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Eco-friendly manufacturing strategies for simultaneous consideration between productivity and environmental performances: a case study on a printed circuit board manufacturing

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ABSTRACT

Manufacturing firms are constantly seeking to improve productivity in various activities, such as throughput, on-time delivery, and customer service. However, recently, the Korean government has strongly enforced environmental regulations to reduce the risk of pollutant emissions that violate the climate change convention. As a result, most firms are now attempting to maximize their own productivity while satisfying the environmental regulations mandated by government policies. In this study, a new framework that combines simulation and the Taguchi technique is proposed for the green process design based on the production lines of manufacturing firms. The simulation model is designed for identifying the production bottleneck process in terms of productivity, which has an effect on all processes during the production process and on the environmental bottleneck process caused by violating the environmental regulations. In the simulation analysis, we obtain the productivity and environmental performance by adjusting the lower and upper bounds of the control variables. The Taguchi method with the grey relational analysis is also utilized to determine the best strategy to meet the optimal productivity within a range of satisfying the environmental regulation of pollutant emission concentration among the experimental sets. To validate our research framework, a case study of the PCB manufacturing process was conducted. The case study determined that the best way (A3B3C1) involved the operating strategy with the lowest conveyor speed in the scrubbing and DES process and the fastest conveyor speed in the oxide process, which can reduce approximately 28.38% and 28.81% of the emissions concentration of hydrogen chloride and dust, respectively, in comparison with the current operating strategy (baseline).

1. Introduction

In today's competitive global market, the success of the manufacturing industry relies on the green management of manufacturing fields. The key methods of improving the environmental-friendliness of the manufacturing process are adopting a consumption and pollution source control strategy, such as a green manufacturing mode for managing and controlling the production process, and pursuing technological innovation. A plethora of research addressing various issues related to different aspects of green manufacturing is available in the pertinent literature.

Most of these researches have focused on how to assess the environmental performance and design the clean production process using the various modeling techniques. Aguado et al. (2013) developed the environmental innovation model with multiple criteria such as environment, economic, social, and public policy to help firms harmonize efficiency and sustainability. Chinh et al. (2007) identified the pollution type and location of the sources in coal production using a life cycle approach and analyzed the its environmental impacts by the different pollution prevention and treatment options. Guo et al. (2006) proposed five cleaner production options; 1) Good operating practices/housekeeping, 2) Raw materials improvement, 3) Technology modification, 4) Product changes, and 5) Reuse/recycling to design the optimum cleaner production system, and applied the proposed options to the alcohol industry in China for a real case study. Hermann et al. (2007) developed a new analytical tool which can be used to provide

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detailed information on the overall environmental impact of a business. The tool is composed of the life cycle assessment, multi-criteria analysis and environmental performance indicators. Jia et al. (2006) proposed a methodology to assist in developing and optimizing cleaner production processes from two levels. Generating Pareto-optimal solutions is at search level and identifying the best compromised solution from the obtained conflicting solution is at decision-making level at the same time.

