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ScienceDirect

IFAC-PapersOnLine 48-3 (2015) 2387–2392

Towards Lean and Resilient Production

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Abstract: This paper presents issues and tradeoffs in attempting to achieve lean production by increasing productivity and reducing costs and waste while at the same time operating with resilience in the face of disruptions. A simple mathematical model of the operation of a production system is proposed, which incorporates two types of disruptive events: resource breakdowns and quality loss. The model is used to evaluate different inventory and inspection options for managing disruptions. It is expected that the outputs from this work will lead to industrial guidelines for planning a production system configuration, such as number and location of inspection stations, and size and location of buffers.

Keywords: lean, resilience, production network, disruptions, modelling, optimal control

1. INTRODUCTION

One of the major challenges in manufacturing is in improving productivity whilst reducing waste and cost. Additionally, manufacturing organisations need to cater for changes in demand, customer order changes, rush orders and internal disruptions within the production system.

The efficient management and control of production operations are increasingly becoming complex and there is an inherent need to improve the control of manufacturing processes in the face of unexpected disruptions. These disruptions, such as quality problems, resource breakdowns, material unavailability, order changes and rush orders, can cause significant impact on the performance of a production system and can also lead to delay in delivery dates, impacting customers and wider business functions (Darmoul (2013)).

The ability to be resilient to unexpected disruptions requires the production system to operate effectively in the face of the disruptions and also to anticipate disruptive events and to have a control strategy to minimise the impact. This implies that the production system has resilience properties, which can be defined as the ability to bounce back or to cope with disruptions (Sheffi (2005)).

On the other hand, for improving productivity and reducing waste, organisations have been implementing lean principles for some time (e.g. Womack (1990)). In order to achieve this, organisations have been moving towards just-in-time manufacturing and implementing make-to-order systems. One of the key steps in implementing a lean system is to reduce waste by limiting inventory levels. However, when unexpected disruptions occur, the impact of these unanticipated events will have dire consequences and will therefore need careful consideration when leaning activities are considered.

This implies that there are some conflicting issues that are associated with being both lean and resilient at the same time. Even though the overall objective in each case is to improve productivity, there are conflicts in the area of disruption management strategies such as location and size of inventories, location and number of inspection stations. More inventory and/or greater levels of inspection can reduce normal productivity but may provide greater resilience to disruption.

In this paper, an analytical approach is proposed to understand the balance between lean and resilience. The proposed approach will allow organisations to implement strategies that are lean, but can also cope with disruptions effectively.

This paper is structured as follows: Section 2 provides the review of existing techniques and describes the characteristics needed for modelling. Section 3 describes the basic modelling of the production system and section 4 illustrates the modelling of the disruptions within the proposed analytical model. Numerical case examples are provided in section 5 to illustrate the principles. Two specific disruption cases are discussed, the first explores resource breakdown issues and the second considers product quality problems. Finally, section 6 concludes the paper.

2. LITERATURE REVIEW

Table 1 briefly summarizes the existing literature on disruptions handling.

Several approaches have been proposed in the literature for handling production disruptions and they aimed at solving specific problems such as buffer size (Battini (2009)), quality issues and resource breakdowns (Galante (2007); Paul (2014)). Considerable attention has also been given to distributed control and reconfigurable manufacturing systems as means to handle disruptions during operations (Bruccoleri (2006); Covanich (2009)).

In order to understand the impact of disruptions and the effectiveness of a management strategy, it is essential to represent the production system in a meaningful man-

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.06.445

Table 1. Summary of Literature on Production Disruption Handling.

