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Consideration of workers' differences in production systems modelling and design: State of the art and directions for future research

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ABSTRACT
The effects of workforce differences on manufacturing systems have attracted the attention of a wide range of researchers in recent years. The differences between workers in terms of skills, age, gender and anthropometric measures have a large impact on production system performance. In this study, the workforce differences factors in production system design and modelling were investigated, with the aim of understanding how the differences between workers could influence a production system and how they had been considered in previous studies. The papers selected from the Scopus database were categorised based on whether how human factors are incorporated into manufacturing system optimisation and design approaches is discussed therein or is not. To find relevant papers, two sets of keywords were defined: (1) keywords relating to the differences between workers and (2) keywords relating to the kind of problem under study. Furthermore, the investigated papers helped highlight the strengths and weaknesses of the existing literature and derive a discussion on the possible future research steps.

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Human differences; human factors; production system; assembly system; literature review

1. Introduction

A wide range of tasks in the production sector are human-centred, and their performance largely depends more on workers than on machines (Abubakar and Wang 2019; Calzavara et al. 2020). Workers may have different features and capabilities, though, and production systems can be influenced by such differences. Workforce features may vary between workers in terms of many parameters, such as skills, age, gender and anthropometry measures, and these differences can affect the overall performances of the production system in terms of time (i.e. Rameza-nian and Ezzatpanah 2015), cost (i.e. Martignago, Battaïa, and Battini 2017), throughput (i.e. Buzacott 2002) and human health and job safety (i.e. Deros et al. 2011). Therefore, consideration of workers' differences in production systems can play an important role particularly in sections with higher manual demands. For example, one of the most important components in many production systems is the assembly section, which has high worker involvement. In this unit, several workstations are usually connected together, and unfinished products pass through the stations, where tasks with predetermined precedence relationships are executed either by robots or by human workers. In this environment, the typical goal of managers and engineers is the appropriate assignment of workers to various stations and the balancing of the line (Samouei et al. 2016). Therefore, identifying the workers' features can be considered an important challenge when assigning appropriate workers to the right stations to improve the adaptability of workers to their assigned tasks.

Some studies have already shown the impact of human differences on various factors, but only in general terms, without a direct focus on manufacturing activities or assembly systems (i.e. Zolfaghari, Jaber, and Hamoudi 2004; West and Travers 2008; Ağralı, Taşkın, and Ünal 2017). For example, Zolfaghari, Jaber, and Hamoudi (2004) formulated a multi-period task assignment problem considering the workers' experience and expertise level to improve the conformity of the assigned workers with tasks. In their study, the skills and experience levels of the workers varied. Although they considered the workers' differences in terms of skills and age for task assignment, they did not do so in the context of a manufacturing system or an assembly line but in the context of a university environment. Other studies have put much emphasis on ergonomics issues (i.e. Battini et al. 2015; Battini et al. 2016;) even if related to average

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standard workers instead of considering the actual differences between workers (i.e. Battini et al. 2017; Finco et al. 2020), on the impact of fatigue on task duration (i.e. Ferjani et al. 2017; Calzavara et al. 2019) or on the modelling of the human fatigue level according to the work time and workload increase (i.e. Hu and Chen 2017).

Previous works have already investigated the existing literature regarding human factors in the industrial context. Loos, Merino, and Rodriguez (2016) presented the state of the art regarding ergonomics in the logistics and supply chain domains. Otto and Battaïa (2017) particularly focused on physical ergonomic risks and musculoskeletal disorder risks, providing an overview of the existing optimisation approaches for assembly line balancing and scheduling. Grosse et al. (2017) summarised all the studies that included any human factor in decision support models. Kolus, Wells, and Neumann (2018) examined the available empirical evidence on the impact of human factors consideration (in production and workstation design) on product quality, investigating the quality risk factor in product, process and workstation design. Calzavara et al. (2020) recently published a paper on the state of the art regarding the Industry 4.0 technologies for ageing workers in manufacturing systems. Moreover, Di Pasquale, Miranda, and Neumann (2020) recently conducted a scoping review of papers on ageing and human-systems errors and determined the relationship between the two in production environments. Finally, Hashemi-Petroodi et al. 2020 have considered workforce reconfiguration strategies as part of workforce planning in flexible and reconfigurable manufacturing systems to help industrial companies to quickly adapt to frequent changes.