Some among them are based on how to implement the green production strategies on the manufacturing process and machine level. Krishnan et al. (2004) proposed the environmental value analysis method to evaluate the environmental performance of semiconductor processing. The method develops environmental assessments through a "bottoms-up" analysis by developing equipment environmental models to describe the system. Li et al. (2004) mentioned that green manufacturing is a modern manufacturing mode that considers the environmental impact and resource consumption. Its essence is the embodiment of a sustainable development strategy of human society in the modern manufacturing industry. Li et al. (2011) also proposed a key way to improve the environmental friendliness of iron and steel production processes that involves the control of the source of what is consumed and polluted; namely, the green manufacturing mode manages the steel production process via control and technological innovation. Clean-ability and burr reduction, which are other green manufacturing aspects on the machine level, were studied in various machine tool researches to act as another optimization objective in their attempt to improve machine tool performance. An example of this type of work was presented by Avila et al. (2005) in the aerospace industry. Wang and Lin (2007) proposed a broad triple-bottom-line framework to track and categorize sustainability information at the corporate level through a sustainability index system. The framework incorporated environmental and social costs and values into economic activities to support the decisions of the management. They suggested helping decision makers in their crafting of green manufacturing plans. Burk and Goughran (2007) also presented another framework for sustainability to achieve green manufacturing. The framework was based on their studies of small and medium enterprise (SME) manufacturers who achieved ISO 14001 certification. Lindskog et al. (2011) discussed a method using a discrete event simulation to analyze production systems, which can enable the labeling of the environmental footprint of products. The method includes the steps of data management, determination of the environmental footprint, and communication of the results. The method was developed during a case study of a job-shop-production facility. To evaluate the discrete event simulation method, the results were compared with those of a simplified life cycle assessment (LCA) conducted on the same production system. Ma (2011) described how to reduce the current waste in the manufacturing industry. He described the many ways to reduce pollution, such as 'green' products design and making use of scrap materials. Lu et al. (2011) presented a framework for developing comprehensive products and processing metrics for sustainable green manufacturing, using machined products and machining processes as examples, and addressing all three aspects of the triple bottom line – environment, economy, and society. Further, this paper depicted the need for developing standardized metrics to enable the wider use of these metrics by different manufacturers. Meier and Shi (2012) proposed an approach to the emission calculation in the manufacturing phase based on the hybrid analysis. Therefore, this approach helps companies in this industry to identify the emission reduction potentials in manufacturing by focusing on the resource and energy flows as well as the emission intensities in the manufacturing processes; hence, it contributes to the LCA.

The green manufacturing strategy aims to make the manufacturing industry flexible, energy-saving, and eco-friendly. These objectives can be attained through production control to achieve the target pollutant emission and material flow levels with low energy usage. Coordination and collaboration in different production lines (e.g., work in progress (WIP) information) and production speed are essential to the success of green manufacturing activities. One of the important tasks in green manufacturing is to monitor whether the level of pollutant emission has been controlled under the environmental regulation (Ministry of Environment Republic of Korea, 2013) by identifying the optimum operating conditions. This monitoring is a difficult task due to the complex production line involved in the dynamic customer order generation. To achieve both productivity and good environmental performance concurrently in a complex production line, there is a need to quickly define and control the bottleneck process along with the continuous production lines. Many researchers have addressed the problem of a single operating condition, such as what level of energy use per material unit will enable green manufacturing, to achieve its best performance. Yet, an analytical approach, which addresses the issues of depicting an optimal green manufacturing condition by considering two or more factors at a time, is lacking.

2. Research method

2.1. Proposed methodology

The purpose of our research is to design an optimal eco-friendly manufacturing process. To design such a process, we first focused on selecting the environmental bottleneck process, which is defined as the certain process emitting a large amount of pollutant emissions, controlling the production release rate for improving the productivity, and abiding by the environmental regulations, concurrently. Next, we attempted to ascertain the relationship between productivity, which is evaluated by the on-time delivery rate and the WIP level, and the environmental aspects, which are measured by the allowable levels of pollutant concentrations. We also attempted to validate whether the control of the production release rate can have a positive effect on satisfying the environmental regulations. In addition, we discovered various control variables for managing the production release rate, and designed diverse scenarios for establishing eco-friendly manufacturing strategies via the optimal combination of threshold values for the control variables. At this stage, the threshold values of control variables can be established as a specific value between the maximum values. The threshold values have a range constraint that should satisfy the target production rate while following the environmental regulations.

To implement our research model, a hybrid simulation approach that combines the Taguchi method with the theory of constraint (TOC) is proposed in this paper.

2.2. Application of simulation technique

The simulation technique was used to model the printed circuit board (PCB) production line used for the case study in this paper, which deals with a range of production amounts and pollutant emission levels. In this study, a simulation model using the ARENA package (Law and McComas, 1997) was developed for an experimental analysis of controlling the effect of production speed on the reduction of environmental emission concentration. Fig. 2 shows the detailed model of PCB manufacturing using the simulation package. To enhance the author's existing knowledge of Arena 13.9 (Kelton et al., 2009), that simulation package was chosen for modeling the PCB manufacturing and conducting the experiment.