Economic Impact of Automation:
The Case of Robotic Thermal Spraying

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Abstract

There is growing interest in the application of robotics to manufacturing processes. The techniques developed to evaluate the economic impact of automation technology, however, are in their infant stage. During the process of automation, firms invest in new technology in the absence of analytical methods to determine whether or not they are making the best economic choice. The lack of analytic techniques to assess the productivity effects of automation technology prevents progress from being monitored in financial terms. Without defined economic objectives, any disruption in the production process can be used to abondon the new system. This paper is part of a research project to develop methodologies to assess the economic and productivity effects of new automation technology including robotic operations. In particular we explore the case of thermal spraying robots and provide a methodology to identify the most cost effective robot given the available alternatives of spraying specifications. The methodology can be applied also on other areas of manufacturing automation such as robotic assembly and robotic welding.

1. Introduction

There is growing interest in the application of robotics to manufacturing automation. The techniques developed to evaluate the economic and productivity impact of new automation technology, however, are in their infant stage. Many firms invest in new technology in the absence of analytical methods to determine whether or not they are making the best economic choice [Kutay 89]. Problems encountered during the production process are then blamed on the new systems.

The lack of analytic techniques to assess the productivity effects of automation technology prevents progress from being monitored in financial terms. Without defined economic objectives, any disruption in the production process can be used to justify abondoning the new systems. This paper is part of a research project to develop methodologies to assess the economic and productivity impact of automation technology including robotic operations. In particular we explore the case of thermal spraying robots in rapid tool manufacturing based on sprayed metal tooling and provide a methodology to identify the most cost effective robot given the available alternatives of spraying specifications.

While there are several examples of justification for the initial acquisition of a robot in the literature, the economic analysis of integrating a robot to a manufacturing operation should include all of the significant costs and benefits which may result from the investment. The economic impact analysis of a robotic system can be categorized into three groups:

1. Justification of the initial investment of capital
2. The analysis of the method of performing a function using a particular operation
3. The analysis of the effect of design features of a product upon the costs of operation

Models on justification of the initial investment of capital to purchase the robot have several drawbacks. First, they have excluded the uncertainty of the market brought by rapid technological and economic developments, and second, they have overlooked the importance of the flexibility benefits of robotic systems to enable a company to become more competitive in the market. These factors are reflected only in a few studies in literature.[1]

Studies in the second group investigate the cost effectiveness of using robots to perform certain manufacturing operations such as assembly or welding.[2] The major shortcoming of these studies is their tendency to use traditional methods used by manufacturing engineers to evaluate the cost reductions that can be obtained through new equipment or fixture purchases. The transfer of these traditional methods to evaluate the benefits of robotic systems prove to be unsuccessful.

The third area, analysis of the effect of design features of a product upon the costs of operation using a robotic system, is relatively a new research area. A few studies have focused particularly on the effect of design on the cost of using robots in welding operations [Knott 88] and assembly operations [DeFazio 81].

In this paper, we illustrate a framework of analysis to assist production engineers and designers in selecting the best economic combination of alternative spraying specifications and thermal spraying robots with different capabilities. The methodology is also applicable to other operations such as robotic

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[1] See for example [Kutay 89] and [Kutay 90]

[2] See [Abrahams 79]

assembly and robotic welding.

The use of robots to improve the quality of the spraying process in rapid tool manufacturing based on sprayed metal tooling is one of the new areas of manufacturing automation. The need to accurately execute spray paths based on expert knowledge and to consistently repeat operations makes a robotic system essential in the rapid tool manufacturing domain [Weiss 90].

We suggest that the introduction of a robot into a spraying operation raises questions both of spraying features and producibility that can be approached through a formal framework of analysis. For example, the design of clearance fits and tolerances in the tool determines the success rate of a spraying operation. In section 2, we provide a brief description of the sprayed metal tooling system analyzed in the paper.[3] Section 3 proceeds with the development of a methodology to assess the economic feasibility of thermal spraying robots in the rapid tool manufacturing domain. In section 4, we provide an application of the methodology. In section 5, we demonstrate the relationship between spraying features and robot accuracy by considering different alternatives of spraying specifications and accuracy levels to improve the probability of a successful spraying operation. We then assess the productivity effects by converting the probability of a successful spraying operation to an output rate of components without any defects.

2. Sprayed Tooling

The spraying process analyzed in this paper is a part of a unified CAD/CAM tool manufacturing system. In this system, both prototype and tooling fabrication are based upon compatible shaping deposition processes, while the underlying geometric and process models share a common representational scheme. The system incorporates two commercially available technologies: stereolithography apparatus (SLA) and arc spray equipment. SLA is a new process which creates plastic models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam. As the laser beam draws on the liquid surface it creates cross-sections of the solid shape. Complete three dimensional shapes are built-up by drawing cross-sections on top of each other with each new layer being lowered into the vat by an elevator mechanism. SLA is excellent for rapidly producing plastic prototype models.

