Application of the Operating Window Concept to Improve Fuser Reliability: A Case Study on Failure Modes of Hot and Cold Offset

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Abstract

A robust design is one which makes the system work as desired under variations arising from the environment, production and wear in use. The goal of robust design activities is to improve the quality of a product by minimizing the transmitted effects of the causes of these variations without requiring the causes to be acted upon. An alternate definition proposed by Clausing is that a robust design is one in which the system operates as close as possible to the ideal function or as far as possible from the possible failure modes. This leads to the concept of Operating Window, which Clausing and Frey define as the region in noise parameter space that avoids failure modes and is bounded by significant parameters at which certain failure modes are excited. This concept of operating window is relatively new in the robust design literature and few examples of possible applications of the technique have been published. Application of this principle to Electrophotography, and in particular, the fusing process, represents a good example of its use. This paper present the work completed to date to apply the operating window concept on the offset failures bounded by hot and cold offset in order to demonstrate the utility of the Operating Window method.

Introduction

The demand for printing seemingly continues to increase. Customers are looking for high accuracy and high operating efficiencies. In a recent survey, operating efficiencies were ranked in the top tier for more than 50% of the time amongst the best opportunities for enhancing the value of the printers and in turn, the company [1]. These increased customer demands call for higher quality printing.

Electrophotography consists of six process steps: charging, exposure, development, transfer, fusing, and cleaning. Each of these process steps impact the ultimate image quality output, the potential defects and the image quality degradation over time. As the last step in the image quality chain, fusing can have a large effect on the final image quality produced. Thus, improving fusing quality and reliability can provide great leverage in improving image quality.

There are many approaches that can be applied to improve the performance of the fusing system. These include, but are not limited to trial and error, statistical process control, reliability engineering, and quality engineering. A technique that is commonly used during the product design phase is robust design. This technique exploits nonlinearities in the relationship between input parameters and output system performance by minimizing the transmitted effects of the causes for input variations but does applications of this technique to improve quality and reliability [2], but it's limitations during concept design phase have been well documented [3].

An alternative perspective of robust design is that its objective is to make the system stay as close as possible to the ideal function and as far away as possible from the failure modes [4]. This concept is illustrated in one dimension in Figure 1. The larger the operating window, the less likely the system is to fail. This approach relies on the identification of the "critical few" parameters and is more appropriate for the technology development phase. Robust technology focuses on setting optimum levels of the control factors in order to reduce their sensitivity to noise and improve quality without affecting cost.

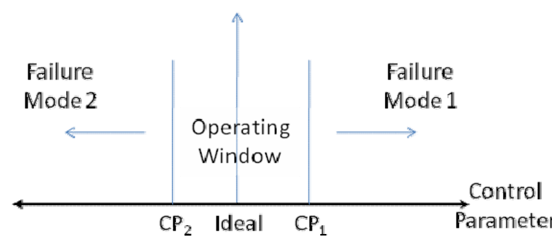

Figure 1: *Operating Window Concept [4]*

The objective of this study is to apply the operating window concept to a fuser system design to illustrate the effectiveness of the approach. For that reason, cold and hot offset failure modes have been selected as a case study as this is a phenomenon that has been studied in depth in the literature. The goal of this study is to generate new insights to improve the design of fuser systems.

Background & Related Work

Hot & Cold Offset

Fusing is a process where the toner particles are fused together and the toner image is permanently fixed to the paper surface [5]. The process of fusing includes heating the toner above its glass transition temperature (causing it to flow), sintering (the individual particles aggregate), spreading over the media, penetration into the media, and re-solidification of the toner [6].

The quality of fusing depends upon the fusing parameters which are those that the fusers, the receiving media, and the toners have in common such as toner temperature, toner properties, roughness of the media surface, fuser sleeve roughness etc. [7]. Acceptable fusing quality is achieved if these parameters are within the fusing window which is bounded by the cold offset failure mode and the hot offset failure mode.

The following descriptions of cold and hot offset are based on Jensen, et al. [8], while image quality effects are based on personal communications by the second author [9]. The unwanted toner transfer onto the receiving media is termed as fuser offset. Fuser offset may occur due to two main causes. One occurs if the fusing temperature is too high (Hot offset) and the other occurs if it is too low (Cold offset). Hot offset occurs when the heat supplied to the fusing roller is too high. This causes an unwanted increase in the fusing nip temperature. When this nip comes in contact with the toner, it heats the toner resulting in reduced viscosity and/or cohesive force beyond the point where the toner will not adhere adequately to the media surface on which it is intended to be imaged. Since the toner viscosity is too low, the dot size will increase and dot shape will deform upon printing and spreads or bleeds into the image causing the image to look distorted.

