ELSEVIER

Int. J. Production Economics 70 (2001) 1–19

international journal of
production
economics

www.elsevier.com/locate/dsw

Learning and process improvement during production ramp-up

Christian Terwiesch[a,*], Roger E. Bohn[b]

[a]*Department of Operations and Information Management, The Wharton School, 1319 Steinberg Hall-Dietrich Hall, Philadelphia, PA 19104-6366, USA*
[b]*University of California, San Diego, CA, USA*

Received 2 June 1999; accepted 18 October 1999

Abstract

Rapid product lifecycles and high development costs pressure manufacturing firms to cut not only their development times (time-to-market), but also the time to reach full capacity utilization (time-to-volume). The period between completion of development and full capacity utilization is known as production ramp-up. During that time, the new production process is ill understood, which causes low yields and low production rates. This paper analyzes the interactions among capacity utilization, yields, and process improvement (learning). We model learning in the form of deliberate experiments, which reduce capacity in the short run. This creates a trade-off between experiments and production. High selling prices during ramp-up raise the opportunity cost of experiments, yet early learning is more valuable than later learning. We formalize the resulting intertemporal trade-off between the short-term opportunity cost of capacity and the long term value of learning as a dynamic program. The paper also examines the tradeoff between production speed and yield/quality, where faster production rates lead to more defects. Finally, we show what happens if managers misunderstand the sources of learning.

Keywords: Yield; Ramp-up; Start-up; Learning curve; Experimentation

1. Introduction

Many high-tech industries are characterized by shrinking product lifecycles and increasingly expensive production equipment and up-front costs. The market window for selling many products has shrunk to less than a year in industries such as disk-drives and telecommunications. These forces pressure organizations to cut not only their development times (time-to-market), but also the time it takes to reach full production volume (time-to-volume) in order to meet their financial goals for the product (time-to-payback).

The period between the end of product development and full capacity production is known as *production ramp-up*. Two conflicting factors are characteristic of this period: low production capacity, and high demand. High demand arises because the product is still "relatively fresh" and might even be the first of its type. Thus, customers are ready to pay a premium price. Yet output is low due to low production rates and low yields. The production process is still poorly understood and, inevitably, much of what is made does not work properly the first time. Machines break down, setups are slow, special operations are needed to

* Corresponding author. Tel.: +215-898-854.
E-mail address: terwiesch@wharton.upenn.edu (C. Terwiesch).

0925-5273/01/$ - see front matter
PII: S0925-5273(00)00045-1

correct product and process oversights, and other factors impede output. Over time, with learning about the production process and equipment, yields and capacity utilization go up (although in many industries they never reach 100%). Due to the conflicts between low effective capacity and high demand, the company finds itself pressured from two sides, an effect referred to as the "nut-cracker" [1].

A recent example of the importance of ramp-up can be found in AMD's efforts to compete with Intel in the microprocessor market. AMD had several generations of product that were slow to ramp, leading to limited market acceptance and financial difficulties for AMD. More recently, Intel experienced problems ramping up the yield of its 0.18 micron version of the Pentium. Industry observers speculate that an effective ramp-up of AMD's K7 processor will allow AMD to compete in the high end segment of the PC market (Electronic Buyers' News, June 21, 1999).

In this article, we analyze the interactions among capacity utilization, yields, and yield improvement (learning) during ramp-up. Traditional learning-curve models implicitly assume that manufacturing performance increases with cumulative output from the plant, more or less independent of managerial decisions. This is clearly an oversimplification, and there is much that managers can do to affect the rate of learning [2]. We concentrate on deliberate learning through experiments such as engineering trials, which are controlled experiments using the production process as a laboratory. Such trials are essential for diagnosing problems and testing proposed solutions and process improvements. But they also use scarce production capacity. This creates a paradoxical trade-off between regular production for revenue and experimentation for learning. We formalize this intertemporal trade-off between short-term revenues and long term learning benefits in form of a dynamic program, and derive solutions for the cost, value, and level of experimentation.

The trade-off between short-term output and experiments, as well as more generally the phase of production ramp-up, is of substantial managerial importance. Launches of high-tech products are often either delayed or scaled back because of ramp-up problems. For example ramp-up problems in the production of video chips led to substantial losses during the launch of the Sega Dreamcast video console [3]. Similarly, pharmaceutical companies are struggling with ramping up the production of biotechnology-based drugs, leading to sales losses at the time when prices are at their premium [4]. This article models the complex dynamics of a new product's ramp-up, and assists decision making by providing concrete values for the cost and benefits of learning efforts. Specifically, we show that a misperception about the underlying drivers of learning can result in substantial financial losses over the lifecycle of a new product.

The remainder of this article is organized as follows. Section 2 provides more background on the assumptions of our model, and discusses several strands of related literature. Section 3 describes the type of production environments our analysis is appropriate for and presents a simple model that captures the interaction among capacity utilization, process knowledge, and yields. The analysis of this (static) model will be the basis for our dynamic model of learning and process improvement during production ramp-up, presented in Section 4. Our results are illustrated by several numerical examples in Section 5, where we show that different cost and demand situations call for different ramp-up strategies. Section 6 provides a summary, managerial implications, and future research directions.

2. Background

This paper draws on three strands of research, as it is about manufacturing *learning* during *ramp-up*, with *yields* the primary dependent variable. Each new product introduced into a factory must undergo a ramp-up. A new product's ramp-up can last a quarter of the product life cycle – several months for a hard disk drive, for example. During this period, yields and production rates gradually increase as learning takes place. Important types of learning typically include adjusting the process recipe, modifying tooling and equipment to reduce defects and downtime, and developing better and faster inspection methods.