Computers & Industrial Engineering 112 (2017) 348–367

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Multi-objective assembly line balancing considering component picking and ergonomic risk

Marco Bortolini [a], Maurizio Faccio [b], Mauro Gamberi [a], Francesco Pilati [a,*]

[a] *University of Bologna, Department of Industrial Engineering, Viale del Risorgimento 2, 40136 Bologna, Italy*
[b] *University of Padova, Department of Management and Engineering, Stradella San Nicola 3, 36100 Vicenza, Italy*

ARTICLE INFO

Article history:
Received 20 February 2017
Received in revised form 26 July 2017
Accepted 23 August 2017
Available online 30 August 2017

Keywords:
Assembly line balancing problem
Component picking
Ergonomic risk
Multi-objective optimization
Assembly station storage

ABSTRACT

Aim of the assembly line balancing problem (ALBP) is the efficient and effective assignment of assembly tasks to stations in one-piece-flow production systems. Although this problem has been studied for decades, few contributions consider the component picking at assembly station level. Yet, this activity has relevant and practical implications for ALBPs in the industrial context. This paper proposes an innovative multi-objective optimization model for the ALBP to assign the assembly tasks to stations by distinguishing the assembly activities involved in task execution and component picking. Thus, a function is proposed to relate the time required for component picking with the component storage location at assembly station level and the component features, namely dimensions, weight and handiness. The aim of the developed model for the ALBP is the simultaneous minimization of the assembly line takt time and ergonomic risk, both determined by the task execution and component picking activities. Furthermore, the proposed model not only defines the optimal task assignment to stations, but it also determines the optimal storage location of each component between the locations available at the different assembly stations. The multi-objective optimization model is validated with an industrial case study dealing with a kitchen appliance assembly line. The final assembly line balancing configuration proposed is distinguished by remarkable performance for both takt time and ergonomic risk objective functions. Such a balancing leads to 36% ergonomic risk reduction with just 2% takt time increase compared to the correspondent single-objective configurations. These outstanding results are determined by a proper component disposition in the different station storage locations defined by the model.

1. Introduction

Mass customization is known as the current production paradigm (Hu et al., 2011). Every single customer demands for a complete product personalization in a limited production lead time. To face these challenging market requirements, production processes exacerbate the adoption of just-in-time and assembly-to-order principles (Faccio, Gamberi, Pilati, & Bortolini, 2015; Jainury, Ramli, Ab Rahman, & Omar, 2014). Indeed, modern assembly systems manufacture a huge quantity of similar products united by a common product structure yet differentiated by the mounted components which define the variants and options. Thus, these assembly systems deal with hundreds of different components, each of which is distinguished by a set of features as the volume, the weight, the handiness, the picking frequency, etc. The components required are typically picked by the assembly worker to perform the assigned tasks. Thus, an effective and efficient design of assembly systems should consider the impact that the component picking activities at assembly station level have both on worker productivity and risk of musculoskeletal disorders (Finnsgård et al., 2011; Baudin, 2002). In fact, a properly designed assembly system enables to both maximize the line productivity and minimize the ergonomic risk to which workers are exposed (Savino, Mazza, & Battini, 2016).

Furthermore, aim of the assembly line balancing problem (ALBP) is the tasks to stations assignment (Scholl, 1995). This selection affects the station workload and influences the assembly line productivity. Nevertheless, this assignment univocally defines the station in which each component has to be stored. Every task is distinguished by a corresponding typology and number of components to assemble. Thus, neglecting the influence of component features and storage location (SL) at station level on assembly activities leads to inefficient ALBP solutions. The division of assembly operations into component picking and task execution (i.e. component fastening) enables to assess the impact of component

---

* Corresponding author.
E-mail address: francesco.pilati3@unibo.it (F. Pilati).

http://dx.doi.org/10.1016/j.cie.2017.08.029
0360-8352/

Nomenclature

Abbreviations

ALBP	Assembly line balancing problem
MO	Multi-objective optimization
MOST	Maynard operation sequence technique
REBA	Rapid Entire Body Assessment
SL	Storage location
T_{MOST_w}	Component picking time from w-th storage location according to MOST general move sequence
TMU	Time measurement units

Component features

A	component volume parameter
B	component density parameter
C	component shape parameter
D	component damage risk parameter
E	component condition parameter
MAG	magnitude index
V	component volume [cm^3]