Cold offset occurs when the heat supplied to the fusing roller is too low. This reduces the fusing nip temperature. When the nip comes in contact with the toner it will not heat up the toner sufficiently and hence the molten toner will not have the required viscosity and/or cohesive force. Such toner when adhered to a printing surface will lead to unacceptable prints. The image will not have sharp definition and the dot size will be reduced. The dot shape will also be randomly disfigured and hence the outcome will be a distorted image.

Fusing Quality Studies

Given the importance of fusing performance to ultimate image quality, it is not surprising that there is much work reported work in the literature. This importance has only increased as the demand for high performance color-toners has grown [10].

Tse, et al. [10], used a toner fusing apparatus to determine the fusing latitude of a variety of toners. They adjusted four process variables (toner, media type, speed, and temperature), in their experiments and used three techniques (visual inspection, crease test, and transmission test) to measure the fixing quality. Two different media types (white paper and clear transparency) were used in order to establish fusing latitudes of four different toners at various speeds.

Jensen, et al.[8], describe a method that increases the fusing latitude of liquid toner in an electrophotographic printer. They used a two stage fusing system, with different covering on the first and the second stage fusing rollers, as opposed to a single stage fusing system. The response variable was the measure of the abrasion resistance of the various fused images. Their study concluded that even at lower temperatures, fusing performance of a system is improved by introducing a two stage roller system instead of one.

Apel, et al. [11], examine the fusing quality versus paper roughness and toner formulation. Different papers were studied to determine the influence of surface roughness on hot roller fusing quality of electrophotographic halftone images. The control variables were the paper roughness and toner formulation. The response variable was the fusing quality as measured by the scotch tape test, fold test, and friction test. Results showed that fusing quality decreases with increase in the paper roughness.

Kato [12] simulated toner fusing performance to design new polymers for toner. Toner fixing characteristics, one of which is hot offset, mostly depend upon the physical properties of the toner. A Molecular Dynamics (MD) model was used in this study to analyze and predict the molecular behavior and characteristics of polymer. This work highlighted the importance of toner properties, such as the glass transition temperature and elasticity, to the fusing performance.

Sankaran and Smith [13] studied the material of the fuser roller and the quality of the print in an electrophotographic digital printing process. They found that soft rollers give excellent print quality but do not last long. On the other hand, hard rollers have a longer life but result in a spotted print. The control variables for this study were the fuser roll materials such as fuser roll coatings, thickness of coatings, surface finish, etc. The response variable was print quality but it was assessed by a team of members who rated and analyzed it. They suggest that the use of hybrid rollers will provide an acceptable print and fuse quality along with durability of the fuser roller.

Briggs, et al. [14], studied the impact of fusing conditions and media design on gloss development. Their research offered new insight into the processes involving complex interactions between the fusing system, toner, media, and the process conditions. The control variables were the fusing temperature, toner coverage, and paper type. The response variable was the gloss. They found that at low gray levels gloss is impacted predominantly by the substrate and at high gray levels by fusing parameters. They also found that as the fusing temperature is raised to increase gloss, basic image quality attributes, such as line quality, may degrade and hence a tradeoff has to be made.

Tse, et al. [15], performed an experimental study in order to explain the effects of process variables such as time, pressure, and temperature and the media variables, and used a crease test to evaluate the fusing quality. Their results showed that basis weight (thickness) is one of the most important media variables and it has a significant impact on the quality of fusing. However, the fusing quality dependence on media thickness can be reduced or eliminated by using a higher fusing temperature and increased applied pressure. They also demonstrate that thermal diffusion is an important rate controlling factor in achieving good fusing quality.

Chaffin, et al. [7], revealed that the type of toner used has the largest effect on gloss after analyzing two current HP Color LaserJet Printers. Their results also showed that image density has the second largest effect on gloss and pressure, temperature, and nip duration are the secondary design variables which should be further used to optimize the fusing system.

Study Objective

The objective of this study is to apply the operating window concept to fusing system using the failure modes of hot and cold offset as the bounds of the operating window. Once the operating window is determined, the design parameters and noise conditions will be taken into consideration in order to open up the operating window to demonstrate how the robustness and reliability of the system could be improved. In this paper, only the work to determine the operating window will be reported.

