

Productivity Analysis of a Scanning Inkjet Printer

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Abstract

This paper presents both a productivity model and a cost model of a scanning inkjet printer. The productivity model shows the performance and efficiency of the printer and the cost model shows the manufacturing costs. The effect of all relevant design parameters on the productivity are explained and guidelines for improving the productivity are given. Analysis of the productivity and in particular of the ratio of productivity and costs is shown to be useful for optimization of the design parameters of the scanning inkjet printer regarding productivity, efficiency and cost price.

Introduction

Our research¹ aims at increasing productivity (defined as the amount of printed surface area per unit of time) of scanning inkjet printing systems, while maintaining or decreasing costs and maintaining or improving print quality. Past research results in the field of scanning inkjet printers are focussed on print quality and not on productivity or costs, see for instance Refs. [1], [2] and [3]. Hardly any results have been published on increasing productivity, and to be more specific, increasing the productivity in a cost-efficient way. Two questions that arise in this respect are: 1) How do printer design parameters relate to productivity? 2) Which design parameters should be adjusted for the productivity of a particular printer configuration to be improved? To be able to answer these questions, a productivity model will be useful. Analysis of the productivity model will provide insight into how to choose the design parameters for printers in the development stage. In Ref. [4], a productivity model is presented that is targeted at design parameters regarding heat management.

In this paper we present a productivity model that describes the relation between 18 independent printer design parameters and the productivity of a printer. In contrast with Ref. [4], we will mainly deal with mechanical design parameters because these are the most relevant parameters that determine the productivity. The model and the visualization of simulation results are designed to give more insight into how printing productivity can be improved for a particular printer configuration. Furthermore, a method is proposed to include manufacturing costs as a trade off when determining a printing system configuration. This is useful when the productivity-cost ratio is to be maximized.

First we introduce the printing process and its relevant design parameters. Second, we define a productivity model of the printing process. Third, we present a cost model. Next, we show the analysis of these models and finally we give some conclusions resulting from the model analysis.

Printing Process

To determine the relation between the design parameters of the printer and the productivity, we create a model of the printing process. A schematic overview of the printing process used to derive the productivity model is shown in Figure 1.

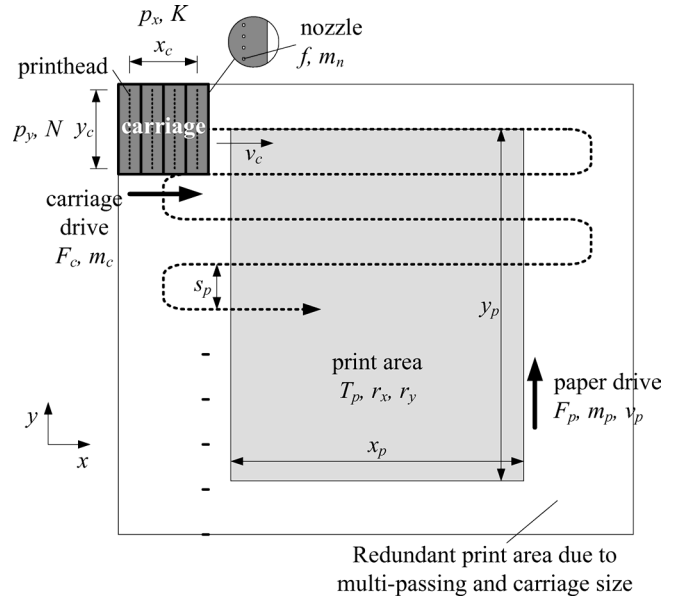


Figure 1. A schematic overview of the printing process used to derive a productivity model.