Body angles

α	neck bending
β	trunk frontal bending
γ	knee angle
δ	shoulder frontal elevation
η	elbow angle
λ	wrist flexion

Indices

$k = 1, \ldots, K$ assembly stations
$j, i = 1, \ldots, J$ tasks
$w = 1, \ldots, W_k$ storage locations (SLs) within each station
$z = 1, \ldots, Z$ components

Parameters

A_{jz}	1 if task j requires component z, 0 otherwise
AT_j	assembly execution time of task j [s]
AE_j	assembly execution ergonomic risk of task j [REBA score]
CT	maximum assembly line cycle time [s]
HM_{wk}	height of storage location w of station k [mm]
H_z	height of component z (standard bin) [mm]
IE	ergonomic risk of idle worker [REBA score]
IT_k	idle time of worker k [s]
LM_{wk}	length of storage location w of station k [mm]
L_z	depth of component z (standard bin) [mm]
LBK	lower bound of the station number
QM_{wk}	weight capacity of storage location w of station k [g]
Q_z	weight of component z (standard bin and contained components) [g]
PE_{zwk}	picking ergonomic risk of component z from location w of station k [REBA score]
PT_{zwk}	assembly picking time of component z from location w of station k [s]
RM_{wk}	width of storage location w of station k [mm]
R_z	width of component z (standard bin) [mm]
ξ_j	immediate predecessors of task j

Variables

X_{jk}	1 if task j is assigned to station k, 0 otherwise
Y_{zwk}	1 if component z is stored in position w of station k, 0 otherwise

Objective functions

ER	assembly line ergonomic risk [REBA score]
G_s	global function
s	Pareto solution index
TT	assembly line takt time [s]

features and SL on picking activities. The component picking time can represent even a large portion of the task total assembly time (Finnsgård and Wänström, 2013). Fig. 1 presents examples of picking at the assembly station, influenced by the component SL with respect to the assembly workspace.

Fig. 1 suggests a further relevant aspect of component picking at assembly station level. The component features and SL significantly affects the worker ergonomic risk while he is performing assembly activities. Although ergonomic ALBP is nowadays a widely debated topic in industrial engineering research, the proposed approaches and methods aim to minimize the worker risk of musculoskeletal disorders without including any variation in the assembly task duration. Commercial software for the manufacturing industry seek to integrate the ergonomic and time aspects in the ALBP (Cheshmehgaz, Haron, Kazemipour, & Desa, 2012). Siemens Jack™ (https://www.plm.automation.siemens.com/en/products/tecnomatix/manufacturing-simulation/human-ergonomics/-jack.shtml) and Dassault Delmia™ (https://www.3ds.com/products-services/delmia/products/v5/portfolio/) are widespread software to virtually represent the manual manufacturing and assembly activities through digital human modelling. The tasks performed by an operator are simulated by a digital mannequin to assess an extensive range of performance indices. These software offer a wide sets of ready-to-use tools to automatically analyse the operator activities both from the time (MTM motion analysis, MOST, etc.) and ergonomic (REBA index, OWAS, NIOSH, etc.) perspectives. However, these software lack any optimization criteria, thus they do not represent a proper solution for the previously described problem.

Considering the formerly analysed scenario, this paper proposes an innovative multi-objective optimization (MO) model for the ALBP to assign assembly tasks to stations by distinguishing the assembly activities involved in component picking and task execution. The former are the activities to pick components from station SLs which are affected by the component storage position and attributes, such as dimensions, weight, shape and handiness. The latter are the activities for component fastening on the assembly workbench which depend on the task to be performed. Aim of the developed MO model is the simultaneous minimization of the assembly line takt time and ergonomic risk, both of which are determined by the task execution and component picking activities. These optimization targets are those selected between the multitude of criteria for the ALBP, e.g. quality, flexibility, etc. Indeed, the current scenario of assembly industry compels to evaluate both these two performance indicators. Takt time minimization is mandatory to guarantee proper efficiency to the assembly process and adequate utilization of the involved resources. Ergonomic risk reduction is required by the European standards EN 1005-2, 3, 4 and 5 which force the risk assessment of lifting and carrying activities as well of the low load handling at high frequency. Furthermore, the ergonomic assessment of assembly processes is even more relevant considering the industrial environment evolution of the last decade. In the last 10 years the percentage of European employees older than 50 years rose from