Methodology and Experimentation

This section will lay the foundation for the experimental methodology, which consists of the development of the experimental apparatus itself and a description of the operating widow concept. This will be followed by a description of the proposed fuser experiment.

Roller-Based Fuser Test Bed

A fusing test apparatus must have a complete fusing system in which the roller speed, temperature, and pressure can be independently adjusted. Also, it must provide control over the material variables such as toner, roller, lubricant, and process variables such as sequence and rate at which the unfused images are fed into the fuser, fuser roller speed, fuser roller surface temperature, roller pressure, and lubrication rate [10].

A roller-based fuser test bed developed at the Print Research and Image Systems Modeling (PRISM) Laboratory at the Rochester Institute of Technology independently controls and senses the normal load, the roller rotational velocity and the roller temperature. It uses a set of rollers from a color laser printer and the actual system is shown in Figure 2.

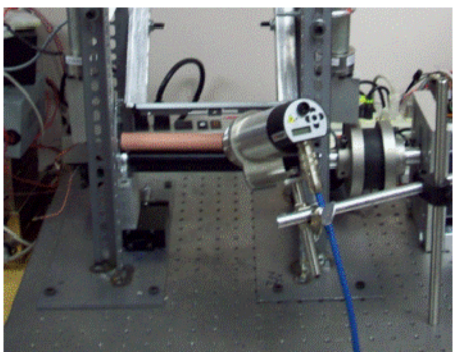

Figure 2: *Roller-Fuser Test Bed*

The test bed was designed for a nip pressure ranging from 0 to 200 psi and pressure sensing accuracy of ± 2 %; the temperature system has a temperature control ranging from 0 to 250 °C and temperature sensing accuracy of ± 1 %; the speed system has a speed control range of 1 to 100 pages / min and speed sensing accuracy of ± 0.05 %. The schematic of the design is shown in Figure 3.

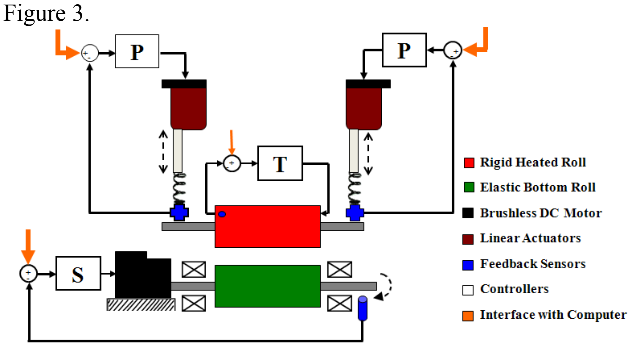

Figure 3: *Schematic of the Roller-Based Fuser test Bed*

Operating Window

The Operating Window concept can be thought of as the range bounded by significant parameters at which certain failure modes are excited. It is the region in noise parameter space that avoids failure modes [16]. The Operating Window approach is a good way to improve robustness as it, along with mistake avoidance, provides system reliability. It has advantages like handling two or more failure modes and can be easily applied to systems where response(s) are difficult to directly observe and measure. A detailed description of the methodology can be found in Clausing and Fey [4]. Only a brief description is provided here.

Noise has two roles in the operating window concept. (a) It forms the basis for the operating window and (b) It is used to intentionally degrade the performance [17]. The goal is to expand the operating window as fast as possible during the development time in order to increase the reliability of the system.

Clausing [17] summarize the Operating Window approach in these steps:

1) Appropriate noise variable(s) are selected and then used as the basis for the Operating Window
2) Fixed but large magnitude of failure rate is defined.
3) Fixed but large magnitude of stressing noise is applied.
4) Range of defining noise variable(s) that produces the fixed magnitude of failure rate is determined.
5) The operating window is expanded by moving through the system control variable space.
6) Set point is adjusted to the interior of the operating window.
7) All this is done during the early stages and the operating window is expanded as much as possible during the available limited time.

After the operating window is expanded, the nominal value is adjusted to the interior of the operating window. If both failure modes are equally undesirable, then this value is set at the midway of the two boundaries of the operating window. However, "when one of the failure modes is more detrimental than the other, then this value is biased away from the more detrimental failure mode" [17].

Fuser Experiment

The objective of this study is to determine the noise factors, the control factors, the response variables, and to establish the operating window and ultimately to expand it for a fuser system using hot and cold offset as the bounds of the operating widow.