The previous studies, however, except that by De Bruecker et al. (2015), did not give any attention to the differences between workers. Rather, they conducted a literature review on workforce planning problems involving skills, concentrating on the skill differences between workers in all sectors. They did not consider other individual differences between workers and focused only on workforce planning. This study, on the other hand, conducted a new literature review on the four human variability factors of skills, age, gender and anthropometry and looked into how these factors had been considered in production systems design and management. Therefore, from a managerial point of view, this study could be helpful to give clues to managers and decision makers on how to consider individual differences in production systems from the initial step of their design, as also requested by Sgarbossa et al. (2020). In fact, Sgarbossa et al. (2020), have recently highlighted the strong need of the design of individualised, customised solutions in the context of managing increased diversity in workers, including a range of perceptual, cognitive and physical capabilities and needs. Then, this study extends the initial study by Katiraee et al. (2019) presented in a conference paper by considering more features, analysing more scientific papers, introducing two new classifications and conducting a deeper analysis of the existing contributions. This extended analysis resulted in the comprehensive future research agenda provided in this paper. In particular, three research questions were investigated in this study, as shown below.

- RQ1: How have the differences between workers been considered in manual production systems in the previous studies?
- RQ2: What conclusions have been made regarding the impact of human variability on the performances of manual production systems?
- RQ3: What is the main research gap in the existing literature, and what future research should be conducted to reduce this gap?

It should be noted that this study focused on the differences between workers (not within workers) in the production context, particularly in assembly systems, where tasks are mainly done manually. More precisely, the following areas were investigated: (1) assembly line balancing and designing; (2) work/worker assignment; (3) job rotation/task switching and (4) workspace, layout and workstation design.

The remainder of this paper is structured as follows. In section 2, the adopted procedures and the steps of the paper selection are explained. In section 3, the classified papers are analysed and discussed. In section 4, the results of the literature review are presented and discussed. In section 5, agenda for future research efforts on this topic are provided. Finally, in section 6, the study conclusions are presented. The results of this study can help engineers and operation managers in designing workstations and managing workers appropriately based on the latter's capabilities and individual differences. The final research agenda can support future research efforts on the design of a manufacturing system when human variability factors need to be considered among the workers involved.

2. Method

To understand the state of the art regarding workforce differences in the production context, a systematic literature search was performed in this study using the method proposed by Neumann and Dul (2010). The focus was on understanding which worker variability factors are considered in the literature, and how the differences between

Table 1. Review methodology and steps adopted.

Step	Years	Keywords	Refine criteria	Exclusion criteria	Papers found	Papers used
1	1992–2019	**Title** = "skilled-work*" OR "skill*" OR "age" OR "aging" OR "gender" OR "body and physical measure" OR "anthropometry" OR "human factor", OR "worker variability" OR "individual factor" OR "heterogenous worker" OR "anthropology" **And Title** = "assembly system" OR "assembly line*" OR "manual assembly line" OR "task assignment" OR "work assignment" OR "job assignment" OR "job schedule*" OR "task schedule*" OR "worker assignment" OR "worker allocation" OR "job rotation" OR "task switching" OR "job sequencing" OR "task sequencing" OR "work space design" OR "layout design" OR "workstation design" OR "facility location" OR "production system*" OR "manufacturing system*"			7,051	
2	1992–2019		LIMIT-TO Language = English **And** LIMIT-TO Source Type = "Journals" **And** LIMIT-TO Subject Area = "Business, Management and Accounting" or "Computer Science" or "Decision Sciences" or "Economics, Econometrics and Finance" or "Engineering" or "Mathematics" or "Multidisciplinary"		1613	
3	1992–2019			Irrelevant and out of scope papers are excluded since they are not concerning human differences factors for industrial workers in manufacturing and production settings		91
4	1992–2019	Papers coming from the snowball approach of the papers selected in ROW 3				9
Total 1992–2019						**100**

workers affect the overall system. The literature search consisted of the steps shown below and in Table 1.

2.1. *Database and keywords selection*

The literature search was conducted in the Scopus database. No time limitations were indicated; as such, all the papers that were uploaded in such database from its inception until the end of 2019 were searched. We used the Scopus database because it is well acknowledged by scientific communities as a reputable database and includes a bigger spectrum of journals compared to other databases (e.g. PubMed, Web of Science). Moreover, its citation analysis is faster and includes more articles than the citation analysis of Web of Science, among other databases (Falagas 2008).

Two main keyword sets were used for article titles and abstracts to identify studies that (1) included the measurement of human differences factors and (2) were conducted in a production setting. The first set of keywords was selected according to workers' individual differences. Workers can be diverse in terms of skills, age, gender and body measurements or anthropometry. In addition, so as not to miss any important paper indexed in Scopus, we used some other keywords referring to workers' features and differences (e.g. 'human factor', 'worker variability', 'individual factor', 'heterogenous worker'). To define the second set of keywords, four categories were first defined according to production systems design and modelling: (1) assembly line balancing and designing; (2) work/worker assignment; (3) job rotation/task switching and (4) working space design and layout design. The second set of keywords was selected on the basis of the aforementioned four categories, as shown in detail in Table 1. The combination of these two sets of keywords enabled us to identify studies that considered workers a variable parameter or as different from one another in the work environment in which they perform certain tasks. Here, the work environment that was mainly considered was the assembly line, where workers' involvement in performing tasks can be widely seen.

