drying process is applied at 85°C - 150°C for five to ten minutes in a continuous belt dryer. This step is necessary to transform the material properties of the resistor to desired levels. During the drying process, the resistor reaches its final shape. A mass balance of the drying process requires

$$M_d = M_w \mu_w$$  \hfill (2.13)

where $M_d$ is the dry mass, $M_w$ is the wet mass, and $\mu_w$ is the initial solids weight fraction of the resistor.

(2.13) can be further expanded to

$$LW_{t_{w,d}}d_d = LW_{t_w}d_w \mu_w$$  \hfill (2.14)

where the average dry thickness of the resistor is represented by $t_{w,d}$, $t_w$ is the wet thickness, $d_d$ is the dry density, $d_w$ is the wet density. $L$ and $W$ denote the length and
width of the resistor. Assuming that the amount of shrinkage is negligible for the length and the width, (2.14) can be rewritten in the following form to give dry resistor thickness:

$$t_{\text{avg}} = \frac{d_s \mu_m}{d_d} t_w$$  \hspace{1cm} (2.15)

The drying stage of LTCC resistor printing is another major contributor of variability in resistance. There occurs nonuniform changes in material properties of the resistor as well as a transformation to a final geometry. Depending on the material properties, environmental conditions such as the furnace temperature, and dimensional attributes, the final shape of the resistor varies significantly. Figure 2.6 shows the major error contributors and the resulting variability during the drying process.

**Figure 2.6:** Error map of resistor drying process
2.3 Post-fired resistance model

After drying, the circuit is fired, and carbon constituents are burned away, leaving hard ceramic with metallic conductors and circuit elements. Figure 2.7 shows the real and simplified geometry of a finished screen printed resistor.

![Figure 2.7: Real and simplified geometry of a screen printed resistor](image)

2.3.1 Development of theoretical resistance model

Based upon the thick film resistor model developed by Beyne et al. (1987), a screen-printed resistor can be considered in two regions. First region is the bulk region which consists of the middle section of the resistor. The geometry of the resistor in this region can be assumed to remain consistent along the length. The longitudinal ends of the resistor are defined as the termination regions that have different geometries and material properties than the bulk region. The difference at the ends are due to the screen printing process characteristics (e.g. the downward force of the squeegee on the screen, sticking of paste as screen lifts off, etc.) and the contact with the conductors.

Thus, the resistance of an LTCC resistor can be defined as a sum of resistance values of these regions:
\[ R = R_b + R_t \]  

(2.16)

where \( R_b \) is the resistance of the bulk area and \( R_t \) is the resistance at the termination area.

**Figure 2.8** and **Figure 2.9** show the simplified geometry of a screen printed resistor.

**Figure 2.8:** Resistor Geometry Model

**Figure 2.9:** Resistor Model Geometrical Parameters
The electrical resistance of a block of material (as in Figure 2.10) can be found by the following simple relationship

\[ R = \rho \frac{L}{Wt} \]  

(2.17)

where \( \rho \) is the bulk resistivity of the material, \( L \) is the length of the block, \( W \) is the width of the block, and \( t \) is the thickness of the block.

![Block Resistor Diagram](image)

**Figure 2.10: Resistance of a block resistor**

Based on the geometrical parameters defined in Figure 2.9 and the above relationship for resistance, \( R_b \) and \( R_t \) can be furthermore defined as:

\[ R_b = \rho_b \frac{(L - 2L_t)}{t_b W - 2 \left( 1 - \frac{t_{bc}}{t_b} \right) W} \]  

(2.18)

where \( \rho_b \) denotes the bulk resistivity, and

\[ R_t = \rho_t \frac{L_t}{t_t W - 2 \left( 1 - \frac{t_{ct}}{t_t} \right) W} \]  

(2.19)

where \( \rho_t \) denotes the termination resistivity that is a result of interaction between the resistor material and the conductor material. This resistivity tends to be higher than the
bulk resistivity due to less conducting content or voids between resistor and conductor surfaces.

Combining (2.18) and (2.19) with (2.16), we obtain the total resistance:

\[
R = \frac{\rho_b}{t_b} \left( \frac{L}{L} \right) \left( \frac{W}{W} \right) \left[ 1 - \frac{2(1 - \frac{t_r}{t_b})}{1 - 2(1 - \frac{t_r}{t_b})} \beta \right]
\]

where

\[
\beta = \frac{1 - 2(1 - \frac{t_r}{t_b})}{1 - 2(1 - \frac{t_r}{t_b})} \frac{(W_r/W)}{(W/W)}
\]  \hspace{1cm} (2.21)

Based on the assumptions stated below, we can approximate \( \beta \equiv 1 \).

\[
2 \frac{W_r}{W} < 1 = \text{limit of the model}
\]

\[
\left| 1 - \frac{t_{b_r}}{t_b} \right| < 1 \quad \text{and} \quad \left| 1 - \frac{t_{b_r}}{t_r} \right| < 1
\]

\[
\frac{t_{b_r}}{t_b} \equiv \frac{t_{b_r}}{t_r}
\]

Therefore (2.20) is simplified to

\[
R = \frac{\rho_b}{t_b} \left( \frac{L}{L} \right) \left( \frac{W}{W} \right) \left[ 1 - \frac{2(1 - \frac{t_r}{t_b})}{1 - 2(1 - \frac{t_r}{t_b})} \right]
\]

\[
\left( \frac{L}{L} \right) \left( \frac{W}{W} \right)
\]

The form of (2.22) that fits with the available measurement data is

\[
R = \frac{\rho_b}{t_b} \left( \frac{L - p_r}{W - 2(1 - \frac{t_{b_r}}{t_b})W_r} \right)
\]

\hspace{1cm} (2.23)
where $p_{r}$ and $p_{l}$ can be found statistically by fitting measured resistance values. $p_{l}$ will be generally fixed to zero as it is very small compared to length, $L$, as determined by statistical fits of resistance, $R$. The estimation of $p_{r}$ is done based on experiments conducted on different pastes from a large number of samples.

Finally, it is desired to relate resistance to the average dry thickness calculated by the models previously established. In order to achieve that a simple relationship is derived to give $t_{aw}$:

$$t_{aw} = t_{b} + 2(t_{w} - t_{b}) \frac{W}{W}$$  \hspace{1cm} (2.24)

Substituting (2.24) in (2.23), the simplest form of resistance equation is obtained:

$$R = p_{r} \frac{L - p_{l}}{t_{aw} W}$$  \hspace{1cm} (2.25)

We have established a model which takes in all the input variables and estimates the final resistance. This model is evaluated in three steps. The final step of the model is illustrated by another error map in Figure 2.11. At this point, for practical purposes, it is desired to show a methodology for estimating statistical parameters from experimental techniques. By determining these parameters, the resistance model will be completed and then used for further sensitivity and improvement analysis in further sections.
2.3.2 Experimental methods and profile modeling

In order to better understand the screen printing process and resistor performances, a set of experiments were conducted using a large sample size. In these experiments, the geometry of the resistors, location on the circuit and resistor ink type were varied and resistance values were measured after firing. Over 7000 resistance measurements were then used to establish statistical models to estimate unknown parameters.