The response variable is the quality of the image and the control variables are the fuser roller temperature, the nip pressure (indirectly controlled through the nominal load, P, on the roller), and print speed. On the basis of the results, the failure modes, hot and cold offset, will be determined and the operating window will be established.

Operating Window Basis Defined

Referring back to Figure 1, in this study the obvious basis for the operating window is the Roller Temperature, T. Low fusing temperatures excite the cold offset failure mode and high fusing temperatures excite the hot offset failure mode. If the fusing temperature is lowered, occurrence rate of the cold offset failure mode is increased and at a certain low value of the fusing temperature (T_C), cold offset failure mode becomes almost certain. If the fusing temperature is increased, the occurrence rate of the hot offset failure mode is increased and at a certain high value of the fusing temperature (T_H), hot offset failure mode becomes almost certain.

Failure Rate and Stressing Noise Determination

Steps (2) and (3) from section 0 will be discussed together because in this study, they were determined together. The media thickness is considered a noise factor. If the thickness of the media is relatively large for a given operating condition, the cold offset failure mode will become more frequent. An excitation mode for hot offset, given an operating condition, would be reduced media thickness. In this noise condition, the greater the thickness of the media is reduced then the more likely hot offset becomes.

Given these choices, the objective was to identify a set of media and set of pressure and dwell time combinations that would induce hot and cold offset at the same temperature simply by changing the media type. Thus, the goal was to identify an operating window range of 0 with a 100% failure rate as the initial starting condition.

Range of Defining Noise Variables that Produce Desired Failure Rate Defined

Two different types of media were selected as the noise stressors, card stock (density = 200g/m^2) to induce the cold offset failure mode and 20 lb. paper (density = 75g/m^2) to induce the hot offset failure mode. With these noise parameters fixed, experiments were run in order to determine the values of the parameters, temperature, pressure, and speed, that induce the cold offset failure mode (on a thick media) and hot offset failure mode (on a thin media).

Given the T_C is the temperature to induce cold offset on card stock and T_H is the temperature to induce hot offset on 20 lb. paper, the objective of the experiment is to find a pressure and speed setting such that $T_H - T_C$ is minimized (zero in the ideal).

Cold Offset Experiments

An experiment was designed to determine the values of temperature, pressure, and speed, at which the cold offset failure mode, would be induced. The first experiment was a single replicate, full factorial 3^3 design, i.e. 3 levels of each of the three factors, temperature, pressure, and speed. The response was '1' or '0' where '1' denoted the failure mode and '0' when no failure could be observed.

Table 1 below shows the three factors and their respective levels for the first experiment to induce cold offset failure mode.

Table 1: Initial Cold Offset Experiment

Response	'1' = Offset; '0' = No Offset
Factors	Levels
Temperature (Deg C)	140,150,160
Pressure (PSI)	10 , 20 , 30
Speed (RPM)	70,100,130

The main effects plot for the response, i.e. whether the image is properly fused or not, is shown in Figure 4.

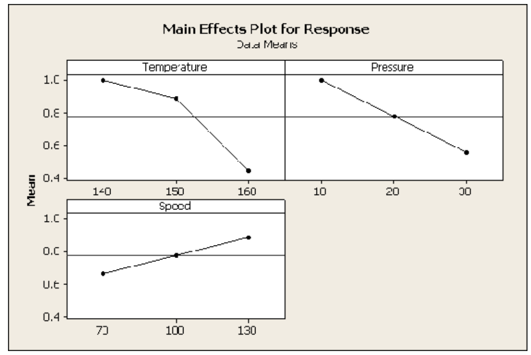

Figure 4: *Main Effects plot for Response for First Cold Offset Experiment*

From Figure 4, it can be seen that as the temperature is lowered, the occurrence of the cold offset failure mode increases, as is expected. Similarly, the occurrence of the cold offset failure mode increases with the decrease in pressure. However, reduction in speed reduces the occurrence of the cold offset failure mode. Thus, the cold offset failure mode can be induced at low values of temperature and pressure, and high values of speed. However, the main aim is to determine the values of temperature, pressure, and speed which would just induce the failure mode. To accomplish this, a second set of experiments was run with the three factors, each at four levels. Table 2 below shows the three factors with four different levels for second experiment.