In arc spraying, metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface. On contact, the sprayed material solidifies and forms a surface coating. Thermal spraying is an arc spraying application in which spray coating are repeatedly applied to incrementally deposit multiple fused layers. The layers, when seperated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can be fabricated. Relative to conventional machining methods, the sprayed metal tooling approach has the potential for fast and cost effective production of tools, particularly for those parts with complex shapes or large dimensions. Thus, with SLA an initial part shape or prototype is quickly created. Thermal spraying is then used to make tools based on the part shapes produced by SLA.

The concept of sprayed metal tooling has been in existence for decades [Gamer 71]. Current commercial technology uses electric arc spraying. The arc spray process, in Figure 1, uses two spools of metal wire which are fed to a spray gun where the wire tips form consumable electrodes. A high current is passed

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[3] See [Weiss 90] for a detailed explanation of rapid tool manufacturing based on sprayed metal tooling.

through the electrodes creating an arc which melts the wire tips. The molten particles are atomized by a high pressure air jet directed at the arc and are accelerated in the air stream. These particles strike the surface where they flatten out and quickly solidify.

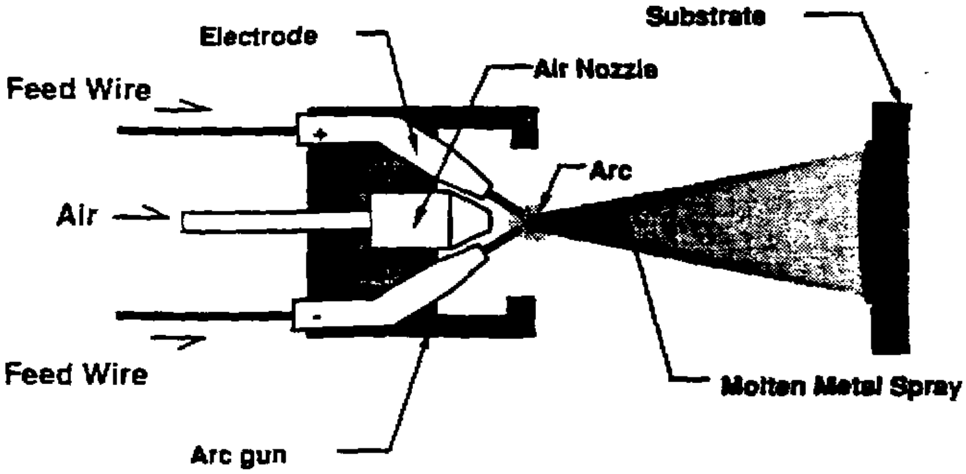

Figure 1: Electric Arc Spraying

A conventional machined injection mold is shown in cross section in Figure 2. The holes represent cooling/heating channels, and the injection geometry is that of a simple sprue gate. Alternatively, the fabrication steps for building a sprayed mold using SLA patterns are depicted in Figure 3.

The steps are:

- **STEP 1:** Build SLA pattern used to make one mold half. This pattern is the complement of the interior of this mold half. In this example, the mold pattern includes the partial part shape, a parting plane, and sprue gate.
- **STEP 2:** Apply a water soluble release agent onto the plastic pattern, such as polyvinyl alcohol (PVA), to facilitate separation of metal from plastic.
- **STEP 3:** Place a metal frame onto the pattern.
- **STEP 4:** Spray metal onto the pattern and around inside edge of frame. Alloyed zinc compositions are used for this particular process because of their relatively low residual stress. Sprayed shell thickness' are typically on the order of 2 to 7 millimeters. Fine pattern details are accurately replicated by this spray process.
- **STEP 5:** Lay in place copper tubing for heating and cooling channels for the injection mold process. Additional injection mold components, such as prefabricated ejector pin assemblies (not shown), can be added in STEP 1 and sprayed in place in STEP 4.

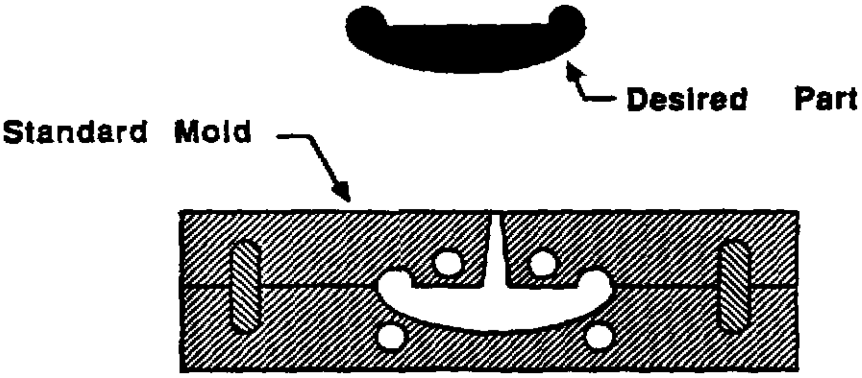

Figure 2: Conventional Mold

- **STEP 6:** Pour in a backing material to support the metal shell. Typical backing materials include epoxy mixed with aluminum shot.
- **STEP 7:** Separate the substrate pattern from the mold half. This is aided by dissolving the PVA in water. This completes the fabrication of the first mold half.
- **STEP 8:** With SLA, build a model of the whole part to be molded, including runners and gates, and insert the model into the first mold half. This forms the pattern for spraying the second mold half.
- **STEP 9:** The second mold half is completed by repeating Steps 2 through 7.