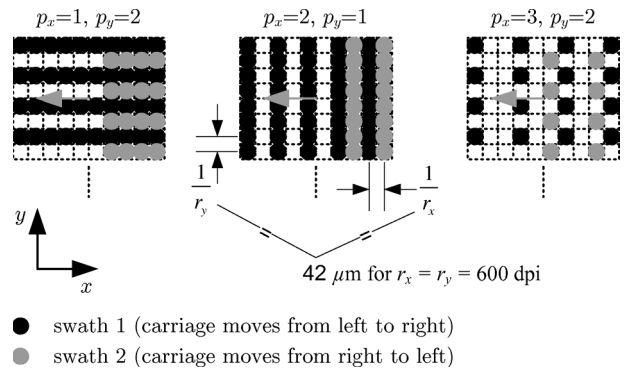


Figure 2. Three examples showing the print strategy multi-pass in x and y. A small part of the print area is shown during the second swath. For the first and second example, 2 swaths are needed to fill all dot spaces. For the third example it is easy to see that $p_x \times p_y = 6$ swaths are needed to fill all dot spaces.

We assume that only one full page is printed and no maintenance is necessary during that print. First, a swath is done which is a movement of the carriage from one side to the other, then it turns simultaneous with a paper translation. This process continues until the whole print area is covered with ink.

Because of the large amount of variables in this paper, a list of definitions is shown in Table 1.

Table 1: Variable Definitions

Var.	Unit	Description
a	$[\text{ms}^{-2}]$	Acceleration
b	$[-]$	Binary variable determining whether bidirectional printing is used ($b=1$) or monodirectional printing ($b=0$).
C	$[\text{€}]$	Total cost price of a printing system
c_n	$[\text{€}]$	Costs per nozzle, partial costs of C depending on the amount of nozzles
c_r	$[\text{€}]$	Costs not depending on the amount of nozzles
D	$[-]$	Amount of dot locations on the print area
f	$[\text{Hz}]$	Jet frequency, the amount of ink drops a nozzle fires per sec
F_c	$[\text{N}]$	Maximum force that the carriage drive can generate
F_p	$[\text{N}]$	Max. force that the print medium drive can generate
K	$[-]$	Amount of colors that can be printed in case N nozzles are available for every color
m_c	$[\text{kg}]$	Total mass of the carriage
m_{cr}	$[\text{kg}]$	Remaining carriage (drive) mass which is not dependent on the amount of nozzles N
m_n	$[\text{kg}]$	Mass per nozzle, partial mass of m_c depending on the amount of nozzles
m_p	$[\text{kg}]$	Total mass of the print medium
m_{pr}	$[\text{kg}]$	Remaining mass not depending on the print medium mass including the print medium drive mass
N	$[-]$	Amount of nozzles of each color
P	$[\text{s}^{-1}]$	Productivity, the amount of prints produced per unit of time
P_0	$[\text{s}^{-1}]$	Productivity of an ideal printer
p_x	$[-]$	Multi-pass in x , amount of swaths necessary to obtain the required resolution in x direction (see Figure 2)
p_y	$[-]$	Multi-pass in y
r_x	$[\text{m}^{-1}]$	Print resolution in x direction
r_y	$[\text{m}^{-1}]$	Print resolution in y direction
S	$[-]$	Amount of swaths required to fill in the whole print area
s_p	$[\text{m}]$	Step-size of the print area after each swath
t	$[\text{s}]$	Time
t_p	$[\text{kgm}^{-2}]$	Type of paper
Δt_c	$[\text{s}]$	Print time correction due to startup and finalizing of a print job such that the initial/final carriage velocity v_c is 0.
Δt_p	$[\text{s}]$	Duration of a print medium step
Δt_s	$[\text{s}]$	Duration of a swath which includes one pass of the carriage, a carriage turn and a paper step
v	$[\text{ms}^{-1}]$	Velocity
v_c	$[\text{ms}^{-1}]$	Velocity of the carriage during printing
v_p	$[\text{ms}^{-1}]$	Maximum velocity of the paper drive
x	$[\text{m}]$	Distance
x_c	$[\text{m}]$	Carriage width
x_p	$[\text{m}]$	Print area width
y_c	$[\text{m}]$	Carriage height
y_p	$[\text{m}]$	Print area height