In these experiments, it was desired to investigate the performance of buried resistors printed on inner layers of a multilayer laminate. Four laminates were designed each consisting of 21 layers. The resistors were then printed on five different layers; layers 1, 6, 11, 16 and 21 (surface layer). On each layer, four different circuits each of which contained sixteen resistors with distinct length and width values were printed. These circuits were located on the layer such that the effect of direction of screen printing could be predicted. Figure 2.12 shows one of the layers with four different circuits.
Figure 2.12: Resistor pattern and circuit configuration on layer 11

Each circuit of resistors consists of sixteen resistors, having combinations of four widths (20, 30, 40 and 50 mils) and sixteen lengths (10, 15, 20, 25, 60, 90, 110, 150, 160, 165, 220, 240, 275, 320, and 400 mils). The combinations were designed such that there would be only four distinct $L/W$ ratios (0.5, 3, 5.5 and 8). For example, the smallest resistor had a width of 20 mils and length of 10 mils ($L/W = 0.5$); the largest resistor had a width of 50 mils and length of 400 mils ($L/W = 8$).

Six different resistor inks were used in the experiments. Four laminates were prepared as described above for each different ink type. The inks were chosen to have distinctive resistivity values so that the effect of resistivity and its variability on resistance performance and error could be assessed in each case.
To experimentally determine the relationship between various geometrical variables, the profiles of a small subset of resistors were recorded using a Dektak device before the lamination and firing process. The profiles were recorded along the width of two different sizes of resistors, \((L=320, \ W=40)\) and \((L=275, \ W=50)\). The measurements were taken for each laminate and each circuit type for three different kinds of inks. The output of the measurements were Dektak printouts. Since the data files were not saved, the printouts were scanned to get profile measurements. Several graphical software packages were then utilized to manually record the position of each point on the profile. An initial Dektak printout is shown in Figure 2.13.

![Dektak profile](image)

**Figure 2.13:** Dektak profile (Ink QT013, \(L=320, \ W=40\), Circuit A)

After the necessary transformations were completed, the shape of the profile was fitted into a U-shape to estimate the theoretical variables such as \(W, W', t_h, \) and \(t_v\). In
this fitting procedure, the mid-points between the zero thickness values and the two peaks were assumed to be the edges of the resistor to estimate the width, \( W \). The average of the peaks was assumed to be \( t_w \). The areas remaining outside the estimated width on both sides were added to the cavity in the middle of the resistor. Finally, \( t_h \) and \( W_c \) could be simultaneously found by satisfying the condition that the area under the normalized profile should be equal to the area under the initial profile. The dotted line in Figure 2.14 represents the normalized profile for the original resistor profile.

![Graphical representation of profile](image)

**Figure 2.14:** Transformed profile (Ink QT013, \( L=320 \), \( W=40 \), Circuit A)

Once the profile modeling was completed for a subset of the data (ink type QT131), it was observed that \( t_h \) and \( t_{he} \) were mutually dependent. Linear regression techniques were used to analyze the relationship. It was found that the two variables were linearly dependent with an R-square of 83%. The significant correlation between the two variables is shown in Figure 2.15.
Figure 2.15: The linear relationship between $t_h$ and $t_{bw}$.

For QT131 resistors, this relationship can be numerically expressed as

$$t_{bw} = 0.435 + 0.737t_h$$

(2.26)

It is thus shown that the empirical relationship between $t_h$ and $t_{bw}$ can be derived experimentally for all the inks. Subsequently, this could reduce the necessary number of measurements to build a resistance model of LTCC resistors. Despite this useful
observation, in the modeling of the experiments, the two variables can be represented by the average thickness, $t_{av}$, for simplicity. Thus, it is possible to reduce the number of variables to be fitted without a full set of profile measurements.

### 2.3.3 Statistical analysis of LTCC resistor data

A statistical analysis was conducted on a subset of data to determine the unknown parameters for the resistance model. Three ink types with Dektak profiles were selected for further analysis since we lacked profiles for the other three inks. Based on the profile modeling efforts, the geometrical characteristics of the resistors were calculated. The results are shown in the Appendix for the three ink types; QT031, QT131, and QT141. The dimensional values obtained for the resistors were then combined with the corresponding resistance measurements. JMP statistical software was utilized to run nonlinear regression models on the data.

Initially, (2.23) was used as a base model for the data. It was observed that the magnitude of parameter, $p_1$, was statistically insignificant based on nonlinear fitting of the data. Therefore, its value was set equal to zero and similar fitting methods were repeated to obtain the values for parameter, $p_\sigma$, that represents the resistivity of the resistor material. Figure 2.16 shows one of those fittings for ink type QT031. The $p_\sigma$ value was found to be 3690 Ohm-mils with a approximate standard deviation of 173 Ohm-mils (4.69%). The goodness of the fit could be observed by Root Mean Square Error (RMSE) value which was around 11320.
Figure 2.16: Nonlinear fitting for ink type QT031 based on 78 measurements

After the initial fitting process, it was observed that the resistors on the surface layer (layer 21) of the laminates seemed to respond unlike the buried resistors. The errors on these resistors were also significantly higher. The surface resistors were directly influenced by the environmental conditions such as the furnace temperature during the cofiring process. Therefore, we excluded these resistors from the analysis for a more robust fitting.

The removal of the surface resistors significantly improved the quality of the nonlinear fitting on the remaining four layers (layers 1, 6, 11, and 16). Figure 2.17 shows the results of the nonlinear fitting without surface resistors. The new value of $p_\nu$ was
4184 Ohm-mils and its standard error was reduced to 111 Ohm-mils (2.65%). RMSE value was also reduced to 6764 from 11320.

Figure 2.17: Nonlinear fitting for ink type QT031 excluding surface layer resistors

Finally, it was desired to remove the effect of resistor layer location on the resistance performance. The resistor locations were determined in x-y coordinate system and this information was appended to the JMP data sheets. To be able to isolate the effect of resistor location, the original nonlinear model of (2.23) was combined with a linear regression model with two additional parameter for x and y measurements. The modified regression model can be written as:
\[ R = \frac{p_x}{t_b} \left( \frac{L}{W - 2 \left( 1 - \frac{L}{t_b} \right) W} \right) + p, X + p, Y \]  \hspace{1cm} (2.27)

where \( X \) is the horizontal distance between the center of the layer and the center of the resistor, and \( Y \) is the vertical distance between the center of the layer and the center of the resistor. \( p_x \) and \( p_y \) are statistically determined parameters. Figure 2.18 represents the results of the fitting model with resistor locations.

\[ \frac{PR}{(T_b)} \left( \frac{L}{W - 2 \left( 1 - \frac{L}{(T_b^*)} \right) W} \right) + P_x x + P_y y \]

\[ \frac{1}{(T_b)} \left( \frac{L}{W - 2 \left( 1 - \frac{L}{(T_b^*)} \right) W} \right) \]

\[ \begin{array}{c|c|c|c|c|c}
\text{Parameter} & \text{Current Value} & \text{Lock} & \text{SSE} \\
\hline
PR & 4248.9576737 & 1 & 2154003155.2 \\
Px & 3.2187836668 & 1 & 2298762903.2 \\
Py & 0.5406255677 & 1 & 2154003155.2 \\
\end{array} \]

\[ \begin{array}{c|c|c|c|c|c|c|c}
\text{Parameter} & \text{SSE} & \text{DFE} & \text{MSE} & \text{RMSE} \\
\hline
PR & 2154003155.2 & 59 & 36508528 & 6042.2287 \\
Px & 3.2187836668 & 0.78374755 & 1.65814291 & 1.77942442 \\
Py & 0.5406255677 & 0.62542941 & 0.7047635 & 1.78601463 \\
\end{array} \]

Figures 2.18: Nonlinear fitting for ink type QT031 with X-Y position information

With the additional information, the quality of the fit and the parameter estimates were improved further. The new value of \( p_x \) was 4249 Ohm-mils and its standard error was reduced to 101 Ohm-mils (2.37%). RMSE value was further reduced to 6042 from
6764 as well. These values represent average parameter estimates since the regression was conducted on four different layers combined. It was possible to get more accurate information by running the model from (2.27) for each layer separately. The parameter predictions for each ink at various layers were thus conducted. Table 2.1 shows the results.

