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Technical Paper

Performance analysis of a composite work cell with a gantry and system reconfiguration

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ABSTRACT

In this paper, a reconfigurable composite work cell with a gantry that is in charge of moving materials/parts from one machine to another is considered. To diagnose the work cell performance, demand dissatisfaction is proposed to evaluate the discrepancy between market demand and system output. Demand dissatisfaction consists of the effect of work cell capacity as well as the impact of disruption events. Production loss attribution of each machine is identified as machine's impact on the work cell performance. A reconfiguration strategy is proposed to satisfy possible demand changes and serve the purpose of energy saving. A gantry work cell for composite lay-up process is used for a case study, by which the performance diagnostic methodology and reconfiguration strategy are demonstrated.

1. Introduction

Manufacturing systems must rapidly respond to market demands and minimize system cost to remain competitive. Manufacturing system performance is often affected by various uncertain disruption events such as random machine failures, material shortages and labor absence, as well as unpredictable market demands. Therefore, real-time modeling and analysis of manufacturing system become extremely important in order to achieve high efficiency.

A production line in a factory can be made up of multiple production stations or work cells. Each station/work cell includes one or multiple machines or equipment performing a specific function, such as pretreatment, multilevel processing, testing, and assembly. Fig. 1 illustrates a schematic of a composite production line based on long fiber prepreg laminated composites, which includes 3 stations/work cells, i.e., lay-up station, vacuum bagging station and autoclave station. In each station/work cell, one or multiple machines/process steps are needed to finish one function. For example, as shown in Fig. 2, the lay-up station includes five process steps to finish the prepregs' lay-up, i.e., vertical-direction prepregs, horizontal-direction prepregs, release films, bleeders, and breather films are added in order. In addition, in each work cell, robots or humans (denoted as R1-R3 in Fig. 1) move between machines/process steps to load and unload parts. Since robots or humans in this kind of work cell system serve for material loading/unloading, they can be abstracted as gantries ascribed to the same functionality. In this paper, this kind of work cell, referred to as a gantry work cell, is studied.

In manufacturing research area, tremendous works have been devoted to modeling and analysis of performances of production lines in face of uncertainties. A good effort has been contributed to steady-state analysis [1–10]. Real-time analysis of disruption event impact in serial production lines is proposed and the relationship between bottleneck phenomenon and disruption events impact are explored in [11–14]. However, all these works focus on the analysis of production lines from the high system level point of view, where the stations are abstracted and treated as one entity without considering inner interactions within each station. On the other hand, manufacturing process researches mainly focus on the physical parameters and their impacts of a specific operation/process while ignoring the interrelationships between operations. There exists an explicit gap from manufacturing system level analysis to process level studies, which potentially hampers the efficiency improvement of manufacturing system as a whole. For example, based on the system level analysis, if a throughput bottleneck (see monograph [15–18]) is identified to be a certain station which includes a couple of machining processes, it is important to further zoom into that station to find the root cause of the processes steps so that

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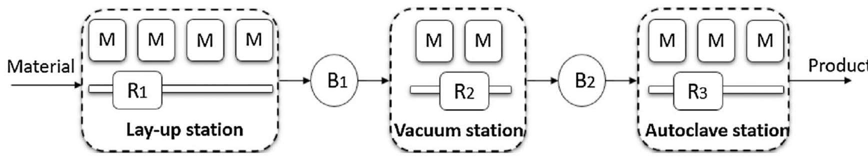

Fig. 1. Schematic of a Composite Production Line.

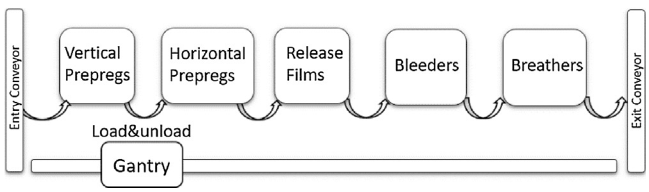

Fig. 2. Composite Lay-up Station with a Gantry.

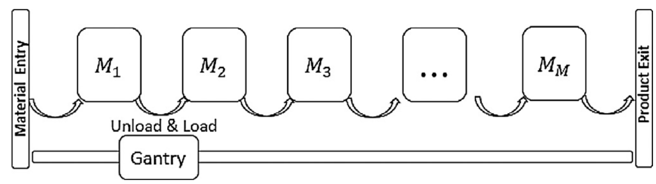

Fig. 3. Schematic of a Composite Work Cell with Single Gantry.

the limited resources can be prioritized to achieve more efficient throughput improvement. However, analysis of individual machining process does not necessarily provide this knowledge. To fill the gap between the high-level system analysis and the specific process analysis, the work cell performance analysis that we will address in this paper is indispensable.

