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Human-robot collaboration in decentralized manufacturing systems: An approach for simulation-based evaluation of future intelligent production

Lennart Bochmann[a,b], Timo Bänziger[a,b], Andreas Kunz[a,]*, Konrad Wegener[a]

[a]*Institute of Machine Tools and Manufacturing (IWF), ETH Zurich, Leonhardstr. 21, 8092 Zurich, Switzerland*
[b]*Volkswagen Group, Berliner Ring 2, 38436 Wolfsburg, Germany*

* Corresponding author. Tel.: +41-44-3625771; fax: +41-44-6321125. *E-mail address:* kunz@iwf.mavt.ethz.ch

Abstract

The development towards decentralized manufacturing systems aims at increased flexibility and robustness by maintaining the level of productivity. In order to meet these requirements, human-robot collaboration is considered as basic framework within future intelligent manufacturing cells. For industrial implementation, the concepts of smart production need to be refined and their benefits have to be quantified. This paper introduces concepts for the design of decentralized manufacturing systems and a detailed simulation-based approach for evaluating the performance of the system. Particularly, the relationships between factory layout planning, production scheduling, and human-robot work distribution are investigated.

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Keywords: Flexible manufacturing system (FMS), Planning, Optimisation, Human-robot collaboration

1. Introduction

Decentralized manufacturing systems (DMS) are of major interest within the concepts of Industry 4.0, the next industrial revolution. They face the tradeoff between increasing fluctuations in the market demands for highly individualized products and the demand of today's production systems for well-balanced and strongly deterministic production programs [1]. Therefore, they need to handle increased manufacturing complexity caused by decreased production volumes per product variant [2]. The basic design approach of DMS concentrates on highly flexible product and material transport units to allow individual and non-dedicated material flow paths by decentralized decision-making processes for each order. This approach has major impacts on the layout planning, the production scheduling and the work distribution regarding human-robot collaboration. In the context of layout planning, challenges regarding the optimal positioning of manufacturing cells as well as distributing process capabilities among these cells arise. Concerning production scheduling, increased flexibility is needed to allow improved utilization of information about the system's current state and the adaptation of production schedules. For a more efficient and ergonomic production, human-robot collaboration is a key concept and requires new approaches for distributing work tasks between humans and robots.

This work presents a holistic approach for the simulation-based evaluation of future intelligent production characterized by human-robot collaboration in decentralized manufacturing systems. In-depth explanations of dependencies between layout planning, production scheduling and human-robot work distribution are discussed.

The remainder of this paper is structured as follows. Chapter 2 provides the technical background with focus on future intelligent production, layout planning, production scheduling, and human-robot collaboration and finishes with the research demand and goal of this work. Chapter 3 introduces the concept of decentralized manufacturing systems (DMS) and an approach for a simulation-based evaluation of DMS. Main elements of the simulation concept are layout planning, scheduling and human-robot work

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distribution. Finally, Chapter 4 concludes the research progress and provides an outlook about future research needs.

2. Technical Background

Conditions that strongly influence the performance of manufacturing systems have changed dramatically in recent years [3]. In manufacturing, main reasons for inefficiencies in today's production are increasing product individualization and shorter product life cycles whilst remaining competitive in almost saturated markets [1,2,4]. Zuehlke [4] states that the complexity of manufacturing systems increases in order to manage the market driven complexity increase of products. The smart factory, a conceptual approach described by Lucke et al. [3], aims at facing dynamic internal changes, e.g. machine breakdowns, and external changes, e.g. fluctuations in the market demand, by collecting and analyzing manufacturing information from physical objects as well as virtual planning systems. Bochmann et al. [5] introduce decentralized manufacturing systems as a more focused subcategory of the smart factory. The decentralization refers to the production layout, which dictates material flow, flexible scheduling of orders based on decentralized decision-making, and context-aware work distribution between humans and robots within the same manufacturing cell.

2.1. Layout Planning

Drira et al. [6] describe a facility layout as an arrangement of everything needed for production of goods or delivery of services. In this context, Heragu [7] defines a facility as an entity that allows any job, e.g. machine tools, manufacturing cells, departments or warehouses. Yang et al. [8] state that facility planning and material handling is crucial to achieve a high company's productivity and profitability. According to Francis et al. [9], material handling costs are 20% – 50% of the total operating expenses in manufacturing and they claim that a cost reduction of 10% – 30% can be achieved through effective facility planning. Singh and Sharma [10] define the facility layout problem (FLP) as the determination of the physical organization of a production system. Generally, Koopmanns and Beckmann [11] classified the FLP as a quadratic assignment problem (QAP). Since the QAP is NP-complete, where NP refers to 'nondeterministic polynomial time' and states that the required time to solve to problem with any currently known algorithm increases strongly with the size of the problem. Therefore, an exact solution is difficult to obtain and optimizations are often carried out on these kind of problems [12–14]. With respect to layout planning, the main optimization objective is to minimize material handling costs, but also research on multi-objective approaches exists [9].

Methods for solving the QAP are categorized in mathematical/exact algorithms and heuristics [15]. The fastest exact algorithms are branch-and-bound algorithms, but they can only solve QAPs consisting of maximal 20 objects within reasonable time due to high computational complexity [15]. Heuristics can be further subdivided into construction, improvement, hybrid, and graph theoretic algorithms [13,15]. Construction heuristics try to locate facilities iteratively until the complete layout is obtained [13]. Improvement heuristics try to improve an initial solution successively by systematic exchanges of the solutions' characteristics. Examples for improvement heuristics are the CRAFT algorithm, simulated annealing, tabu search, and genetic algorithms [13,15]. Hybrid algorithms combine exact algorithms with heuristics to obtain more exact solutions in shorter time. Algorithms based on graph theory are often also construction algorithms. They represent the FLP as a weighted graph with relationships between the facilities and identify maximal planar subgraphs to obtain a solution [13].

2.2. Production Scheduling

According to Zobolas et al. [16], production scheduling problems are faced by every company that is engaged in the production of tangible goods. Due to more degrees of freedom (DoF) for the scheduling of orders in a smart factory, the production scheduling is of great importance and belongs to the category of shop production scheduling problems. Shop production scheduling problems are differentiated regarding their job arrival as static or dynamic, their inventory policy as open or closed, and their a priori knowledge about job processing times and machine availabilities as deterministic or probabilistic [16]. Additionally, a distinction based on the considered production environment as single or multi stage is made. For practical applications static, deterministic, multi stage shop scheduling problems are relevant [16].

With flow shop scheduling problem (FSSP) (see [17]), job shop scheduling problem (JSSP) (see [18]), and open shop scheduling problem (OSSP) (see [19]) three basic shop scheduling problems exist, which build the basis for more specific ones. Important extended problems are the flexible job shop scheduling problem (FJSSP) (see [18, 20]), the mixed shop scheduling problem (MSSP) (see [21]), and the group shop scheduling problem (GSSP) (see [22]). It is important to notice that extended shop scheduling problems are of at least equal complexity than the three basic problems and solving methods for basic problems can be applied to extended problems with little modifications [16]. With respect to DMS, none of the existing shop scheduling problem is capable of covering the whole dynamics and DoF. Thus, an extended shop scheduling problem needs to be defined and solution methods need to be developed.

2.3. Human-robot collaboration

The higher complexity and flexibility of decentralized manufacturing systems has to be handled in the workstations, which is a key element towards the factory of the future, as stated by Krueger et al. [23]. The human worker in the workstation is affected by these new manufacturing concepts. Repetitive work within an assembly line is replaced by fast changing situations in workstations of a decentralized