The mold fabrication is completed by removing the SLA insert.

The potential affect of combining thermal spraying with SLA to build tooling is enhanced by integrating and automating these processes within a unified CAD/CAM environment. Integration reduces the number of iterative cycles through design, prototyping, and fabrication. Another step in the CAD/CAM approach is to automate the thermal spray process with robotics. Tooling manufacture by thermal spraying is currently a labor intensive manual art-form. Shifting emphasis to robotic spraying, driven by an off-line trajectory and process planner, improves tooling quality by achieving consistent and predictable performance of the sprayed metal shell. In robot motion control, the accuracy of the robot is very important. Accurate execution of spray paths based on expert knowledge and to consistently repeat operations makes a robotic system essential. Arc spraying robots [Metco 85] currently provide repeatability in surface coating applications [Tafa 85]. However, the spray paths are manually generated with a teach pendant for all but the simplest part geometries. Automated and intelligent decision making capabilities, using expert knowledge compiled in design models for off-line path generation, are absent from these systems.

Automated thermal spraying requires the scheduling of the arc spray parameters and the selection of the

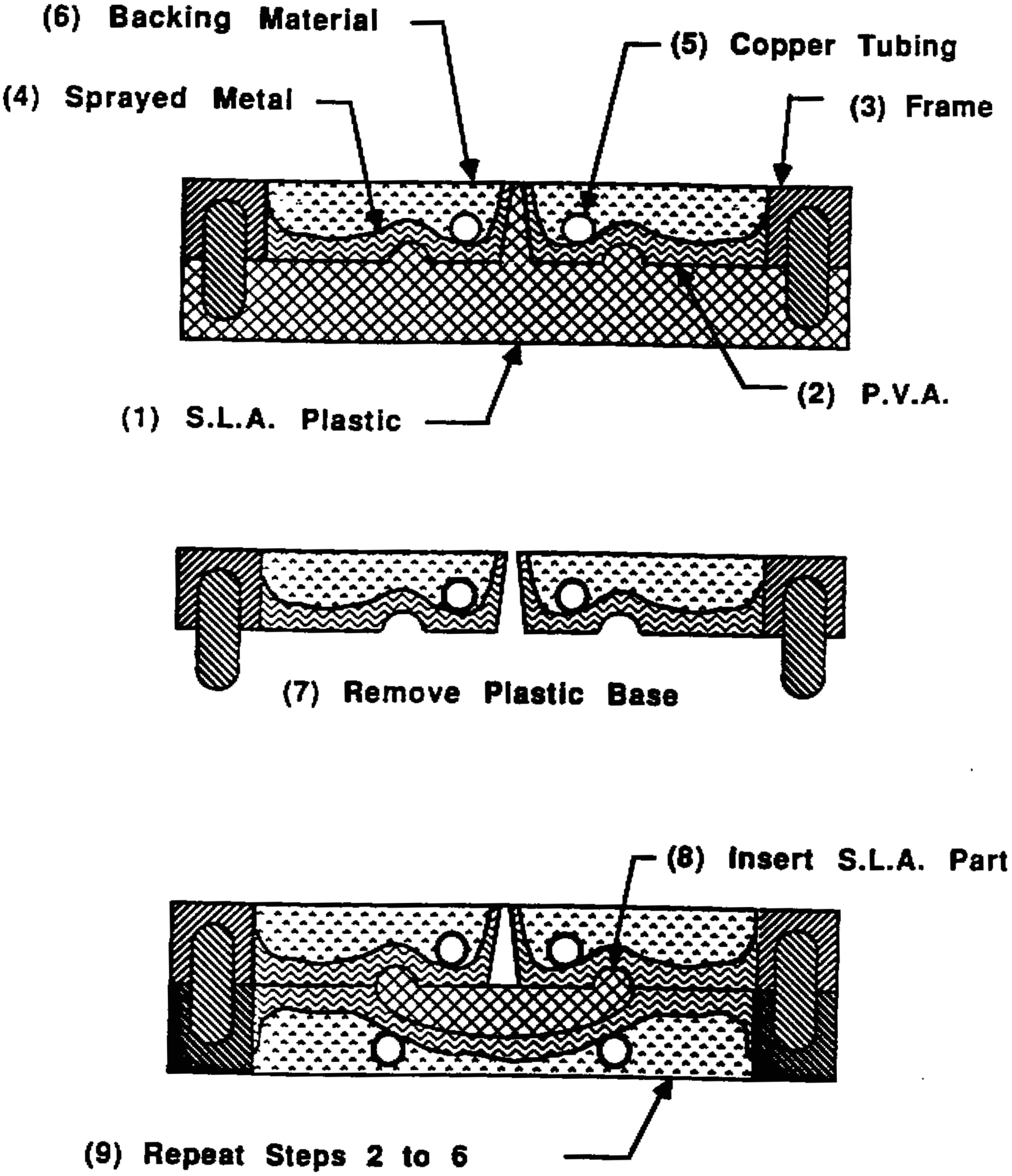

Figure 3: Sprayed Tool Process

robot trajectory. The arc parameters include arc voltage, wire feed rate, atomizing gas pressure, automizing gas type, wire diameter, and nozzle geometry. While statistical methods exist to tune the thermal spray process prameters to produce optimal coating quality [VanDoren 84], extending the optimization to include robot trajectory provides added dimensions to the problem. Trajectory planning involves determining the relative path of the spray on the part and feature-based planning may be considered as one approach. While arc parameters directly affect the sprayed shell quality, the path of the gun is also important. To prevent problems of overspray, particle trajectories should align with the surface normals to assure maximal splattering of the molten particles. As the angle between the particle trajectory and surface normal increases, shell quality degrades. The particles may bounce of the surface as wasted overspray or become entrapped in the shell reducing its strength.

There is also interdependence between the accuracy of the robot, tolerances on the motions of the robot arm, and the quality of the sprayed part. The ability to accurately control gun orientation is critical since overspraying an area affects the quality of the tool surface and causes the manufacture of components which do not meet design specifications.

3. The Methodology

In this section, we develop a methodology to select the best economic combination of spraying features such as tolerance and clearance, and thermal spraying robots with different accuracy levels. *Tolerance* is a specified permissible magnitude of error from the prespecified distance of the spray gun from the surface and the horizontal orientation of the spray gun. The main factors that affect tolerance is the limits of the *accuracy* of the robot and the requirements for obtaining an optimal deposition process.