The gantry work cell, referred to as robotic cell in the robotic research field, has been analyzed in the last decade. Most of these researches focus on the robot move scheduling and part sequencing to minimize the cycle time [19,20]. Cyclic scheduling of identical parts is discussed in [20,21]. In [22], the scheduling problem for multiple part types is studied. Evaluation of cycle time with different robot move sequences for a two-machine robot cell is presented in [23,24]. For a cell with more than two machines, a heuristic algorithm is proposed in [25]. However, these scheduling and sequencing considerations mainly focus on the robot rather than the whole system performance. Moreover, these studies only focus on the design/planning stage rather than improving the real-time performance of the cell.

In addition, market demands may change frequently in reality. Even for a well-designed system, it may fail to keep the optimal performance while facing the challenge of market demand fluctuation. Reconfigurable manufacturing system (RMS) is developed to quickly respond to volatile demands by adjusting production capacity and functionality. It is designed to easily change the structure, i.e., the machines can be added, removed, modified or interchanged as needed to match different demands. Reconfigurable manufacturing systems (RMS) have been firstly proposed by Koren et al. [26] as a solution for volatile demands. The capacity scalability of RMS is analyzed for parallel identical machines in a single station by line balancing method [27]. The most practical approach to reconfiguring the system is adding, removing machines or changing the structure of production line [28,29]. A heuristic method for process planning and scheduling is proposed in RMS [30]. A dynamics model is developed for capacity scalability analysis with stochastic demands and to minimize the delay in scaling the system's capacity [31]. However, these analyses and optimizing methods are based on static system parameters such as machine capacity, while the impact of random disruption events (e.g., machine random failures) is not considered.

To address the aforementioned issues and challenges, this paper is dedicated to establishing a mathematical model for real-time performance analysis of a gantry work cell, in order to fill the research gap between a high system level and a specific process/machine level. Market demand dissatisfaction and production loss are defined and quantified at a work cell level, which forms a theoretical base for system reconfiguration. For a reconfigurable system in face of market demand fluctuation, reconfiguration strategies are proposed to maximize the profits and reduce the cost, considering both the system capacity and the dynamic performance. The rest of the paper is organized as follows: Section 2 provides a description of a composite gantry work cell; mathematical analysis of the work cell performances under disruption events is performed and production loss attribution is formulated in Section 3; then reconfiguration strategies based on the performance analysis are proposed in Section 4; Section 5 presents a case study to demonstrate the effectiveness of the methodologies; conclusions and future directions are discussed in Section 6.

2. System description

The gantry work cell as shown in Fig. 2 is a typical structure that widely used in many industries, from which a generic schematic is illustrated in Fig. 3. The work cell includes a fixed sequenced M machines/process steps and a single gantry which serves for loading and unloading materials/parts to each machine. The gantry moves by following the sequence of the machines/process steps, i.e., from the first to the last and back to the first, while skipping and moving out of this order are not allowed. Usually, due to the physical constraints of a work cell, e.g., in composite work cells and auto body shops, there may be no work-in-process (WIP) buffers between consecutive machines/process steps. Therefore, intermediate parts are moved directly from a process to the next one instead of being transferred to buffers.

In such a work cell, the following assumptions and notations are used:

(1) The work cell consists of one gantry and M machines/process steps with fixed processing sequence for a single type of product, where M_i denotes the i^{th} machine/process steps, $i = 1, 2, \ldots, M$.
(2) Each machine has four possible states: up (processing part), loading/unloading, down and waiting for gantry. The down state is caused by various uncertain disruption events in real-time operation, such as random machine failures, material shortages and labor absence. The disruption event is detailed in the following notation (16). The machine waiting state is incurred when the machine has finished its current processing while the gantry is not available yet, and it depends on the machines' and gantry's capacities as well as disruption events.
(3) The gantry has two possible states: working (loading/unloading) and waiting for the machine. The gantry waiting state is incurred when the gantry is available to a machine but the machine has not finished its current processing yet, and it depends on the machines' and gantry's capacities as well as disruption events.