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Assembly system design in the Industry 4.0 era: a general framework

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Abstract: Assembly system design defines proper configurations and efficient management strategies to maximize the assembly system performances. Beyond assembly line balancing and scheduling, several other dimensions of this problem have to be considered. Furthermore, the assembly system design has to consider the industrial environment in which the system operates. The latest industrial revolution, namely Industry 4.0, leverages Internet connected and sensorized machines to manufacture customer-designed products. This paper proposes an original framework which investigates the impact of Industry 4.0 principles on assembly system design. The traditional dimensions of this problem are described along with the industrial environment evolution over the last three centuries. Concerning the latest industrial revolution, the technology innovations which enabled the manufacturing process digitalization are presented. The application of these enabling technologies to the assembly domain results in a new generation of assembly systems, the here defined assembly system 4.0. Finally, the distinctive characteristics of these novel systems are proposed and described in detail.

Keywords: Assembly system, Industry 4.0, Framework, Design and management, Internet of things, Smart manufacturing, Assembly line balancing, Modeling of assembly units, Process supervision, Logistics in manufacturing.

1. INTRODUCTION

A century later from the introduction of the first assembly line in Highland Park Ford Plant in Michigan both the industrial technologies and the market demand radically changed. Breakthrough innovations as the global communication network, e.g. Internet, and interconnected intelligent sensors are enabling technologies for production systems. Similarly, the market demand rapidly evolved over the last decades requiring high volumes of products individually personalized considering the single customer requirements, introducing the concept of mass customization. These trends determined a disruptive leap for manufacturing processes resulting in a remarkably higher production efficiency, product quality and customer satisfaction. This recent revolution of the industrial environment is named "Industry 4.0" (I40) (Kagermann et al., 2013). Traditional assembly lines descended from the Ford model T one are no longer suitable for today industrial environment. A new generation of assembly systems (ASs) is sought to seize the opportunities that the fourth industrial revolution offers.

This paper presents the first original framework which investigates the impact that I40 principles have on ASs. Aim of this paper is the improvement of the design and configuration of modern ASs to leverage I40 features establishing the here defined "Assembly System 4.0" (AS40). The manuscript is organized as follows. Section 2 presents the traditional dimensions of AS design and it analyses the related AS configurations. Section 3 investigates the evolution of the industrial environment in the last centuries and it presents the most recent trends, whereas Section 4 describe the technology innovation of the fourth industrial revolution. Based on these analysis, Section 5 assesses the impact that I40 has on modern ASs in term of novel assembly line configurations, innovative technologies and new management principles proposing the main characteristics of AS40. Finally, conclusions and further research opportunities are drawn in Section 6.

2. ASSEMBLY SYSTEM DESIGN

AS design is a process of interrelated decisions whose aim is to define a proper configuration and efficient management strategies for a production system which assemblies components into a final product. Several are the dimensions to consider in AS design.

Balancing is certainly the most investigated one. Since the first mathematical formulation of ALB by Salveson (1955), researchers and practitioners developed several models and methods to assign assembly tasks to workstations to optimize a certain objective function and to satisfy a set of constraints. Traditional objective functions deal with the minimization of the workstation station number or the assembly line cycle time, whereas the constraints usually ensure the assembly precedence relations and represent the assembly task attributes as the time, cost or space to perform them (Boysen et al., 2007).

Sequencing is the short-term counterpart of the ALB problem. This problem arises in mixed-model lines which assembly several product models from a common product

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family to fulfil the requirements of mass customization. In these ASs, tasks of different models are performed in the same workstation during consecutive cycles. Aim of the assembly line sequencing is to define an intermixed sequence of product models such that the customer demand of all models is satisfied minimizing the sequence dependent work overload. Work overloads occur if several work intensive models follow each other at the same workstation. These overloads could result in the entire assembly line stop, the support of utility workers to the critical workstations or unfinished tasks to be completed off-line (Boysen et al., 2009).