<table>
<thead>
<tr>
<th>Ink Type</th>
<th>Layer</th>
<th>PR</th>
<th>Px</th>
<th>Py</th>
</tr>
</thead>
<tbody>
<tr>
<td>QT031</td>
<td>Average</td>
<td>4249</td>
<td>3.218</td>
<td>0.541</td>
</tr>
<tr>
<td>QT031</td>
<td>1</td>
<td>3860</td>
<td>1.839</td>
<td>0.54</td>
</tr>
<tr>
<td>QT031</td>
<td>6</td>
<td>5142</td>
<td>5.029</td>
<td>-0.009</td>
</tr>
<tr>
<td>QT031</td>
<td>11</td>
<td>4079</td>
<td>2.483</td>
<td>1.50</td>
</tr>
<tr>
<td>QT031</td>
<td>16</td>
<td>3886</td>
<td>-0.552</td>
<td>0.977</td>
</tr>
<tr>
<td>QT131</td>
<td>Average</td>
<td>242</td>
<td>-0.089</td>
<td>-0.092</td>
</tr>
<tr>
<td>QT131</td>
<td>1</td>
<td>244</td>
<td>0.032</td>
<td>-0.279</td>
</tr>
<tr>
<td>QT131</td>
<td>6</td>
<td>222</td>
<td>0.13</td>
<td>-0.203</td>
</tr>
<tr>
<td>QT131</td>
<td>11</td>
<td>262</td>
<td>0.049</td>
<td>-0.07</td>
</tr>
<tr>
<td>QT131</td>
<td>16</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>QT141</td>
<td>Average</td>
<td>196</td>
<td>-0.096</td>
<td>-0.053</td>
</tr>
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<td>QT141</td>
<td>1</td>
<td>178</td>
<td>-0.067</td>
<td>-0.011</td>
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<td>QT141</td>
<td>6</td>
<td>205</td>
<td>-0.109</td>
<td>-0.024</td>
</tr>
<tr>
<td>QT141</td>
<td>11</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>QT141</td>
<td>16</td>
<td>224</td>
<td>-0.073</td>
<td>-0.033</td>
</tr>
</tbody>
</table>

**Table 2.1**: Parameter estimates for three inks

The model developed in this section involves two major components. The first component is the derivation of a theoretical resistance model based on physical characteristics of the product and the manufacturing process. The second component of the model is an empirical analysis which is necessary to estimate unmeasured parameters in the theoretical model. Both steps are necessary for an accurate understanding of the resistance performance of LTCC circuits. **Figure 2.19** shows the accuracy of the model as the model resistance values are plotted versus the measured resistance value.
Figure 2.19: The model and actual resistance values for ink QT141
Chapter 3

Simultaneous Quality Design Tool

To understand the quality of different product configurations at different process operating points, the three models of the manufacturing processes described in the previous section must be integrated into one combined model. This black box model takes all design, process, and material variables as well as statistical parameters as inputs. The model output is the desired nominal product performance, and its standard deviation as a measure of quality. Such a design tool was built for the LTCC resistor performance in a Microsoft® Excel workbook.

3.1 LTCC Design Tool user interface

In a product design and development effort, the manufacturability of a design alternative is desired to be known at the early stages of concept generation. The need for integrated design and manufacturing simulation tools has been lately recognized. From injection molding to sheet metal forming, tools for designers have been developed to analyze product/process tradeoffs. Inspired by such tools, LTCC Design Tool provides designers an easy-to-use interface that combines product and process information with engineering modeling to predict best product performance with least possible error.
Figure 3.1 shows the user interface worksheet of the LTCC Design Tool built within Excel workbook environment.

<table>
<thead>
<tr>
<th>LTCC DESIGN TOOL</th>
<th>Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Unit</th>
<th>Standard Error (CI)</th>
<th>Cumulative Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Design Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L, Resistor Length</td>
<td>320</td>
<td>20</td>
<td>320</td>
<td>mils</td>
<td>9.6</td>
<td>7.5%</td>
</tr>
<tr>
<td>W, Resistor Width</td>
<td>40</td>
<td>10</td>
<td>50</td>
<td>mils</td>
<td>1.2</td>
<td>7.5%</td>
</tr>
<tr>
<td>τe, Emulsion height</td>
<td>0.8</td>
<td>0.7</td>
<td>1</td>
<td>mils</td>
<td>0.024</td>
<td>8.7%</td>
</tr>
<tr>
<td><strong>Equipment Design Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D, Screen Wire Diameter</td>
<td>0.2</td>
<td>0.15</td>
<td>0.25</td>
<td>mils</td>
<td>0.001</td>
<td>0.0%</td>
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<tr>
<td>Mj, Mesh Count</td>
<td>0.25</td>
<td>0.1</td>
<td>0.3</td>
<td>per mil</td>
<td>0.008</td>
<td>0.2%</td>
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<tr>
<td><strong>Process Variables</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vsq, Squeegee Speed</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>mils/sec</td>
<td>0.3</td>
<td>0.7%</td>
</tr>
<tr>
<td>τr, Residual Ink Thickness</td>
<td>0.05</td>
<td>0</td>
<td>0.08</td>
<td>mils</td>
<td>0.002</td>
<td>0.0%</td>
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<td>Δτsq, Squeegee Penetration</td>
<td>0.1</td>
<td>0</td>
<td>0.16</td>
<td>mils</td>
<td>0.003</td>
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<td>Xsq, Xsqueegee</td>
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<td>20</td>
<td>mils</td>
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</tr>
<tr>
<td>Wsq, Wsqueegee</td>
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<td>0</td>
<td>10</td>
<td>mils</td>
<td>0.15</td>
<td>0.2%</td>
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<tr>
<td>αs, Squeegee Angle of Attack</td>
<td>25</td>
<td>10</td>
<td>89</td>
<td>degrees</td>
<td>0.75</td>
<td>10.4%</td>
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<td><strong>Material Variables</strong></td>
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<tr>
<td>daqy, Dry Density of Ink</td>
<td>2.25</td>
<td>1.5</td>
<td>3</td>
<td>lb/in³</td>
<td>0.068</td>
<td>7.5%</td>
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<tr>
<td>dws, Wet Density of Ink</td>
<td>2.12</td>
<td>1.5</td>
<td>3</td>
<td>lb/in³</td>
<td>0.106</td>
<td>20.7%</td>
</tr>
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<td>μs, Solids Weight Fraction</td>
<td>0.8</td>
<td>0</td>
<td>1</td>
<td>%/100</td>
<td>0.04</td>
<td>20.7%</td>
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<tr>
<td>n, Power Law Exponent</td>
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<td>0</td>
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<td></td>
<td></td>
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<tr>
<td>INK TYPE</td>
<td>QT131</td>
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<tr>
<td>Layer</td>
<td>6</td>
<td>0</td>
<td>21</td>
<td>(use 1,6,11,16, or avg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ps, Resistivity</td>
<td>222</td>
<td></td>
<td></td>
<td>Chm-mils</td>
<td>6.66</td>
<td>7.5%</td>
</tr>
<tr>
<td>Pb, conductor fraction L</td>
<td>0.000</td>
<td></td>
<td></td>
<td>%/100</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Pb, x position coefficient</td>
<td>0.130</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb, y position coefficient</td>
<td>-0.203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE THICKNESS</td>
<td>1.14 mils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STANDARD ERROR</td>
<td>0.11 mils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESISTANCE</td>
<td>1558 Ohms</td>
<td></td>
<td>Error Resistor (3 sigma)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STANDARD ERROR</td>
<td>17.1 Ohms</td>
<td></td>
<td>33%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.1: LTCC Design Tool

The highlighted cells represent the numerical values that can be modified by the user. These inputs include nominal values for each input variables as well as their input standard variation. Further, each nominal value is interval limited by a pre-agreed bound.
This permits a design team to optimize and conduct what-if studies of the product-process as a system.