Productivity Model

The productivity of an ideal printer P_0 , where all nozzles N jet with jet frequency f without any interruptions including turning of the carriage, is computed by

$$P_0 = \frac{fN}{D} \quad (1)$$

$$D = r_x x_p r_y y_p \quad (2)$$

D is the total amount of dots to be placed on the print area. In reality, it is impossible to achieve a productivity P_0 in any printing system because of the nonzero carriage size and the limited actuator power. The carriage width increases the traveling distance of the carriage and the carriage height increases the redundant print area in combination with multi-pass. The limited actuator power results in a nonzero turning duration.

On the basis of Figure 1, we can obtain an expression for the productivity P by computing the necessary amount of swaths S , computing the duration of a swath Δt_s and correcting for startup and finalization Δt_c ;

$$P = \frac{1}{\Delta t_s S + \Delta t_c} \quad (3)$$

$$\Delta t_c = \frac{2m_c v_c}{F_c} - \max\left(\frac{2m_c v_c}{F_c}, \Delta t_p\right) \quad (4)$$

$$\Delta t_s = \frac{x_p + x_c}{v_c} + \max\left(\frac{2m_c v_c}{F_c}, \Delta t_p\right) \quad (5)$$

$$S = (2 - b) \left(\text{floor}\left(\frac{y_p}{s_p}\right) + p_x p_y \right) \quad (6)$$

(the operator "floor" rounds its argument to the nearest integer towards minus infinity.)

$$\Delta t_p = \text{traj}\left(s_p, v_p, \frac{F_p}{m_p}\right) \quad (7)$$

with $t = \text{traj}(x, v, a)$ defined as

$$t = \begin{cases} \frac{x}{v} + \frac{v}{a} & \text{if } \frac{x}{v} - \frac{v}{a} \geq 0 \\ 2\sqrt{\frac{x}{a}} & \text{if } \frac{x}{v} - \frac{v}{a} < 0 \end{cases} \quad (8)$$

which is the duration of a displacement using a second order setpoint. For sake of simplicity, a third order setpoint is not chosen, which is normally used for a motion system.

$$v_c = \frac{f p_x}{r_x} \quad (9)$$

$$m_c = NKm_n + m_{cr} \quad (10)$$

$$m_p = T_p x_p y_p + m_{pr} \quad (11)$$

$$s_p = \frac{y_c}{p_x p_y} \quad (12)$$

$$y_c = \frac{N p_y}{r_y} \quad (13)$$

Cost Model

In the previous section, we have only considered the productivity, however costs are equally important. This is easily shown by the following reasoning: If the productivity is increased by a factor of 2, the manufacturing costs are not allowed to increase by a higher amount than a factor of 2. If this condition is not satisfied, it would be more cost effective to buy two slower printers instead of one fast printer. We propose the following cost model:

$$C = NKc_n + c_r \quad (14)$$

which is, compared to the productivity model, a highly simplified model. Obviously, the cost model can be adapted to specific configurations and can become as complex as the productivity model, however this is not done here because we only want to explain the procedure where the simplified model is adequate. Only N and K are taken into account and the rest of the parameters are concealed in c_n and c_r . With a model for P and C , the optimal configuration can be determined by examining the maximum of P/C .

Print Process Analysis

Productivity Analysis

The productivity model, presented in the previous section, is implemented using Matlab.⁵ It contains 18 design parameters which can be chosen independently. The influence of several design parameters is studied and will be discussed next.