The methodology should assist production engineers to select the most cost effective robot system given robot accuracy levels and the spraying features. The methodology should also help designers to identify hard to obtain spraying features so that they can be modified before reaching the fabrication stage. The methodology, however, is applicable only when gun orientation is normal to the substrate and the gun axis is perpendicular to a flat surface. The case of convex and concave surfaces and cavities is the subject of future research.

During the spraying process, distribution of sprayed particles on the surface follows a Gaussian distribution. As depicted in Figure 4, a prespecified length of overlap of two adjacent spray areas is necessary to obtain a smooth sprayed surface. This requires that the gun is kept at a specified vertical distance from the surface and second make the precise specified horizontal motion. These conditions are demonstrated in Figure 4. As can be seen in Figure 4, in order to achieve a successful spraying operation, the distance of the gun from the surface has to be H^*. If the vertical distance of the gun is other than H^*, surface quality reduces due to non-optimal deposition. In addition, the spray gun has to make the precise horizontal movement L^*. Otherwise, surface quality problems may arise due to a non-optimal deposition process. Thus, a successful spraying operation requires that the spray gun is kept at a vertical distance H^* from the surface *and* the horizontal motion of the gun from one point to the next is L^*.

We define:

H – actual distance of the spray gun from the surface

h_{min} – a minimum allowable tolerance for an acceptable spraying operation

h_{max} – a maximum allowable tolerance for an acceptable spraying operation

L – actual horizontal distance of the spray gun from one spray point to the next

l_{min} – a minimum allowable tolerance for an acceptable spraying operation

l_{max} – a maximum allowable tolerance for an acceptable spraying operation

If the spraying operation is done manually, the conditions for a quality spraying operation are:

$$h_{min} \leq |H^{*} - H| \leq h_{max}$$

and

$$l_{min} \leq |L^{*} - L| \leq l_{max}$$

The distributions of H and L can be represented by h and l with the following mean and standard deviation:

$$\mu_h = \frac{minimum\ heigth + maximum\ heigth}{2}$$

$$\mu_l = \frac{minimum\ length + maximum\ length}{2}$$

$$\sigma_h = \frac{tolerance_h}{6}$$

$$\sigma_l = \frac{tolerance_h}{6}$$

Defining the variable

$$y_h = |H^{*} - H|$$

with mean and variance

$$\mu_{y_h} = Tolerance_h$$

$$\sigma_{y_h}{}^2 = (\sigma_h)^2$$

Defining the variable

$y_l = |L^* - L|$

with mean and variance

$\mu_{y_l} = Tolerance_l$

$\sigma_{y_l}^2 = (\sigma_l)^2$

Under manual spraying, the condition for a successful spraying operation is:

$Y_h \geq 0$ and $Y_l \geq 0$

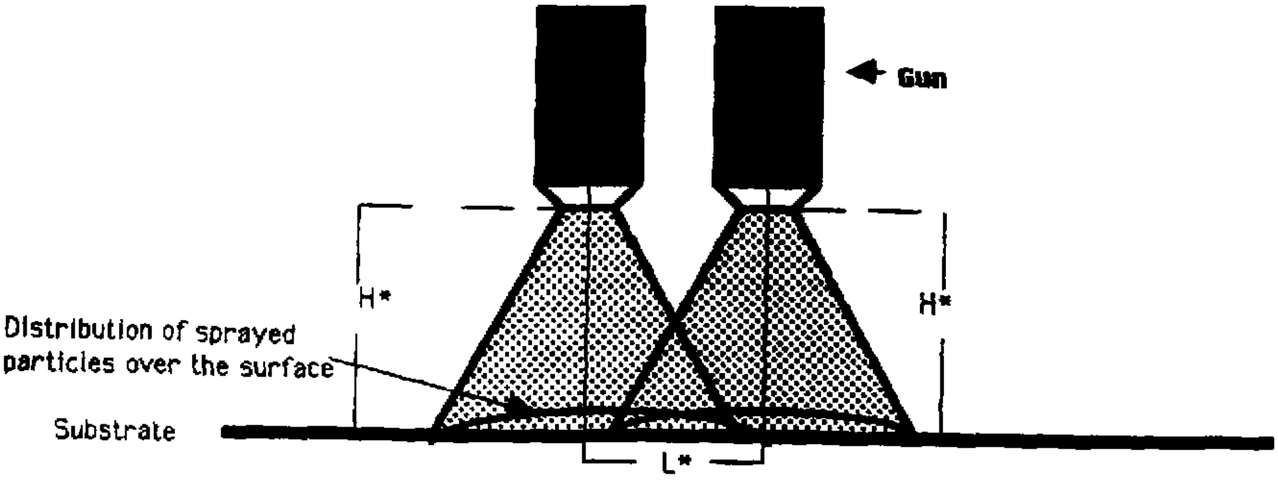

Figure 4: The Conditions for a Successful Spraying Operation

In order to analyze robotic spraying, we define:

d - the displacement from H* and L*,

X_A - the accuracy of the robot,

Then d is a random variable in the range:

$$-X_A \leq d \leq +X_A$$

Since displacement in any direction will cause an unsuccessful spraying operation, the following conditions must be satisfied for successful spraying:

$$d \leq 0.5|L^* - L|$$

and

$$d \leq 0.5|H^* - H|$$

where L and H are in the range of a specified permissible magnitude of error (i.e., tolerance) from L* and H*.

We represent:

$$|L^* - L| = D_L$$

$$|H^* - H| = D_H$$

3.1. The Probability of a Successful Spraying Operation for Normally Distributed Clearance and Uniformly Distributed Accuracy

The distributions of L and H can be represented by l and h, which can be approximated to a normal distribution with mean μ_l, μ_h, and variance $(\sigma_l)^2$, $(\sigma_h)^2$. Similarly, the distributions of D_L and D_H can be represented by d_L and d_H with the mean and standard deviation:

$$\mu_{d_L} = \frac{minimum\ length + maximum\ length}{2}$$

$$\mu_{d_H} = \frac{minimum\ heigth + maximum\ heigth}{2}$$

$$\sigma_{d_L} = \frac{tolerance_L}{6}$$

$$\sigma_{d_H} = \frac{tolerance_H}{6}$$

The 6σ limit encompasses an area of 0.997 under the normal distribution and is a very close approximation.

Redefining the variable $y_L = 0.5D_L$ with mean and variance:

$$\mu_{y_L} = 0.5\mu_{d_L}$$

$$\sigma_{y_L}{}^2 = 0.5^2(\sigma_{d_L})^2$$

Redefining the variable $y_H = 0.5D_H$ with mean and variance:

$$\mu_{y_H} = 0.5\mu_{d_H}$$

$$\sigma_{y_H}{}^2 = 0.5^2(\sigma_{d_H})^2$$

where μ_{y_L} and μ_{y_H} are the mean values of the clearance range, and $\sigma_{y_L}{}^2$ and $\sigma_{y_H}{}^2$ are the variances of the clearances.