Beyond understanding the basic nominal performance, however, the errors in performance are also predicted. However, this requires more than a simple error propagation analysis, for a variety of reasons. First, the mapping among the variables is not simple, but requires simultaneous equation solving. Second, in-line process control can be an option, and needs exploration, as will be discussed later. In any case, in the last column, the cumulative contribution of each variable to the output variability is shown.

3.2 Numerical calculation of the dry resistor thickness

The average dry thickness of a resistor is one of the most important factors on resistance. There are many process and product attributes affecting the output thickness. Based on the equations shown in the previous chapter, numerical algorithms were used to calculate the dry thickness. A step-by-step calculation process was followed. Figure 3.2 shows the worksheet with a numerical example.
### Calculation of dry paste thickness

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_a$</td>
<td>density of dry paste</td>
</tr>
<tr>
<td>$d_w$</td>
<td>density of wet paste</td>
</tr>
<tr>
<td>$\mu_{so}$</td>
<td>initial solids weight fraction</td>
</tr>
<tr>
<td>$t_{w}$</td>
<td>wet paste thickness</td>
</tr>
<tr>
<td>$V_{sa}$</td>
<td>squeegee translational speed</td>
</tr>
<tr>
<td>$t_{r}$</td>
<td>paste residue thickness</td>
</tr>
<tr>
<td>$t_{eq}$</td>
<td>equivalent flow passage height under squeegee</td>
</tr>
<tr>
<td>$V_p$</td>
<td>paste flow speed under squeegee</td>
</tr>
<tr>
<td>$a$</td>
<td>equivalent open area height</td>
</tr>
<tr>
<td>$D$</td>
<td>screen wire diameter</td>
</tr>
<tr>
<td>$M$</td>
<td>screen mesh count per inch</td>
</tr>
<tr>
<td>$\Delta t_{eq}$</td>
<td>average squeegee penetration height into the screen</td>
</tr>
<tr>
<td>$n$</td>
<td>power law exponent</td>
</tr>
<tr>
<td>$V_{s}$</td>
<td>paste flow speed under squeegee</td>
</tr>
</tbody>
</table>

### Figure 3.2: Dry thickness calculation worksheet

Each box in the worksheet is created to carry out a computation of an unknown variable as a function of known variables. By known variables, variables which can be measured or closely predicted are meant. In the worksheet, computed variables are shown in shaded boxes (e.g., $t_{ae}$, $t_a$, $t_{e}$, $V_p$ are unknown (computed) and $d_a$, $d_w$, $\mu_{so}$, $V_{s}$, $D$, $M$ are known (measured) variables). The computations are based on equations (2.2)-(2.15). For $V_p$, an iterative algorithm was used to simultaneously solve (2.10).
3.3 Cumulative Error Contribution Concept

During early stages of concept generation, it is important to know how a product or process variable can affect the quality of the output. In a typical product/process development, as in many physical relationships, 80-20 rule applies. This means that 80% of the variability in a product performance parameter can be approximately devoted to 20% of the variables affecting the performance. Therefore, to understand the major contributors of variability to the system is the first and most crucial step in improving quality.

Based on the models developed earlier, we have already identified and showed the input variables to the LTCC system. These variables are simply the product/equipment design, material, and process variables with highlighted input cells in the LTCC Design Tool. To be able to realize the error contribution of each variable to the resistance standard error, the dependencies among the variables were exploited. The effect of one variable on another variable could be determined from the physical relationships between them.

The variability of a product performance can be calculated by

\[
\sigma^2(d) = \int_{\mathbb{R}^n} \left( f(d, \bar{n}) - \bar{y} \right)^2 \text{pdf}(\bar{n}) d\bar{n}.
\]  

(3.1)

where \( \bar{d} \) is a vector of design variables, \( \bar{n} \) is a vector of noise variables, \( f \) is a mapping to a performance metric, \( \bar{y} \) is the target value, and \( \text{pdf}(\bar{n}) \) is the probability density function representing the probabilities of noise variable values, and generally are also dependent on the design variables values.
To a first order approximation, (3.1) can be approximated by the error propagation formula,

\[ \sigma^2 = \sum \left( \frac{\partial f}{\partial n_i} \right)^2 \sigma^2_i \]  

(3.2)

which proves more simple to evaluate for systems operating at points without excessive non-linearity across perturbations.

In the case of LTCC resistance variability, this equation can be written as

\[ \sigma^2_{R} = \left( \frac{\partial f}{\partial L} \right)^2 \sigma^2_L + \left( \frac{\partial f}{\partial W} \right)^2 \sigma^2_w + \left( \frac{\partial f}{\partial L_{avg}} \right)^2 \sigma^2_{L_{avg}} + \left( \frac{\partial f}{\partial p_r} \right)^2 \sigma^2_{p_r} + \left( \frac{\partial f}{\partial p_l} \right)^2 \sigma^2_{p_l} \]  

(3.3)

where

\[ f(L, W, L_{avg}, p_r, p_l) = R = p_r \frac{L - p_l}{L_{avg} W} \]  

(3.4)

and \( \sigma^2_{R} \) is the cumulative resistance error. The expansion of (3.3) requires calculation of variance for all the input variables in a similar fashion. This was achieved by the following spreadsheet shown in Figure 3.3.
**Figure 3.3: Error Contribution Computation Worksheet**

The error contribution of each variable to the final resistance error is calculated based on the hierarchical relationships among the variables. First, the individual variability of each independent variable has to be determined by experiments or expert estimations. Then, using the principles of error propagation, the variability of dependent variables can be found. The error contribution of each independent variable to a dependent variable is represented by a percentage value. The contributions of lower level dependent variables to higher level dependent variables are also determined in a similar fashion. This process continues till we reach the final resistance error as the highest level dependent variable.
Once all the intermediate error contributions are expressed in percentage terms, the error contribution of an independent variable is simply the sum of the products of all percentage values occur at every level of variable-specific error contributions.

In order to illustrate the calculation process, the error contribution calculation of the squeegee angle of attack, \( \alpha \), is shown in a hierarchical form in Figure 3.4. For the system variables shown in Figure 3.1, the error contribution of \( \alpha \) to the resistance error is the product of the all intermediate contributions which is 10.4%.

![Hierarchical error contribution computation for \( \alpha \).](image)

**Figure 3.4:** Hierarchical error contribution computation for \( \alpha \).

### 3.4 Benefits of LTCC Design Tool

For a given set of process and material variables, LTCC Design Tool enables a designer to obtain the most robust design through iteration. In order to illustrate the use of the tool, we considered the LTCC product configuration in Figure 3.1. At this point, all the process and material variables are assumed to be uncontrollable. The necessary information to fill out these boxes can be obtained from experiments, manufacturing teams or relevant literature. Based on the provided information, the designer is, thus, able to adjust the product design and equipment design variables considering the effects of downstream process and material variables.
Considering the configuration in Figure 3.1, if a 1000-Ohm resistor is desired, the designer can initially choose to decrease the length of the resistor to an acceptable lower limit. If there are no constraints on length, the designer should be able to reduce the length to a level where the resistance reaches 1000 Ohms.