Authors	Basic representation of production resources			Capturing disruptions		Control variables			Methodology
	Two-stage system	Serial multi-stage system	Network	Resource breakdown	Quality loss	Production rate	Quantity & location of inventory	Location of inspection/ Inspection rate	
Battini et al. (2009)	×			×			×		Simulation model
McNamara et al. (2013)		×		×			×		Simulation model
Tezcan and Gosavi (2001)		×		×			×		Simulation model
Yang et al. (2005)			×	×			×		Mathematical model
Shiau (2002)		×			×			×	Mathematical model
Tirkel and Rabinowitz (2014)		×			×			×	Mathematical model
Galante and Passannanti (2007)		×			×	×		×	Mathematical model
Paul et al. (2014)	×			×	×		×		Mathematical model
Hu et al. (2009, 2010, 2013)			×	×		×	×		Optimal control problem

ner. In the literature, the production system consisting of resources and inventories are modelled as a two-stage system (Battini (2009)), serial multi-stage system (McNamara (2013); Tezcan (2001); Shiau (2002); Tirkel (2014); Galante (2007)) or a network of resources (Yang (2005); Hu (2009, 2010)).

Existing approaches have only considered specific problems to devise a disruption mitigation strategy. For example, Battini (2009); McNamara (2013); Tezcan (2001); Yang (2005) considered only resource breakdowns, where as Shiau (2002); Tirkel (2014); Galante (2007) considered quality problems. However, in reality, it is important to consider the impact of combined disruptions and the cascading effects of dependencies between disruptions. Therefore, there is a need for a global modelling approach to consider these in a combined manner.

The disruption mitigation and management is in general a control variable problem, where the production resources and inventory need to be controlled. Battini (2009); McNamara (2013); Tezcan (2001); Yang (2005) developed techniques to determine the optimal quantity and location of inventory during disruptions. Others, such as Shiau (2002); Tirkel (2014); Galante (2007) have considered the optimal inspection strategy to mitigate quality control problems.

Additionally, various modelling approaches have been proposed in the literature. Simulation approaches have been used to demonstrate the impact of disruptions and their associated mitigation strategies Battini (2009); McNamara (2013); Tezcan (2001). Analytical modelling approaches have been used by Yang (2005); Shiau (2002); Galante (2007); Hu (2009, 2010, 2013).

For the approach presented in this paper we take the model initially developed by Hu (2009, 2010, 2013), which will be presented with several modifications in the next section, and extend it, so it covers quality problems and suggests the best inspection strategy as a solution of optimal control problem.

3. MATHEMATICAL MODEL OF THE OPERATION OF A PRODUCTION LINE

A production line can be structured as a network of nodes representing resources (Hu (2009, 2010, 2013)), see figure 1. Each resource performs an operation to transform one or more products into one or more other products. The dynamics of nodes describes the flow of products, the use of resources, the capacity of operations, and the cost and responsiveness to change.

Fig. 1. A production line network

There are n_o nodes or operations in the system and n_p types of products, each type is denoted as pr_i, $i = 1, 2, \ldots, n_p$. Let $x_i(t)$ indicate the quantity of pr_i at time t. Then vector

$$x(t) = [x_1(t)\ x_2(t) \ldots x_{n_p}(t)]^T$$

will represent the quantity of all n_p products in the system.

An operation of each node i is represented by a $(n_p \times 1)$ vector b_i. For example, for the production line shown in figure 1

$$b_7 = [0\ \ 0\ \ 0\ -1\ -1\ \ 1\ \ 0\ \ 0]^T.$$

In this case, operation b_7 represents an assembly of one unit of pr_4 with one unit of pr_5 to produce one unit of pr_6. Let us define the $(n_p \times n_o)$ matrix

$$B = [b_1, b_2, \ldots, b_{n_o}].$$

The $(n_o \times 1)$ vector $u(t)$ represents the production rate at time t, such that the value of the element $u_i(t)$ is the production rate of node i at time t. The above definitions bring us to the following inventory update equation:

$$x(t+1) = x(t) + Bu(t). \quad (1)$$

There are several constraints for the system, which are common to most production operations.

- *No backorder constraint* means that the inventory of each product can not be negative:

$$x(t) \geq 0; \quad (2)$$