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Improving configuration of complex production lines via simulation-based optimization

Mustafa Fatih Yegul [b,1], Fatih Safa Erenay [b,*], Soeren Striepe [a,2], Mustafa Yavuz [a,3]

[a] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON, Canada
[b] Department of Management Sciences, University of Waterloo, Waterloo, ON, Canada

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ABSTRACT

Optimizing the configuration of a complex production line is an NP-hard problem in various machine settings. Solving real-life-size instances of this problem becomes a more common challenge because the current trend of *reshoring* induces multi-national firms to transfer manufacturing facilities from workforce-intensive to capital-intensive production environments which usually require re-configuration of the transferred manufacturing systems according to the availability of better machinery in a capital-intensive environment. This paper focuses on the problem of optimizing production line configuration and proposes several simulation-based optimization approaches based on myopic search, ant-colony, simulated annealing, and response-surface methodologies. We investigate the relative performances of these proposed algorithms on a real-life manufacturing system transfer case in automotive industry according to solution quality and computation-time metrics under different parameter scenarios. Thus, our numerical results may guide the decision makers in choosing a suitable solution approach for this problem depending on the problem size and time availability. Our results also illustrate that ant-colony optimization, a methodology not widely applied in simulation-based optimization, provides high-solution quality for this problem when matched-up with a myopic search to find a good initial solution.

1. Introduction

Determining the best manufacturing system configuration (MSC) may significantly improve reliability, product quality, capacity scalability, and costs in production facilities; hence, it is crucial for profitability. For instance, (Koren, Hu, & Weber, 1998) report that improving MSC may lead to up to 22% savings in costs and up to 100% improvement in productivity. However, optimizing MSC is a complex problem which requires specifying many factors including facility layout, production flow, station structures, configuration of the machinery (machinery type and process capacity, buffer size, job allocation mechanism, etc.), number of workers, and skill sets (Wang & Chatwin, 2005). In production-line-based assembly systems (e.g., flow-shops), the problem complexity of optimizing MSC may quickly increase with the number of considered stations (Jeong & Kim, 2000). For example, the optimal buffer allocation in flow-shops, that considers only one of the aspects of MSC listed above, is reported to be an NP-hard combinatorial optimization problem (Huang, Chang, & Chou, 2002).

Optimal MSC problems generally arise when a facility is first built or upgraded. Recently, challenging MSC problems have arisen when manufacturing systems are transferred from workforce-oriented to automation-oriented environments as a re-shoring practice. In such cases, the transferred manufacturing system is reconfigured based on the machinery availability of the automation-oriented environment. We refer to such a transfer as 'reverse transfer of manufacturing system' (RTMS) following the 'reverse transfer of technology' concept of (Elshout, 1995). As the practice of relocating manufacturing services back to Europe and North America draws more attention (Ellram, 2013), RTMS is becoming a more common practice especially for

Abbreviations: MSC, Manufacturing System Configuration; RTMS, Reverse Transfer of Manufacturing System; GA, Genetic Algorithm; SA, Simulated Annealing; TS, Tabu Search; ANN, Artificial Neural Networks; WIP, Work-In-Process; ACO, Ant Colony Optimization; GS, Greedy Search; FGS, Fast Greedy Search.

* Corresponding author at: 200 University Avenue West, CPH-4323, Waterloo, ON N2L3G1, Canada.

E-mail addresses: mfyegul@uwaterloo.ca (M.F. Yegul), ferenay@uwaterloo.ca (F.S. Erenay), striepe@bell.net (S. Striepe), myavuz@uwaterloo.ca (M. Yavuz).

[1] Address: 200 University Avenue West, E5-3011, Waterloo, ON N2L3G1, Canada.
[2] Address: 18579 Centre Street, Mt. Albert, ON L0G1M0, Canada.
[3] Address: 200 University Avenue West, E5-3011, Waterloo, ON N2L3G1, Canada.

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high-value-added products prototyped in workforce-oriented production cultures. Therefore, RTMS related manufacturing system configuration problems may draw more attention in the future.

Optimizing MSC in case of RTMS could be an especially complex problem because (1) it may need to be solved in real-life-size instances as the transferred manufacturing system already has a particular work-flow that cannot be altered; (2) better machinery availability in the automation-oriented environment increases the number of options to be considered (e.g., replacing workers with machinery, upgrading machinery, determining the working pace for the altered components, etc.). Because close form formulations of the objective functions for real-life-size MSC problems are hard to attain if not impossible (Huang et al., 2002), discrete-event simulation could be an appropriate tool to model RTMS-related MSC problems. Therefore, efficient simulation-based optimization approaches are needed to solve such MSC problems.