It is assumed that the robot accuracy X_A has a probability density function of $f(X_A)$. If *c* is the domain of clearance, and *t* is the domain of accuracy, then the probability of obtaining L* or H* is:

$$P(C \geq T) = \int_{C=0}^{C_{max}} \int_{T=0}^{C} f(t)\, f(c)\; dt\; dc$$

Assuming that $f(X_A)$ has a uniform distribution:

$$P(C \geq T) = \int_{C=0}^{X_A} \int_{T=0}^{C} \frac{1}{X_A} \theta(c)\, dt\, dc + \int_{X_A}^{\infty} \theta(c)\, dc$$

where:

$$\theta(c) = \frac{1}{\sqrt{2\Pi}\sigma_c} exp\,[-\frac{1}{2}(\frac{c-\mu_c}{\sigma_c})^2]$$

$$P(C \geq T) = \frac{1}{X_A}\{[\int_{-\infty}^{\infty} c\theta(c)\, dc - \int_{-\infty}^{0} c\theta(c)\, dc - \int_{X_A}^{\infty} c\theta(c)\, dc] + [1 - \int_{-\infty}^{X_A} \theta(c)\, dc\}$$

$$P(C \geq T) = \frac{\mu_y}{X_A} - \frac{1}{X_A}[\int_{-\infty}^{0} c\theta(c)\, dc + \int_{X_A}^{\infty} c\theta(c)\, dc] + [1 - \int_{-\infty}^{X_A} \theta(c)\, dc]$$

The probability of $Y<0$ is very small and

$$\int_{X_A}^{\infty} c\,\theta(c)\, dc = \sigma_y \theta(X_A) + \mu_y [1 - \int_{-\infty}^{X_A} \theta(c)\, dc],$$

$$P(C \geq T) = \frac{1}{X_A}\{\mu_y - \sigma_y \theta(X_A) - \mu_y [1 - \int_{-\infty}^{X_A} \theta(c)\, dc)]\} + [1 - \int_{-\infty}^{X_A} \theta(c)\, dc]$$

A successful spraying operation requires that both L* and H* are obtained. Since H* and L* are independent, the probability of a successful spraying operation *P(S)* for normally distributed clearance and uniformly distributed accuracy is:

$$P(S) = [P(C \geq T)]_{H^*} . [P(C \geq T)]_{L^*}$$

4. Application of the Methodology

Using X_A = 0.04 in. and the following spraying specifications, the probability of a successful spraying operation can be calculated as follows:

Distance of the spray gun from the surface, (H*) = 2.50 in.

Tolerance = +/- 0.06 inches

Range = 2.56 inches maximum - 2.44 inches minimum

Clearance = 0.12 inches

Horizontal distance of the spray gun between two spray points, (L*) = 3.00

Tolerance = +/- 0.07 inches

Range = 3.07 inches maximum - 2.93 inches minimum

Clearance = 0.14 inches

$$\mu_{d_H} = 0.06$$

$$\sigma_{d_H} = \frac{0.06}{6} = 0.01$$

$$\mu_{y_H} = 0.5\ \mu_{d_H} = 0.03$$

$$\sigma_{y_H} = 0.5^2\sigma^2 = 0.05$$

$$P(C \geq T)_{H^*} = \frac{1}{0.04}\ [0.03 - (0.05)\ (0.1476) - 0.03\ (1 - .9207)] + [1 - 0.9207] = 0.75$$

$$\mu_{d_L} = 0.07$$

$$\sigma_{d_L} = 0.07/6 = 0.0117$$

$$\mu_{y_L} = 0.5(\mu_L) = 0.035$$

$$\sigma_{y_L} = 0.5^2\sigma^2 = 0.00585$$

$$[P(C \geq T)]_{H^*} = \frac{1}{0.04}\ [0.035 - (0.00585)\ (0.1476) - 0.035\ (1 - 0.9207)] + [1 - 0.9207] = 0.8733$$

$$P(S) = [P(C \geq T)]_{H^*} . [P(C \geq T)]_{L^*} = 0.75 \times 0.8733 = 0.66$$

Thus, using a robot with an accuracy level of 0.04, the probability of a successful spraying operation for tolerance level of 0.06 on H*, and a tolerance level of 0.07 on L*, is 66%.[4]

4.1. The Probability of a Successful Spraying Operation for Uniformly Distributed Clearance and Uniformly Distributed Accuracy

We may extend the result obtained above to the case of uniformly distributed clearance and robot accuracy:

If $Y_{max} > X_A$, then,

$$P(C \geq T) = \int_{C=0}^{X_A}\int_{T=0}^{C} f(t)f(c)\,dt\,dc + \int_{X_A}^{Y_{max}} f(c)\,dc$$

$$P(C \geq T) = \int_{0}^{X_A}\int_{0}^{C} \frac{1}{X_A}\frac{1}{Y_{max}}\,dt\,du + \int_{X_A}^{Y_{max}} \frac{1}{Y_{max}}\,du$$

$$P(C \geq T) = \int_{0}^{X_A} \frac{c}{X_A}\frac{1}{Y_{max}}\,dc + \frac{Y_{max}-X_A}{Y_{max}}$$

$$P(C \geq T) = \frac{[X_A]^2}{2X_AY_{max}} + \frac{Y_{max}-X_A}{Y_{max}}$$

$$P(C \geq T) = \frac{2Y_{max}-X_A}{2Y_{max}}$$

If $Y_{max} \leq X_A$, then,

$$P(C \geq T) = \int_{C=0}^{Y_{max}}\int_{T=0}^{C} f(t)f(c)\,dt\,dc$$

$$P(C \geq T) = \int_{C=0}^{Y_{max}} \frac{c}{X_A} f(c)\,dc$$

$$P(C \geq T) = \frac{[Y_{max}]^2}{2X_AY_{max}}$$

$$P(C \geq T) = \frac{Y_{max}}{2X_A}$$

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[4] In this example, for illustrative purposes we selected different tolerance levels on H* and L*. Usually tolerance levels on H* and L* should be equal.

5. Implications for the Spraying Process

If the probability of a successful spraying process is not adequate, other alternatives can be considered to improve the process. Improving the accuracy of the robot may be one option. Another option may be to modify design to improve the probability of successful spraying by increasing allowances.

	SPRAYING FEATURES	
Tolerance	Clearance Range	μ_y
0.06	2.44 - 2.56	0.030
0.07	2.43 - 2.57	0.035
0.08	2.42 - 2.58	0.040
0.09	2.41 - 2.59	0.045
0.10	2.40 - 2.60	0.050

Table 1: Alternatives of Spraying Features

We first considered increasing allowances for H^*. As can be seen in Table 1, the clearance range has increased by 8 inches, from 2.44 in. - 2.56 in., to 2.40 - 2.60, when tolerance level has increased from .06 to .10 in.

Table 2 shows the probability of holding H^* or L^*, (i.e., $P(C \geq T)$) for various robot accuracies and tolerance levels. As can be seen in the table, to achieve $P(C \geq T) = 0.75$ for a tolerance level of 0.01, we need a robot with an accuracy level of 0.01. We, however, need a robot with an accuracy level of 0.03 to achieve the same level of probability for a tolerance level of 0.04.

Similarly, if the most accurate robot we can obtain has an accuracy level of 0.07, we may improve the probability level from 14.3 to 80.6, by increasing tolerance from 0.01 to 0.09 through design modifications. The probability level, however, can be as high as 97.2 with a robot accuracy level of .01.

Figure 5 demonstrates that for more precise spraying operations, the probability of obtaining optimal spraying is highly affected by robot accuracy level. The probability of optimal spraying, however, is less affected by robot accuracy level for tolerance levels .06 and higher.

We can convert the probability level of holding the spray gun at H^* and L^* to an output rate of components without any defects. Assuming that sequential operations of individual spraying operations on an SLA mold part are independent and that the production of parts without any defects are directly affected by the quality of the spraying operation on the mold, the productivity rate is given by:

	ROBOT ACCURACY (X_A)						
TOLERANCE	.07	.06	.05	.04	.03	.02	.01
.01	.143	.167	.200	.250	.333	.500	.750
.02	.286	.333	.400	.500	.625	.750	.875
.03	.423	.500	.583	.667	.750	.833	.917
.04	.563	.625	.688	.750	.813	.875	.938
.05	.650	.700	.750	.800	.850	.900	.950
.06	.708	.750	.792	.833	.875	.917	.958
.07	.750	.786	.821	.857	.893	.929	.964
.08	.781	.813	.844	.875	.906	.938	.969
.09	.806	.833	.861	.889	.917	.944	.972

Table 2: The Probability of Holding the Robot Gun at a Prespecified Position for Various Combinations of Robot Accuracy and Tolerance Level