It should be noted that studies that considered workers' differences in terms of disability were also found. Since the pioneering study by Miralles et al. (2007), the integration of workers with disabilities in assembly line balancing and worker assignment has received considerable attention among researchers (Araújo, Costa, and Miralles 2012; Borba and Ritt 2014; Castellucci and Costa 2015; Cortez and Costa 2015), including variants of such topic, such as disabled-friendly job rotation objectives (Costa and Miralles 2009), line layouts (Araújo, Costa, and Miralles 2015) and more general industrial settings, extrapolating data from sheltered work centres for the disabled (Moreira, Miralles, and Costa 2015). However, we did not include this topic in our research keywords as our objective was to study the general framework of workers' differences.

Using the two aforementioned sets of keywords, we found 7,051 papers in our initial search (covering the years 1992 to the end of 2019).

2.2. Refined criteria

The number of selected papers was reduced to 1,613 by introducing two additional filters: (1) only papers written in the English language and published in all journals; and (2) published papers on the relevant subject areas ('business, management and accounting', 'computer science', 'decision sciences', 'economics, econometrics and finance', 'engineering', 'mathematics' and 'multidisciplinary').

2.3. Papers analysis

The resulting 1,613 papers were read and further screened to select relevant papers where the differences between workers were considered in the production sector. The final set of relevant papers included 91 articles. Finally, the snowball approach was applied, resulting in the final selection of 100 papers for the analysis. The analysis was done as shown below.

- First, the papers were classified according to the workers' differences in terms of skills, age, gender and anthropometry under four types of problems in production systems, as can be seen in Table 2: (1) assembly line balancing and design, (2) work/worker assignment, (3) job rotation and task switching and (4) working space design and layout design.
- Second, as was done by Abubakar and Wang (2019), the papers were classified according to the impacts on production systems, such as time, cost, efficiency, safety and workers' health (see Table 3).
- For the readers' convenience, Table A1 in the Appendix, which provides comprehensive information regarding each analysed paper, was prepared.
- In addition, we used the VOSviewer software to visualise the following trends: (1) how the attention towards this issue has evolved over the years, as can be seen in Figure 2; and (2) how selected keywords were connected to each other in previous studies, as can be seen in Figure 3. VOSviewer (http://www.vosviewer.com/) is a software tool for analysing bibliometric networks; in this work, it was used to study the keywords network applying the VOS clustering method (Van Eck and Waltman 2009).

3. Elaborated classification

In this section, the selected papers classified according to two main criteria (i.e. workers' differences [see Table 2] and impacts of workers' differences on production systems [see Table 3]) are presented and discussed.

For each paper, Table 2 shows (1) the human differences factors (i.e. skills, age, gender and anthropometric measurements) and (2) the types of problems the paper deals with (i.e. assembly line balancing and designing, work/worker assignment, job rotation or task switching and layout/workstation design). In addition, we identified the papers that reported real data and case studies.

Below, we discuss all the factors that were considered in our analysis, and we discuss their importance and their presence in the literature.

3.1. Skill

As can be seen in Table 2, skill is the human factor that attracted the researchers' attention the most in the existing literature. To date, the skill differences between workers that have been considered in the previous studies are general personal and professional capabilities such as experience/expertise level, speed, motivation, competency level, ability to learn or having a particular physical attribute needed to do tasks. Therefore, in this study, 'skill' is defined as worker superiority feature that effect on worker performance in performing tasks. For example, some studies have used the competency concept to describe workers' skills and have classified workers according to their competency level. ISO 9001 (2015) defined *competence* as the ability to apply one's knowledge and skills to achieve one's intended results. This definition

Table 2. Classification of the papers according to human differences factors in production system modelling and design (underlined papers include industrial data).