Table 2: Follow-up Cold Offset Experiment

Response	'1' = Offset; '0' = No Offset
Factors	Levels
Temperature (Deg C)	145,150,155,160
Pressure (PSI)	22,24,26,28
Speed (RPM)	80,90,100,110

The main effects plot for the response for the second experiment is shown in Figure 5.

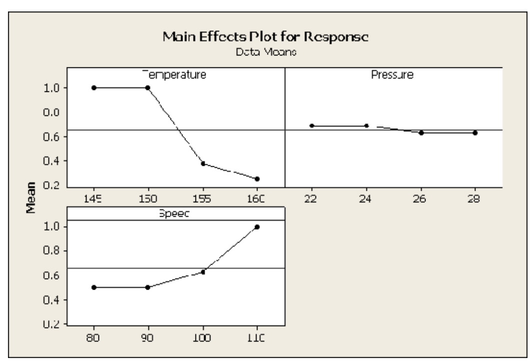

Figure 5: *Main Effects plot for Response for Second Cold Offset Experiment*

Figure 5 shows that an increase in temperature from 145 deg C to 150 deg C, an increase in pressure from 22 psi to 24 psi, and an increase in speed from 80 rpm to 90 rpm does not affect the response. Thus, the values of temperature, pressure, and speed that would just induce the cold offset failure mode were determined to be:

Temperature, T_C: 150 deg C
Pressure: 22 psi
Speed: 80 rpm

Hot Offset Experiments

To determine the optimal values of temperature, pressure, and speed, that would just induce the hot offset failure mode, experiments similar to that of cold offset were run with 20 lb. paper. A 3^3 factorial design with three factors, each at three levels, was design, and is shown in Table 3.

Table 3: Initial Hot Offset Experiment

Response	'1' = Offset; '0' = No Offset
Factors	Levels
Temperature (Deg C)	150,170,190
Pressure (PSI)	10 , 20 , 30
Speed (RPM)	40,70,100

The main effects plot for response is shown in Figure 6.

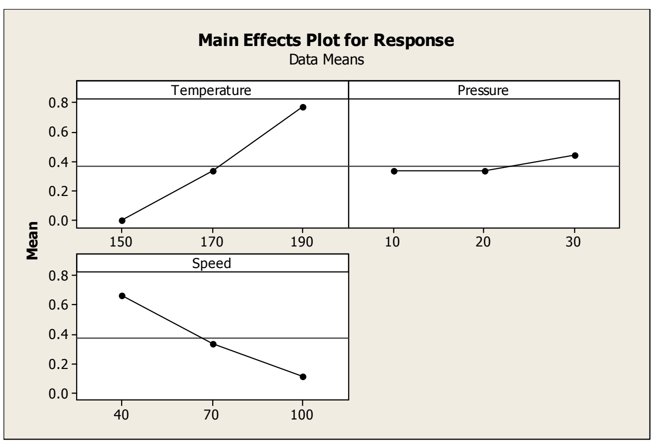

Figure 6: *Main Effects plot for Response First Hot Offset Experiment*

From Figure 6 it can be seen that hot offset failure mode will be induced at high values of temperature and pressure, and low values of speed. Thus, at temperature = 190 deg C, speed = 40 rpm, and pressure = 30 rpm, hot offset failure mode could easily be induced. However, the aim was to determine the optimal values of temperature, pressure, and speed wherein the hot offset failure mode could just be induced. Hence a second set of experiment was run with the levels and values of temperature, pressure, and speed, shown in Table 4.

Table 4: Follow-Up Hot Offset Experiment

Response	'1' = Offset; '0' = No Offset
Factors	Levels
Temperature (Deg C)	165,170,175,180
Pressure (PSI)	20,23,26,29
Speed (RPM)	40,50,60,70

The main effects plot for response for the above experiment is shown in Figure 7.

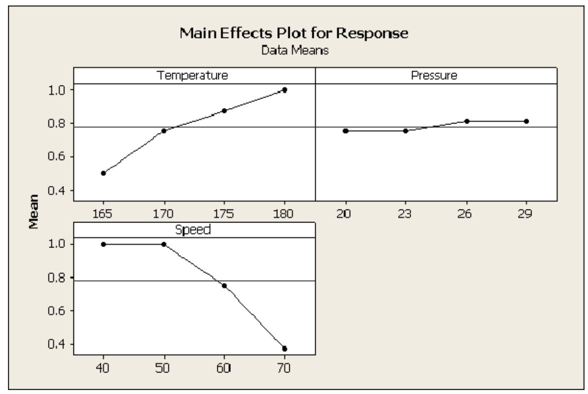

Figure 7: *Main Effects plot for Response Follow-Up Hot Offset Experiment*

From Figure 7 the values of temperature, pressure, and speed which could induce the hot offset failure mode were:

Temperature, T_H: 165 deg C
Pressure: 26 psi
Speed: 50 rpm.