<table>
<thead>
<tr>
<th>LTCC DESIGN TOOL</th>
<th>Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Unit</th>
<th>Standard Error (G.)</th>
<th>Cumulative Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Design Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L, Resistor Length</td>
<td>205.5</td>
<td>20</td>
<td>320</td>
<td>mils</td>
<td>6.165</td>
<td>7.5%</td>
</tr>
<tr>
<td>W, Resistor Width</td>
<td>40</td>
<td>10</td>
<td>50</td>
<td>mils</td>
<td>1.2</td>
<td>7.5%</td>
</tr>
<tr>
<td>t&lt;sub&gt;e&lt;/sub&gt;, Emulsion height</td>
<td>0.8</td>
<td>0.7</td>
<td>1</td>
<td>mils</td>
<td>0.024</td>
<td>8.7%</td>
</tr>
<tr>
<td><strong>Equipment Design Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D, Screen Wire Diameter</td>
<td>0.2</td>
<td>0.15</td>
<td>0.25</td>
<td>mils</td>
<td>0.001</td>
<td>0.0%</td>
</tr>
<tr>
<td>M, Mesh Count</td>
<td>0.25</td>
<td>0.1</td>
<td>0.3</td>
<td>per mil</td>
<td>0.008</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Process Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V&lt;sub&gt;eq&lt;/sub&gt;, Squeegee Speed</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>mils/sec</td>
<td>0.3</td>
<td>0.7%</td>
</tr>
<tr>
<td>t&lt;sub&gt;r&lt;/sub&gt;, Residual Ink Thickness</td>
<td>0.05</td>
<td>0</td>
<td>0.08</td>
<td>mils</td>
<td>0.002</td>
<td>0.0%</td>
</tr>
<tr>
<td>Δτ&lt;sub&gt;eq&lt;/sub&gt;, Squeegee Penetration</td>
<td>0.1</td>
<td>0</td>
<td>0.16</td>
<td>mils</td>
<td>0.003</td>
<td>0.1%</td>
</tr>
<tr>
<td>X&lt;sub&gt;e&lt;/sub&gt;, X&lt;sub&gt;squeegee&lt;/sub&gt;</td>
<td>10</td>
<td>0</td>
<td>20</td>
<td>mils</td>
<td>0.3</td>
<td>8.2%</td>
</tr>
<tr>
<td>W&lt;sub&gt;e&lt;/sub&gt;, W&lt;sub&gt;squeegee&lt;/sub&gt;</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>mils</td>
<td>0.15</td>
<td>0.2%</td>
</tr>
<tr>
<td>α&lt;sub&gt;e&lt;/sub&gt;, Squeegee Angle of Attack</td>
<td>25</td>
<td>0</td>
<td>89</td>
<td>degrees</td>
<td>0.75</td>
<td>10.4%</td>
</tr>
<tr>
<td><strong>Material Variables</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d&lt;sub&gt;dry&lt;/sub&gt;, Dry Density of Ink</td>
<td>2.25</td>
<td>1.5</td>
<td>3</td>
<td>lb/in&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.066</td>
<td>7.5%</td>
</tr>
<tr>
<td>d&lt;sub&gt;wt&lt;/sub&gt;, Wet Density of Ink</td>
<td>2.12</td>
<td>1.5</td>
<td>3</td>
<td>lb/in&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.106</td>
<td>20.7%</td>
</tr>
<tr>
<td>μ&lt;sub&gt;so&lt;/sub&gt;, Solids Weight Fraction</td>
<td>0.8</td>
<td>0</td>
<td>1</td>
<td>%/100</td>
<td>0.04</td>
<td>20.7%</td>
</tr>
<tr>
<td>n, Power Law Exponent</td>
<td>0.6</td>
<td>0</td>
<td>1</td>
<td></td>
<td>0.03</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Statistical Parameters</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer</td>
<td>6</td>
<td>0</td>
<td>21</td>
<td>(use 1,6,11,16, or avg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Y position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;x&lt;/sub&gt;, Resistivity</td>
<td>222</td>
<td></td>
<td></td>
<td>Ohm-miles</td>
<td>6.66</td>
<td>7.5%</td>
</tr>
<tr>
<td>P&lt;sub&gt;x&lt;/sub&gt;, conductor fraction L</td>
<td>0.000</td>
<td></td>
<td></td>
<td>%/100</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>P&lt;sub&gt;y&lt;/sub&gt;, x position coefficient</td>
<td>0.130</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;y&lt;/sub&gt;, y position coefficient</td>
<td>-0.203</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.5:** LTTC tool with modified length to achieve 1000-Ohm resistor

That length value would indeed be 205.5 mils while all other variables are kept fixed as shown in Figure 3.5.
However, in certain situations, there can be other constraints that would not allow such a large reduction in length. For the sake of discussion, we assume that length could only be reduced to 240 mils.

<table>
<thead>
<tr>
<th>LTCC DESIGN TOOL</th>
<th>Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Standard Error (G.</th>
<th>Cumulative Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Design Variables</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L, Resistor Length</td>
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<td>20</td>
<td>320</td>
<td>mils</td>
<td>7.2</td>
</tr>
<tr>
<td>W, Resistor Width</td>
<td>40</td>
<td>10</td>
<td>50</td>
<td>mils</td>
<td>1.2</td>
</tr>
<tr>
<td>t0, Emulsion height</td>
<td>1.015</td>
<td>0.7</td>
<td>1</td>
<td>mils</td>
<td>0.03</td>
</tr>
<tr>
<td>Equipment Design Variables</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D, Screen Wire Diameter</td>
<td>0.2</td>
<td>0.15</td>
<td>0.25</td>
<td>mils</td>
<td>0.001</td>
</tr>
<tr>
<td>M, Mesh Count</td>
<td>0.25</td>
<td>0.1</td>
<td>0.3</td>
<td>per mil</td>
<td>0.008</td>
</tr>
<tr>
<td>Process Variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vsq, Squeegee Speed</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>mils/sec</td>
<td>0.3</td>
</tr>
<tr>
<td>t0, Residual Ink Thickness</td>
<td>0.05</td>
<td>0</td>
<td>0.1</td>
<td>mils</td>
<td>0.002</td>
</tr>
<tr>
<td>Δt00, Squeegee Penetration</td>
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<td>0</td>
<td>0.2</td>
<td>mils</td>
<td>0.003</td>
</tr>
<tr>
<td>Xs0, Xsqueegee</td>
<td>10</td>
<td>0</td>
<td>0.2</td>
<td>mils</td>
<td>0.3</td>
</tr>
<tr>
<td>Ws0, Wsqueegee</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>mils</td>
<td>0.15</td>
</tr>
<tr>
<td>α, Squeegee Angle of Attack</td>
<td>25</td>
<td>10</td>
<td>89</td>
<td>degrees</td>
<td>0.75</td>
</tr>
<tr>
<td>Material Variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>davg, Dry Density of Ink</td>
<td>2.25</td>
<td>1.5</td>
<td>3</td>
<td>lb/in³</td>
<td>0.068</td>
</tr>
<tr>
<td>dwet, Wet Density of Ink</td>
<td>2.12</td>
<td>1.5</td>
<td>3</td>
<td>lb/in³</td>
<td>0.106</td>
</tr>
<tr>
<td>δμ0, Solids Weight Fraction</td>
<td>0.8</td>
<td>0</td>
<td>1</td>
<td>%/100</td>
<td>0.04</td>
</tr>
<tr>
<td>n, Power Law Exponent</td>
<td>0.6</td>
<td>0</td>
<td>1</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Statistical Parameters</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Layer</td>
<td>6</td>
<td>0</td>
<td>21</td>
<td>(use 1,6,11,16, or avg)</td>
<td></td>
</tr>
<tr>
<td>X position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
</tr>
<tr>
<td>Y position on laminate</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>mils</td>
<td></td>
</tr>
<tr>
<td>Pn, Resistivity</td>
<td>222</td>
<td></td>
<td></td>
<td>Ohm-mils</td>
<td>6.66</td>
</tr>
<tr>
<td>Pt, conductor fraction L</td>
<td>0.000</td>
<td></td>
<td></td>
<td>%/100</td>
<td>0</td>
</tr>
<tr>
<td>Pxy, x position coefficient</td>
<td>0.130</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pxy, y position coefficient</td>
<td>-0.203</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE THICKNESS:</td>
<td>1.33 mils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STANDARD ERROR:</td>
<td>0.13 mils</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RESISTANCE:</td>
<td>1000 ohms</td>
<td></td>
<td></td>
<td>Error Resistor (3 sigma)</td>
<td></td>
</tr>
<tr>
<td>STANDARD ERROR:</td>
<td>110 ohms</td>
<td></td>
<td></td>
<td>33%</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.6:** LTCC tool with modified length and thickness for 1000-Ohm resistor