Main Productivity Parameters f and N

The two main parameters to increase the productivity are the jet frequency f and the amount of nozzles N . In Figure 3 the productivity is shown as a function of $f \in [10^3, 10^7]$ Hz and $N \in [10, 1.98 \cdot 10^4]$ where $1.98 \cdot 10^4$ matches with the print medium height y_p . The independent design parameters are chosen as follows:

$x_p = 0,84$ m (= A0 width)	$p_x = 1$ (no multi-pass in x)
$y_p = 1,188$ m (= A0 height)	$p_y = 1$ (no multi-pass in y)
$v_p = 1$ ms ⁻¹	$b = 1$ (bidirectional printing)
$F_p = 100$ N	$K = 1$ (single color)
$T_p = 0,1$ kgm ⁻²	$m_n = 2$ g
$m_{pr} = 0,5$ kg	$m_{cr} = 1$ kg
$r_x = 2,36 \cdot 10^4$ m ⁻¹ (= 600 dpi)	$F_c = 100$ N
$r_y = 2,36 \cdot 10^4$ m ⁻¹ (= 600 dpi)	$x_c = 0,1$ m

The other parameters in Table 1 depend on these parameters. For this particular configuration, F_c is dominant over F_p , so F_p will not be present in the results. If we substitute (4) to (13) into (3) assuming

$$\frac{x_p + x_c}{v_c} \gg \frac{2m_c v_c}{F_c}$$

(printing duration \gg turning duration) we obtain

$$P = \frac{fN}{(x_p + x_c)(y_p + y_c)r_x r_y} \quad (15)$$

and assuming

$$\frac{x_p + x_c}{v_c} \ll \frac{2m_c v_c}{F_c}$$

we obtain

$$P = \frac{F_c r_x N}{2m_c f (y_p + y_c) r_y p_x^2} \quad (16)$$

The floor-operator is also neglected, it only produces the sawteeth for high nozzle amounts visible in Figure 3. We see that the productivity approximates P_0 if the printing duration is dominant over the turning duration. If the turning duration becomes dominant, the approximation of the productivity changes dramatically. Important observations are: the productivity drops with increasing f , the productivity drops with p_x^2 , the productivity depends on the ratio r_x/r_y representing an asymmetric print raster.

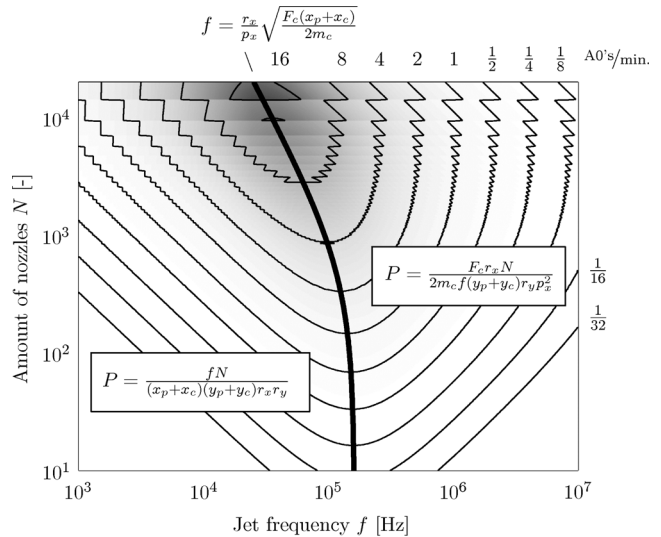


Figure 3. Productivity in A0's / min. as a function of the jet frequency f and the amount of nozzles N . Two areas are shown with an approximation of the productivity for each area. In the left area, the printing duration is dominant, and in the right area, the turning duration is dominant.

The cross section of the two approximations (15) and (16) is the separation between two areas where the printing duration and the turning duration are dominant respectively.

$$f = \frac{r_x}{p_x} \sqrt{\frac{F_c(x_p + x_c)}{2m_c}} \quad (17)$$

We want the printing duration to be dominant otherwise too much efficiency is lost. So if we want to increase the productivity, f and/or N , and the point (f, N) gets near the border (17) in Figure 3, then we have to aim at increasing the actuator force F_c , decreasing the carriage mass m_c , decreasing the carriage width x_c , avoiding the use of multi-pass in x and increase r_x , the print resolution in x , to avoid too much efficiency loss.