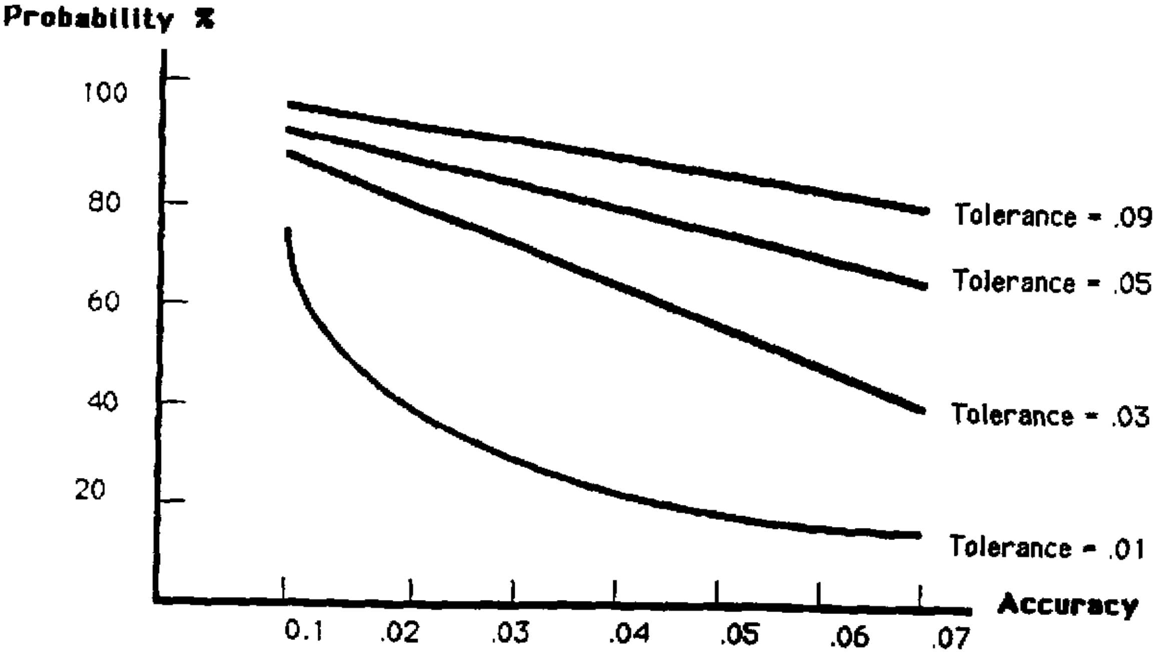

Figure 5: The Relationship Between Probability of Successful Spraying and Robot Accuracy for Various Levels of Tolerance

$$P_r = P(C \geq T)\frac{1}{ct}$$

The output per hour of components without any defects for a cycle time of 45 seconds is shown in Table 3. As can be seen in Table 3, the probability level of 97.2 for holding H* or L*, can be converted to an average productivity rate of 78.6 units per hour.

Similarly, the probability of a successful spraying operation P(S), can be converted to a productivity rate

$$P_r = P(S)\frac{1}{ct}$$

where:

$$P(S) = P(C \geq T)_{H^*} \times P(C \geq T)_{L^*}$$

The values for $P(C \geq T)_{H^*}$ and $P(C \geq T)_{L^*}$ can be obtained from Table 2.

Assuming that sequential operations of individual sprays on an SLA mold part are independent and that the production of parts without any defects are directly affected by the quality of spraying operation on the mold, Table 4 shows the productivity effect of a successful spraying operation for various combinations of robot accuracy and tolerance levels.[5]

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[5] The productivity effect has been calculated based on the assumption that tolerance levels on H* and L* are equal.

	ROBOT ACCURACY (X_A)						
TOLERANCE	.07	.06	.05	.04	.03	.02	.01
.01	11.4	13.3	16.0	20.0	26.7	40.0	60.0
.02	22.9	26.7	32.0	40.0	50.0	60.0	70.0
.03	34.3	40.0	46.7	53.3	60.0	66.7	73.3
.04	45.0	50.0	55.0	60.0	65.0	70.0	75.0
.05	52.0	56.0	60.0	64.0	68.0	72.0	76.0
.06	56.7	60.0	63.3	66.7	70.0	73.3	76.7
.07	60.0	62.9	65.7	68.6	71.4	74.3	77.1
.08	62.5	65.0	67.5	70.0	72.5	75.0	77.5
.09	63.8	64.4	66.7	68.9	71.1	73.3	78.6

Table 3: Productivity Implications of Holding the Robot Gun at a Prespecified Position

	ROBOT ACCURACY (X_A)						
TOLERANCE	.07	.06	.05	.04	.03	.02	.01
.01	1.63	2.22	3.20	5.00	8.89	20.0	45.0
.02	6.53	8.89	12.8	20.0	31.3	45.0	61.3
.03	14.7	20.0	27.2	35.6	45.0	55.0	67.2
.04	25.3	31.3	37.8	45.0	52.8	61.3	70.3
.05	33.8	39.2	45.0	51.2	57.8	64.8	72.2
.06	40.1	45.0	50.1	55.6	61.3	67.2	73.5
.07	45.0	49.4	54.0	58.8	63.8	69.0	74.4
.08	48.8	52.8	57.0	61.3	65.7	70.3	75.1
.09	51.9	55.6	59.3	63.2	67.2	71.4	75.6

Table 4: Productivity Implications of Various Combinations of Robot Accuracy and Tolerance Level

6. Concluding Comments

The decision to introduce a robot into a spraying operation raises considerations of robot selection and spraying features. This paper provided a framework of analysis for designers and production engineers to identify the best economic combination of alternative spraying features and thermal spraying robots with different accuracy levels. We also provided an application of the methodology and demonstrated how the probability of a successful spraying operation can be improved by considering different alternatives of spraying specifications and robot accuracy levels. We then assessed the productivity effects by converting the probability of a successful spraying operation to an output rate of components without any defects.

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