In that case, the designer could simultaneously use another design variable to achieve target resistance. For example, the emulsion height could further be adjusted to 1.015 mils which results in also 1000 Ohms as shown in **Figure 3.6.** If the increased thickness was a
consideration, the designer could further include additional design variables and iterate the process.

In the iteration example above, it was shown how the LTCC Design Tool could be used to select an optimal design. In these examples, the variability of the modified variables were proportionally adjusted for simplicity. Therefore, the output resistance error remained constant despite design changes. However, in reality, the variability behavior as a function of nominal variable values is quite complex. In many cases, the relationship between the nominal value and the error value will be nonlinear. This nonlinearity can also help the designer to reduce the output resistance error in the system.

In conclusion, this tool provides a design and manufacturing team the ability to adjust the nominal values of any variables to predict the performance and variance of the manufactured product. Thus, it also makes it possible for the designers to change the product design to minimize variability in the end product performance. Also, the cumulative error contribution predictions help the manufacturing teams to understand the major error contributors in the process. Once the design variables are determined, this tool can be used for an overall process optimization. After several iterations, one should be able to find a set of variable values which guarantees the target performance within an acceptable error range.
Chapter 4

System Level Process Redesign

A methodology has been introduced to find the optimal design alternative in a product development case. However, the optimal design configuration based on the available manufacturing information does not necessarily guarantee the best possible product performance at all times. The available manufacturing information in LTCC simulation is based on the historical behavior of the variables. The real manufacturing variables in the system, in fact, change instantaneously as production occurs. Past behavior in a system can not exactly predict present or future state of a variable due to various noise factors. Therefore, in many cases, the optimal product configuration required cannot be reliably produced.

The best way to accommodate for real time variations in production is to make real time changes in the manufacturing system. In-line process control techniques and processing technology improvements are common practices. If sufficient quality is not being achieved, it may warrant the introduction of on-line quality control. However, in many systems, it can be unclear how to redesign the system to reduce variation. Without a useful tool, it can be hard to recognize where to make changes. It is also desired to know
what amount of change is sufficient without overcontrolling the system. We now develop a simplified model that can be used in association with any black-box manufacturing system model to explore these questions, and demonstrate its efficacy with the LTCC product and process.

4.1 System Variation Models

Rather than minimizing the variability of each error source independently to achieve more robust performance, a system wide variation model as described earlier can be used to reduce variational errors in a product at lower cost. However, this does not consider the factory floor process control actions that might be taken to reduce variation. The concept of using tuning variables for robust product design (Otto and Antonsen, 1993, Otto, 1994) has been introduced to minimize the error variation caused by noise. Tuning variables represent factory floor manufacturing adjustments after a design is selected (represented by design variables). They can be treated as feedback control variables that are set by the manufacturing team after the noise has occurred. The tuning variables practically offset the influences of noise variables to reduce total variation.

Without considering the tuning variables, the variability of a product performance can be calculated by (3.1), as described in the previous chapter,

$$\sigma^2(z) = \int \left( f(z, n) - \bar{y} \right)^2 pdf(n) \, dn. \tag{3.1}$$

With on-line process control, values of tuning variables can be selected to minimize variability after the design and noise variables are determined. (4.1) shows the form of the variability equation including the tuning adjustments.
\[ \sigma^2(\tilde{d}) = \int \min_{\tilde{t}} \left( f(\tilde{d}, \tilde{n}, \tilde{t}) - \bar{y} \right)^2 pdf(\tilde{n}) d\tilde{n}. \] (4.1)

While accurate, (3.1) and (4.1) are computationally difficult. To a first order approximation, (3.1) can be approximated by the error propagation formula,

\[ \sigma^2_y \approx \sum \left( \frac{\partial f}{\partial n_i} \right)^2 \sigma^2_{n_i} \] (3.2)

which was also previously mentioned.

The linearized error propagation formula (3.2) is often used to understand the propagation of errors in already manufactured products. Unfortunately, it is not valid in the presence of on-line process adjustments. The adjustments tune out the variation of some of the noise, and may introduce other (hopefully much smaller) errors. A similarly simplified version of (4.1) is needed to easily consider error propagation in manufacturing systems with adjustments. Yet until now there has been no linearized version of (4.1), the model with on-line process control.

To derive this formula, one must consider the mechanics of on-line process control. Generally, to do an in-line adjustment, an operator must measure a pre-determined set of incoming variations on the work in progress. Based upon these in-line measurements, a value of the adjustment process variable is selected. Thus, there are two important aspects of the mechanics that are important for the earlier system and product design phase. Notably, the subset of noise variables to be measured and adjusted out must be selected. Second, at some point downstream a model or lookup table must be
provided that instructs the operators what value of adjustment to use for each measurement of incoming noise.

To derive an error propagation formula incorporating process adjustment capability, consider categorizing the input noise variables $\bar{n}$ into those $\bar{n}_m$ that will be measured and used in a control law to determine values for the on-line adjustment, and those $\bar{n}_n$ that will not. The error propagation formula considering adjustments will then become

$$\sigma_y^2 = F(\sigma_{n_m}, \Delta_j) + \sum_{n_n} \left( \frac{\partial f}{\partial n_n} \right)^2 \sigma_{n_n}^2$$  \hfill (4.2)

where $F$ is some function to be derived below. The point of (4.2) is to explicitly point out that in-line process adjustment and control can only reduce the output variation caused those input variations that are explicitly measured in-line. All other sources of variation are unaffected by the adjustment process and will continue to cause variation unabated.

To derive $F$, define $\sigma_u$ as the standard deviation of the variation which is sought to be adjusted out

$$\sigma_u^2 = \sum_{n_n} \left( \frac{\partial f}{\partial n_n} \right)^2 \sigma_{n_n}^2,$$  \hfill (4.3)

and let $\Delta_j$ be the range on output that the adjustment process can accommodate

$$\Delta_j = \left| \frac{\partial f}{\partial n_n} \right| \Delta_n,$$  \hfill (4.4)

where $\Delta_n$ is the range of the in-line process adjustment.
The error propagation formula (3.2) applies to independent Gaussian distributed sources of variation. Consider the Gaussian distribution of (4.3), the variation to be adjusted out, and (4.4) the range of the in-line process adjustment, as shown in Figure 4.1. The density function of (4.3) is

\[
pdf(y) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{y^2}{2\sigma^2}}.
\]  

Figure 4.1: Distribution of error to be adjusted out.

The shaded area in Figure 4.1 will be removed after the adjustment. The new distribution of variation after the adjustment is shown in Figure 4.2, with a delta function at zero. Note the delta function at zero implies perfect ability to measure and adjust. If this is not the case, errors on these new terms can be added in the standard way (3.1).
Figure 4.2: Distribution of error after adjustment.