Carriage Height y_c and Width x_c

The carriage height can cause redundant carriage movement area depending on the amount of multi-passes used, and depending on the carriage height relative to the print area height. Redundant area is decreased by 1) decreasing the amount of multi-passes in x and y and 2) by choosing y_c such that y_p / y_c is an integer. Finally, it is possible to start with the next print when the current print is not finished yet. This will overcome the problem of redundant area at the top and bottom of the print area.

On the other hand, x_c increases the swath length $x_p + x_c$, which can not be avoided in any way, causing redundant print area on the left and right side of the print area instead of on the top and bottom of the print area. To conclude, staggering printheads in y is preferred above staggering in x .

Multi-pass p_x and p_y

The use of multi-pass in x needs to be avoided for higher productive systems. This is because the carriage velocity becomes higher by a factor p_x and the amount of dots printed per swath decreases by a factor p_x . So, if the turning duration approaches the printing duration, multi-pass in x dramatically reduces the productivity.

On the other hand, p_y is less of a problem, as it can only cause extra redundant carriage movement area in combination with the carriage height y_c , as previously mentioned. Therefore, multi-pass in y is preferred over multi-pass in x . The only advantage of multi-pass in x is that it can camouflage nozzle failures because every line is built up by several nozzles.

Productivity/Cost Analysis

A way to include manufacturing costs in the consideration of which configuration to choose, is to divide the productivity (3) by the costs (14). In this simple example of the costs model we made the costs linear-dependent on the amount of nozzles plus a constant value for all other costs. The parameters are chosen as follows: $c_n = \text{€ } 2$, $c_r = \text{€ } 10000$.

The result of P/C is shown in Figure 4. We see an optimum emerge which can be seen as the optimum choice of f and N in terms of

productivity and manufacturing costs. However, this optimum depends on a lot of design parameters, and is thus only valid for this particular example.

Conclusions

Both a productivity and a cost model for scanning inkjet printing systems have been proposed. These models provide insight in how the productivity and costs depend on the design parameters of a printer configuration: 1) A higher jet frequency can result in a lower productivity. 2) x_c and y_c should be minimized regarding productivity however increasing y_c is less problematic than increasing x_c . 3) Using asymmetric rasters (increasing r_x/r_y) results in a higher productivity for more productive printers. 4) Multi-pass in x decreases the productivity dramatically. 5) Considering the productivity/costs ratio is shown to be useful for optimizing a printer configuration.

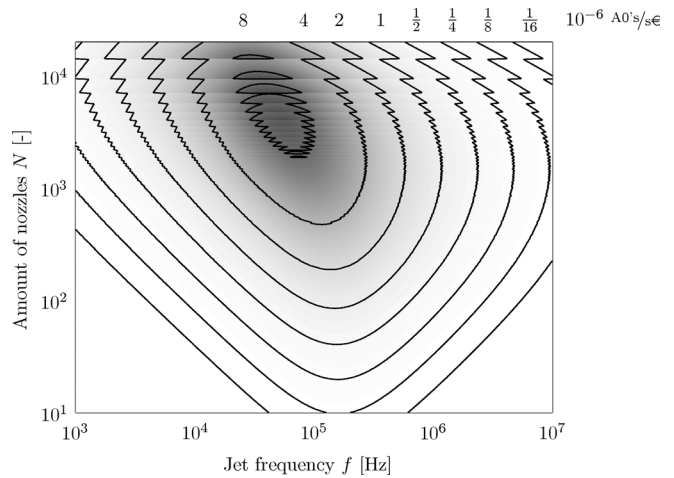


Figure 4. Ratio of productivity and costs in 10^{-6} AO's/s€

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Author Biography

Dennis Bruijnen received his Masters degree in Mechanical Engineering from Eindhoven University of Technology at the Control Systems Technology group in 2003. Upon completion of his degree, he started as a PhD student in the same group to investigate mechatronic solutions for improving scanning inkjet printing systems in association with Océ Technology BV.