In this context, this paper proposes eight simulation-based optimization algorithms to derive an efficient configuration (i.e., a good and feasible combination of configuration parameters) for production-line-based manufacturing systems. We test the performances of the proposed metaheuristics on a complex real-life automotive industry case for which an approximately optimal MSC needs to be derived for a prospective production line of a high-value-added product to be built in a capital-intensive country based on a similar existing workforce-oriented manufacturing system. We develop a stochastic discrete-event simulation model mimicking the processes in the transferred production system for any given combination of decision variables assuming that the demand for end-products is constant, and the stations and process flow in the existing system are preserved. The proposed algorithms derive approximately optimal (i.e., a good feasible solution) configuration parameters of the prospective production line including number of machines, number of workers, processing rates, and buffer sizes to maximize the expected profit.

Most of the proposed algorithms are based on conventional metaheuristics commonly used in simulation-based optimization such as greedy search, response surface method, and simulated annealing. We also propose an algorithm based on ant-colony optimization, which has not been widely applied to simulation-based optimization, due to its promising performance in some production line optimization problems (Chehade, Amodeo, & Yalaoui, 2011; Mohan & Baskaran, 2012; Rossi & Lanzetta, 2013). In addition, we also examine a couple of hybrid algorithms to measure the benefit in combining some of the proposed algorithms to enhance their performance. Lastly, we compare the performances of the proposed algorithms with an optimizer available in simulation packages (OptQuest) illustrating to what extend an easy-to-implement commercial simulation-based optimization tool can satisfy decision makers in terms of solution quality and speed.

The appropriate parameter settings for these proposed algorithms are specified via initial testing on a test-bed problem with different parameter instances. The test-bed problem represents an artificial smaller-scale production line which has similar characteristics (production flow, machinery environment, etc.) with the aforementioned real-life automotive industry case. The production line in the test-bed problem can be simulated much faster and has less decision variables compared to the one in the real-life case, i.e., the best production line configuration parameters of the test-bed problem can be derived via total enumeration of all possible combinations of discrete decision variables. Therefore, we also use the test-bed problem to evaluate the performances of the proposed algorithms compared to the optimal configuration parameters (i.e., the best solution found by total enumeration) in small problem instances.

There are two main contributions of this paper: (1) We propose and test several simulation-based optimization approaches based on metaheuristics for optimizing configuration of complex production lines, and illustrate their relative strengths under different parameter scenarios in terms of solution quality and speed. (2) This is the first study that considers the problem of optimizing production line configuration in an RTMS case. The considered real-life production system (i.e., an asynchronous and inhomogeneous production line with series-parallel flow including reworking, scrapping, and product splitting/merging) is very complex compared to those analyzed in the literature; therefore, appropriately represents the challenge associated with the production line configuration problems in case of RTMS.

In short, we provide an interesting case study analysis on eight-way comparison of conventional simulation-based optimization methods applied to a challenging production line configuration problem in an RTMS case using real data. Given the current trends (e.g., reshoring) and political developments in the North American manufacturing sector, more companies are likely to face the challenge of optimizing configurations of their new or old production lines in an RTMS setting. Therefore, the case study provided in this paper is of interest for both practitioners and academics since it informs about the potential of simulation-based optimization to address such challenges and provide guidance in selection of an appropriate simulation-based optimization method.

2. Details about the real-life RTMS case

A capital-intensive North American corporation, ABC,[4] plans to build a new manufacturing plant in North America to produce electric car components based on an existing early-stage manufacturing system designed by a relatively workforce-intensive Asian company. ABC prefers building a new plant because: (1) ABC can better manage the potentially large demands and reduce transportation cost by producing these components in the same continent as its major customers rather than outsourcing them from another continent. (2) ABC may benefit from better product quality and more reliable supply chain by producing these components with better automated-machinery.

The existing manufacturing system is a flow-type production line which needs to be reconfigured to incorporate automated machinery options to improve efficiency. ABC desires to reach a throughput level equal to an annual demand estimated through discussions with potential customers. Therefore, the objective is set as maximization of annual profit incorporating equipment, raw-material, inventory, and lost-sale costs.

ABC established a team of engineers, production planners, and managers to decide which station structures are available for each station. A station structure includes specifying machinery vs. workforce selection and machine type. For each station, ABC engineering team chose one station structure out of all possible combinations by elimination based on performance and cost. The selected station structures and the material flow in the prospective production line are described in Section 4.1. Then, the team collected the necessary input such as costs and processing times.

Based on these information and overall station structure setting, we develop the Operations Research approach summarized in Fig. 1 to find the approximately optimal station configuration variables including the number of machines, machine speeds, min/max buffer allocations, and number of workers for particular stations. The approach starts with the creation of a set of decision variable values based on the selected simulation-based optimization algorithm. These values are fed into the simulation module that is run for three replications. The average result is fed back into the optimization module to be evaluated by the algorithm. If the

[4] Actual name is withheld for confidentiality.