The equation of the new density function becomes

\[
    pdf(y) = \begin{cases} 
    \frac{1}{\sigma_y \sqrt{2\pi}} e^{-\frac{(y-\Delta_y)^2}{2\sigma_y^2}} & y \leq 0 \\
    \frac{1}{\sigma_y \sqrt{2\pi}} e^{-\frac{(y+\Delta_y)^2}{2\sigma_y^2}} & y \geq 0 
    \end{cases} 
\]  \hspace{1cm} (4.6)

The standard deviation, \( \sigma \), of this function must be determined. Applying (3.1) to (4.6),

\[
    \sigma^2 = \frac{1}{\sigma_y \sqrt{2\pi}} \int_{-\infty}^{0} y^2 e^{-\frac{(y-\Delta_y)^2}{2\sigma_y^2}} dy + \frac{1}{\sigma_y \sqrt{2\pi}} \int_{0}^{\infty} y^2 e^{-\frac{(y+\Delta_y)^2}{2\sigma_y^2}} dy. 
\]  \hspace{1cm} (4.7)

Integrating, the result that we seek is

\[
    \sigma^2 = (\Delta_y^2 + \sigma^2_y) \left( 1 - \text{erf} \left( \frac{\sqrt{2} \Delta_y}{2 \sigma_y} \right) \right) - \frac{2}{\sqrt{\pi}} \sigma \Delta_y e^{-\frac{\Delta_y^2}{2\sigma_y^2}}. 
\]  \hspace{1cm} (4.8)

This expression is exact for \( \sigma_y \), exact as the standard deviation of a normal distribution.

Combining this with the variation that is not measured in-line and cannot be adjusted out, the error propagation formula with adjustment is
\[ \sigma_i^2 = (\Delta_i + \sigma_a^2) \left( 1 - \text{erf}\left( \frac{\sqrt{2} \Delta_i}{2 \sigma_a} \right) \right) - \frac{2}{\sqrt{\pi}} \sigma_a \Delta_i e^{-\frac{\Delta_i^2}{2 \sigma_a^2}} + \sum_{\text{unadjusted terms}} \left( \frac{\partial}{\partial \eta} \right)^2 \sigma_a^2 \]  

(4.9)

where \( \Delta_y \) is given by (4.4) and \( \sigma_a \) is given by (4.3).

(4.9), while exact, can be difficult to compute quickly. An alternative is to expand (4.8) into a series, and keep only the initial lower order terms. Dividing (4.8) by \( \sigma_a^2 \) produces

\[ s^2 = (r^2 + 1) \left( 1 - \text{erf}\left( \frac{\sqrt{2} r}{2} \right) \right) - \frac{2}{\sqrt{\pi}} r e^{-\frac{r^2}{2}}, \]  

(4.10)

where \( s = \frac{\sigma}{\sigma_y} \) and \( r = \frac{\Delta}{\sigma} \). Expanding \( \text{erf}(\cdot) \) and \( \exp(\cdot) \) into series and combining, one can derive a series expansion for (4.10) about \( r = 0 \) as

\[ s^2 = 1 + r^2 + \frac{2}{\sqrt{\pi}} \sum_{i=1}^{\infty} \frac{(\frac{1}{2})^{i-1}}{i! (2i+1)} (2 + 2i + r^2)^{2i+1}. \]  

(4.11)

The graph of the actual function and the first five expansions of (4.11) is shown in Figure 4.3. One would like to have \( \Delta_y \) be capable of adjusting out all effects of \( \sigma_a \), and so the required range of approximation is out to about \( r = 3 \). Examining Figure 4.3, it is clear that a rather large expansion of \( s^2 \) is then needed.
Figure 4.3: Reduced variance as a function of adjustment range with five orders.

For more rapid relative comparisons among different adjustment options, however, the second order approximation of (4.8) might be useful, which then becomes

$$\sigma^2 = \Delta^2 + \sigma^2 - 2 \sqrt{\frac{2}{\pi}} \sigma \Delta.$$  (4.12)

4.2 Application to the LTCC Production System

In the LTCC manufacturing case, the error on a performance metric of an LTCC resistor (e.g. resistance, thickness, etc.) can be related to noise variable errors as shown in Figure 4.4. The linearized form of the variability equation (3.2) can be used to predict the standard error of resistance, as shown in the LTCC Design Tool in Figure 3.1, and discussed in the previous section. The amount of variation predicted, however, proved excessive for many desired electric circuit product configurations, as indeed actual
production bore out. This posed a new problem on how to improve the current processing capability. Either new process technology or process control was needed, though it was not clear what or where.

**Figure 4.4:** Box model of the LTCC errors without the tuning adjustments.

Given that, the notion of variability reduction using tuning adjustments was applied to the LTCC error model. As candidate errors whose effects might be adjusted out, four noise variables that prove easy to measure were chosen: emulsion thickness $t_e$, initial solids weight fraction of the resistor paste $\mu_{init}$, wet paste density $d_w$, and the power law exponent $n$ that depends on paste viscosity. These are easily measured before each screen printing job, and so offer good candidates to base the setting of an adjustment control. Next, different adjustment variables were considered, including the squeegee translational speed, $V_s$, and the squeegee angle of attack $\alpha$. These variables can be adjusted relatively easily by the operators with no change in the equipment. In summary, the proposed concept is that either $V_s$ or $\alpha$ might be adjusted by the screen
printing operator based upon a lookup table (yet to be developed) of measurements of $t_r$, $\mu_m$, $d_w$, and $n$.

Based on this proposed process control, Figure 4.5 shows the modified systems model for LTCC error behavior. The errors on the adjustable variables are measured to determine the required change in the tuning adjustment variable. In this model, the control model box takes the adjustable variables and determines an optimal amount of change on $V_{sq}$ necessary to reduce variation in the system. The optimization process can also be started without a control model; in that case how much $V_{sq}$ should be changed can be determined after several iterations.

**Figure 4.5:** Box model of the LTCC errors with the squeegee speed as the tuning variable.

The application of the tuning adjustment concept to the LTCC Design Tool is shown in Figure 4.6. In this particular case, it was assumed that $V_{sq}$ with a nominal value of 10 mils/sec could be varied $\pm$ 3 mils/sec depending on the requirements of the system. By doing so, the errors on the four adjustable variables that sums up to 72.8% of the total
variation could be reduced significantly. For simplicity, the errors on certain variables were fixed to zero.