The assembly of different product models in the same workstation requires to properly manage the feeding of several components. This relevant dimension of AS design is known as *material feeding* (or part logistic). Its aim is to feed the AS with the right type and quantity of components at the right location and time. Two are the most relevant material feeding decisions, the material storage and the feeding policy. The former defines the packaging type and dimensions to store the components along the AS (Bortolini et al., 2016). Considering the latter decision that deals with material feeding, three are the possible feeding policies to adopt (Faccio et al., 2015). Line side stocking suggests to store each component in individual containers, transport them from the warehouse to the workstations and replace them when empty. Kitting feeding uses identified areas to group in one container specific components and subassemblies which together support the assembly tasks of a particular product model. Finally, kanban feeding policy stores each component type in proper bins to which are attached kanbans. The containers are formed in a supermarket area whereas they are stored in defined quantities at station level. When the components in a container are depleted, the related kanban is released and the material replenishment occurs.

A further dimension of AS design is the *equipment selection.* Certain tasks could require specific piece of equipment to be performed, whereas others could benefit from the adoption of automation to reduce their duration. Purpose of the equipment selection is the definition of which pieces of equipment to purchase and install in which workstations to optimize a set of AS key performance indices (KPIs) (Bukchin and Tzur, 2000).

Learning effect is a relevant dimension to design ASs. It refers to the inversely proportional relationship between the task duration and the number of task repetitions done by a worker (Cohen et al., 2008). This effect is particularly relevant for ASs operating in today industrial environment. The mass-customization and the reduced life cycle of products determine the frequent launch of high-personalized new goods. The introduction of a new product in an AS is distinguished by an initial period, called learning stage, characterized by a limited productivity due to worker training of new assembly activities. Shortened learning stage results in increased product sales in the life cycle phase distinguished by the highest revenues, which is the time a new product reaches the market.

Finally, recent advances in the literature suggest to include the *ergonomic risk* into AS design. Assembly workers are intrinsically prone to musculoskeletal disorders, due to strenuous operations repeated at high frequency. Ergonomic risk at AS has a negative impact both on worker health and life quality as well on company economic results and reputation. The latest developments in legislations (EU Machinery directive, 2006/42/EC, 89/391/EEC, Occupational Safety and Health act) and the workforce aging in the developed countries force to include the ergonomic aspect into AS design (Otto and Scholl, 2011). The following Fig. 1 summarizes the aforedescribed dimensions of AS design.

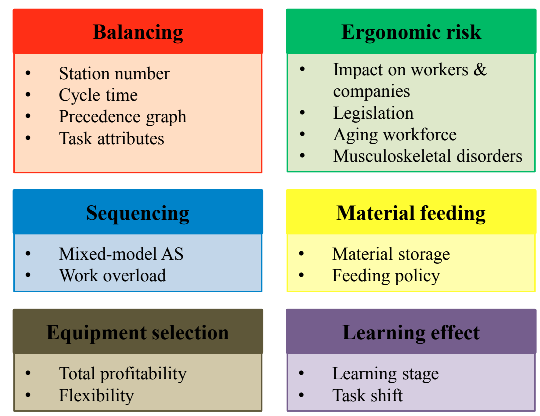

Fig. 1. Dimensions of assembly system design

3. INDUSTRIAL ENVIRONMENT EVOLUTION

AS design has to consider the industrial environment in which the production system operates. Indeed, the industrial environment discontinuously evolved over the centuries. Discontinuities are identified by disruptive leaps in manufacturing processes resulting in remarkably higher productivity. These discontinuities result in four industrial revolutions. The first revolution occurred from late 18th to mid 19th century. The technology innovations which enabled a significant productivity leap were the steam power and machine tools. These technologies allow to manufacture few complex and expensive products customized on the end-user needs. This production paradigm is named “craft production” (Koren, 2010). The second industrial revolution took place from late 19th to mid 20th century and involved the introduction of electricity in manufacturing processes. This enabled to produce large volume of identical products at low unitary cost introducing the concept of “mass production” (Langlois and Robertson, 1989). During this period, the ASs were introduced and adopted for the first time in the history. The mass production paradigm is overcome during the third industrial revolution (from late 20th to early 21st century) with the introduction of electronic, information technology (IT) and automation. These technologies enabled to develop a novel production paradigm to face the customer demand of a greater product variety at competitive costs and in large quantities, namely “mass customization” (Misthal et. al, 2016). Finally, the industrial environment is nowadays experiencing its fourth industrial revolution, called I40. The ubiquitous use of cheap sensors and actuators communicating through a network, e.g. Internet, enables the real-time