Operating Window

The goal was to create the smallest operating window possible by varying temperature and by keeping pressure and roller speed constant. From the main effects plots (Figure 5 and Figure 7) temperature was found to have the most significant effect in the response followed by speed. The objective of the next experiment was to determine the values of pressure and speed that could be kept constant. The desired values of roller speeds ranged from 80 rpm for cold offset to 50 rpm for hot offset.

From the experiments performed above, it could be seen that the hot offset failure mode was easy to achieve at low rpm and the cold offset failure mode was easy to achieve at high rpm. Given this tradeoff, engineering judgment coupled with some trial and error experimentation led to the selection of 70rpm as the speed where the minimum operating window was achievable.

At a speed of 70 rpm and a pressure of 22 psi (pressure was relatively insensitive to changes in the ranges chosen), it was observed that the hot offset failure mode could be induced at temperature, T_H = 180 deg C and cold offset could be induced at a temperature, T_C = 145 deg C. The resulting Operating Window is summarized in Figure 8. As can be seen, the operating window has, in fact, increased from 15 degrees (where pressure and speed and optimized for each individual failure mode) to 35 degrees where the only parameter that is allowed to be changed is the noise stressors.

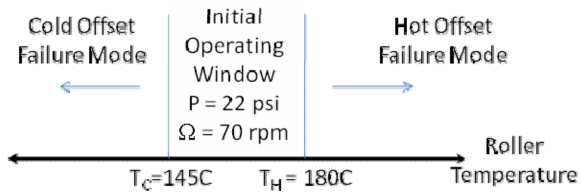

Figure 8: *Resulting Operating Window*

Next Steps and Discussion

Up to this point an Operating Window and operating conditions have been established such that either failure mode can be induced by changing the noise stressor and operating temperature. The next step in the operating window process would be to develop a set of fuser design parameters that could be changed such that under the conditions identified above, it would open up the operating window. As an example, consider the effect of roller material as discussed by Sankaran and Smith [13]. Clearly the material choice would affect many image quality characteristics and should affect the onset of offset.

By a similar process, important design parameters would be identified. Some of the factors have already been identified in the literature review. Other factors can be identified by employing techniques such as fishbone diagramming (to identify cause and effect relationships) and the application of mechanistic models to identify pertinent design parameters.

After the design parameters of interest have been identified, experimentation would proceed in the high fail rate conditions identified above. The parameters need to be systematically studied so that the operating window is progressively opened up. At some point the decision is made that enough experimentation has been performed. The last step in this process would be to return the fusing system to its normal operating conditions, as would be dictated by customer requirements. If the operating window concept was successful, this would result in improved field performance.

A final comment should be made about the measurement of the response variable. In this study a binary variable, yes/no, was used. In the future, optical density, gloss and standard fixing quality tests will also be used to determine quality.

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Author Biography

Marcos Esterman Jr. received his BS and MS in Mechanical Engineering from the Massachusetts Institute of Technology (1988 and 1990) and his PhD in Mechanical Engineering from Stanford University (2002). Marcos has worked for Hewlett-Packard's Imaging and Printing Division in Boise, Idaho. At HP, he held a variety of positions in manufacturing and R&D. His analysis work at HP enhanced design and product architecture decision-making. Marcos also worked as an x-ray tube development engineer at General Electric Medical Systems in Milwaukee, Wisconsin. Currently, Marcos is an assistant professor in the Industrial and Systems Engineering (ISE) Department and is the director of the Print Research and Image Systems Modeling (PRISM) Laboratory at the Rochester Institute of Technology (RIT), which focuses on the modeling of printer and imaging systems to support product architecture and business decisions.

Sourabh Dargan is an MS Candidate in the ISE Department at the RIT. Jonathan Arney and Brian Thorn are both collaborators on this project. Dr. Arney is a Professor in the Center for Imaging Science at RIT and a Senior Scientist in the PRISM lab. He has conducts research in the area of toner optics and behavior. Dr. Thorn is an Associate Professor in the ISE Department at RIT and has expertise in applied statistics and the design of experiments.