<table>
<thead>
<tr>
<th>LTCC DESIGN TOOL</th>
<th>Value</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Standard Error (%)</th>
<th>Cumulative Contribution</th>
<th>Adjusted Delta (Ω/Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product Design Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L, Resistor Length</td>
<td>320</td>
<td>20</td>
<td>320</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>W, Resistor Width</td>
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<td>10</td>
<td>50</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
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<td>0.8</td>
<td>0.7</td>
<td>1</td>
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<td>Yes</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D, Screen Wire Diameter</td>
<td>0.2</td>
<td>0.15</td>
<td>0.25</td>
<td>0.001</td>
<td>0.1%</td>
<td>1.5E+07</td>
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<tr>
<td>M, Mesh Count</td>
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<td>0.3</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Vws, Squeegee Speed</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>3.0</td>
<td>10.8%</td>
<td>569505</td>
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<td>0.08</td>
<td>0.002</td>
<td>0.0%</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Vws, Wsqueegee</td>
<td>5</td>
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<td>0</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>α, Squeegee Angle of Attack</td>
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<td>10</td>
<td>89</td>
<td>0.75</td>
<td>15.1%</td>
<td>0.0</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>1.5</td>
<td>3</td>
<td>4.066</td>
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<td>569505</td>
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<td>δ, Wet Density of Ink</td>
<td>2.12</td>
<td>1.5</td>
<td>3</td>
<td>0.106</td>
<td>30.0%</td>
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<td>µ, Solids Weight Fraction</td>
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<td>1</td>
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<td>n, Power Law Exponent</td>
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<td>avg</td>
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<td>21</td>
<td>(use 1, 6, 11, 16, or avg)</td>
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<td>mts</td>
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</tr>
<tr>
<td>Y position on laminate</td>
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<td>1</td>
<td>mts</td>
<td>0</td>
<td>0.0%</td>
</tr>
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<td>242</td>
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<td>Ohm-mts</td>
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<td>0.0%</td>
<td>0</td>
</tr>
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<td>Pt, conductor fraction L</td>
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<td></td>
<td></td>
<td>90</td>
<td>0.0%</td>
<td>90</td>
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<td>Pr, x position coefficient</td>
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<td></td>
<td></td>
<td>90</td>
<td>0.0%</td>
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<td>90</td>
<td>0.0%</td>
<td>90</td>
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<td>90</td>
<td>0.0%</td>
<td>90</td>
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<td></td>
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<td>90</td>
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<tr>
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<td>90</td>
<td>0.0%</td>
<td>90</td>
</tr>
<tr>
<td><strong>STANDARD ERROR</strong></td>
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<td></td>
<td>90</td>
<td>0.0%</td>
<td>90</td>
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<tr>
<td><strong>REDUCED ERROR</strong></td>
<td>155 ohms</td>
<td></td>
<td></td>
<td>90</td>
<td>0.0%</td>
<td>90</td>
</tr>
</tbody>
</table>

**Figure 4.6:** LTCC Design Tool with squeegee speed used as a tuning parameter.

The effect of using the squeegee translational speed $V_{ws}$ as a tuning variable can be observed from the values of total resistance standard error with and without the adjustment. While the standard error was 155 Ohms without the in-line control mechanism, after the addition of the tuning variable, the standard error could be reduced to
90 Ohms. This represents a 41.9 % reduction in standard error, all without any replacement of equipment, only changes in process operation.

In the second approach, the squeegee angle of attack, $\alpha$, was explored as a tuning variable. Figure 4.7 shows how this can be represented in an error box model. In this model, the control model box takes the adjustable variables and determines an optimal amount of change on $\alpha$ necessary to reduce variation in the system. $\alpha$ was expected to be better variable to control than $V_w$ since smaller changes on $\alpha$ are sufficient to reduce the adjustable error to the maximum possible level.

Figure 4.7: Box model of the LTCC errors with the angle of attack as the tuning variable.

The results of using $\alpha$ as a control variables are shown in Figure 4.8. Here the error contribution of the adjustable noise factors can be reduced by 47.7%. The range of $\alpha$ to be varied is also much smaller than the range required for $V_w$ (a 30% range was used with $V_w$ whereas even a 16% range with $\alpha$ was more effective). The reduction in total variation proves larger, and also easier for an operator to control. Therefore $\alpha$ offers the most improvement with least effort.
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<tr>
<th>LTCC DESIGN TOOL</th>
<th>Lower Limit</th>
<th>Upper Limit</th>
<th>Standard Error (Ω)</th>
<th>Cumulative Contribution</th>
<th>Out?</th>
<th>Adjusted</th>
<th>Δt (Ω/°mil)</th>
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<td>0</td>
<td>0.0%</td>
<td></td>
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</tr>
<tr>
<td>W, Resistor Width</td>
<td>40 mils</td>
<td>50 mils</td>
<td>0</td>
<td>0.0%</td>
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<tr>
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<td>0.7 mils</td>
<td>0.024</td>
<td>12.6%</td>
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<td></td>
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</tr>
<tr>
<td>D, Screen Wire Diameter</td>
<td>0.2 mils</td>
<td>0.15 mils</td>
<td>0.001</td>
<td>0.1%</td>
<td></td>
<td>1.5E+07</td>
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</tr>
<tr>
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<td>0.6 mils</td>
<td>0</td>
<td>0.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Process Variables</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{sq}$, Squeegee Speed</td>
<td>5.0 mils/sec</td>
<td>100 mils/sec</td>
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<td>1.1%</td>
<td></td>
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<td>0.0%</td>
<td></td>
<td>1260087</td>
<td></td>
</tr>
<tr>
<td>$\Delta t_{sq}$, Squeegee Penetration</td>
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<td>0.16 mils</td>
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<td>0.0%</td>
<td></td>
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</tr>
<tr>
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<td>20 mils</td>
<td>0</td>
<td>0.0%</td>
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</tr>
<tr>
<td>$W_{sq}$, Wsqueegee</td>
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<td>10 mils</td>
<td>0</td>
<td>0.0%</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$\alpha$, Squeegee Angle of Attack</td>
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**Figure 4.8:** LTCC Design Tool with angle of attack used as a tuning parameter.

The final LTCC design concept shown so far has turned out to be a powerful tool for not only choosing the best design alternative but also optimizing the manufacturing process such that the selected design concept could be feasibly produced. In the studied example, we were able to quantify the difference between two possible variables that were considered for feedback control purposes. LTCC Design Tool clearly showed the implications of using any of the two variables based on two criteria; total variation reduction and required measurable range on control variables. Doing so, we were able to discover $\alpha$ to be the better option as a control variable.
Chapter 5

Conclusions

In this thesis, a new methodology for the integration of design and manufacturing domains was introduced. The developed ideas were inspired by the concurrent engineering concepts that revolutionized engineering and management fields in the past decade. Quality through integrated systems thinking has become an important philosophy for companies to remain competitive in increasingly global markets. Taking the concepts of simultaneous engineering one step further, we have shown how integrated modeling of design and manufacturing activities could generate robust products with increased quality.

This work consisted of three major evolutionary steps. In the first phase of our research work, many efforts were focused on investigating the engineering models required to represent the physics of the product development and manufacturing operations. A practical case was investigated based on a state-of-the-art electronics packaging technology, in particular, the components of LTCC circuits. Due to the recent development of LTCC circuits, information was limited, mostly based on in-line factory data. We have achieved to integrate such information with previous theoretical works done in the past. Thus, it was possible to build a complete LTCC resistance model.

In the second phase of the work presented, the development of a user-friendly worksheet platform was aimed. The need for a systematic design tool to evaluate design
alternatives directed us to create the LTCC Design Tool. The tool, an extension of the previous engineering models, used simultaneous equation solving capabilities of a computer to quickly calculate different design outcomes including a variational analysis of the system parameters. Thus, many iterations, as intended in the beginning, could be executed to find robust design configurations in a short time.

Finally, in the last phase, we also explored using different available process variables as on-line process control variables to reduce the variation caused by noise variables which must then be measured. The concept of tuning adjustments was applied to the case study. It was discovered that the variational impacts of tuning adjustments were highly significant.

Despite the focus on LTCC resistors, the approach described here should work with any manufacturing system that have been physically modeled. Systems level input-output black-box representations provide a useful means to represent the system components, for visualizing possible measurement and control schemes. Combining the individual models into a quantitative system model as here for total product/process optimization is applicable to many products ranging from sheet metal to injection molded parts. Finally, the implementation of interactive design tools that can also predict variational changes in a system was proven to contribute significantly to the continuous improvement of quality products in the future.
Appendix

Geometrical measurements for three ink type resistors

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Table A.2: Geometrical measurements for QT131 ink resistors
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Table A.3: Geometrical measurements for QT141 ink resistors
Bibliography