Human factors	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design
Skills				
personal and professional capabilities	Chen et al. (2019); Dalle Mura and Dini (2019a); Dalle Mura and Dini (2019b); Samouei and Ashayeri (2019); Digiesi et al. (2018); Fan et al. (2018); Hochdörffer et al. (2018); Lian et al. (2018); Moussavi et al. (2018); Sadeghi et al. (2018); Salehi et al. (2018); Zhang et al. (2018); Dalle mura et al. (2017); Martignago et al. (2017); Moussavi et al. (2017); Oksuz et al. (2017); Öner-Közen et al. (2017); Fattahi et al. (2016); Polat et al. (2016); Samouei et al. (2016); Zacharia and Nearchou (2016); Folgado et al. (2015); Ramezanian and Ezzatpanah (2015); Sotskov et al. (2015); Sungur and Yavuz (2015); Xin et al. (2015); Koltai et al. (2014); Oksuz and Satoglu (2014); Koltai and Tatay (2013); Liu et al. (2013); Manavizadeh et al. (2013); Mutlu et al. (2013); Zhang et al. (2013); Araújo et al. (2012); Chen et al. (2012); Koltai and Tatay (2011); Zhang and Gen (2011); Thongsanit et al. (2010); Moon et al. (2009); Ikou et al. (2008); Nembhard and Shafer (2008); Weng and Onari (2008); Song et al. (2006); Wong et al. (2006); Iima et al. (2005); Shafer et al. (2001); Doerr (2000); Gallwey (1992)	Chen et al. (2019); Chu et al. (2019); Dalle Mura and Dini (2019a); Dalle Mura and Dini (2019b); Hashemoghli et al. (2019); Liu and Yang (2019); Méndez-Vázquez and Nembhard (2019); Samouei and Ashayeri (2019); Digiesi et al. (2018); Gong et al. (2018); Lazzerini and Pistolesi (2018a); Lazzerini and Pistolesi (2018b); Lian et al. (2018); Moussavi et al. (2018); Sadeghi et al. (2018); Salehi et al. (2018); Wu et al. (2018a); Wu et al. (2018b); Zhang et al. (2018); Fichera et al. (2017); Moussavi et al. (2017); Oksuz et al. (2017); Öner-Közen et al. (2017); Rabbani et al. (2017); Fattahi et al. (2016); Li et al. (2016); Liu and Wang (2016); Niakan et al. (2016); Polat et al. (2016); Samouei et al. (2016); Zacharia and Nearchou (2016); Ramezanian and Ezzatpanah (2015); Sungur and Yavuz (2015); Xin et al. (2015); Costa et al. (2014); Koltai et al. (2014); Oksuz and Satoglu (2014); Bentefouet and Nembhard (2013); Costa et al. (2013a); Costa et al. (2013b); Denkena et al. (2013); Koltai and Tatay (2013); Liu et al. (2013); Manavizadeh et al. (2013); Mutlu et al. (2013); Zhang et al. (2013); Araújo et al. (2012); Asensio-Cuesta et al. (2012); Chen et al. (2012); Cheng and Chu (2012); Othman et al. (2012a); Othman et al. (2012b); Koltai and Tatay (2011); Zhang and Gen (2011); Nanthavanij et al. (2010); Thongsanit et al. (2010); Aryanezhad et al. (2009a); McDonald et al. (2009); Moon et al. (2009); Süer and Tummaluri (2008); Weng and Onari (2008); Kuo and Yang (2007); Osawa and Ida (2007); Wirojanagud et al. (2007); Song et al. (2006); Wong et al. (2006); Bokhorst et al. (2004); Buzacott (2002); Norman et al. (2002); Doerr (2000)	Digiesi et al. (2018); Hochdörffer et al. (2018); Moussavi et al. (2018); Mossa et al. (2016); Bentefouet and Nembhard (2013); Costa et al. (2013a); Costa et al. (2013b); Asensio-Cuesta et al. (2012); Nanthavanij et al. (2010); Aryanezhad et al. (2009b); McDonald et al. (2009); Allwood and Lee (2004)	Digiesi et al. (2018);
Number of Papers	48	70	12	1

(*continued*).

Table 2. Continued

Human factors	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design
Age				
Experience	Börsch-Supan and Weiss (2016); Quintana et al. (2008)		Boenzi et al. (2015)	
Number of Papers	2	-	1	-
Functional capacities	Digiesi et al. (2018); Efe et al. (2018); Hanson et al. (2009); Quintana et al. (2008); Baines et al. (2004);	Efe et al. (2018); Digiesi et al. (2018); Botti et al. (2017)	Digiesi et al. (2018); Botti et al. (2017); Boenzi et al. (2015)	Digiesi et al. (2018); Peruzzini and Pellicciari (2017)
Number of Papers	5	3	3	2
gender	Efe et al. (2018); Garbie (2014)	Efe et al. (2018)		Garbie (2014)
Number of Papers	2	1	-	1
Anthropometry	Dalle Mura and Dini (2019b); Baykasoglu et al. (2017); Kara et al. (2014); Deros et al. (2011); Hanson et al. (2009); Shikdar and Al-Hadhrami (2007)	Dalle Mura and Dini (2019b); Kara et al. (2014); Huang and Pan (2014)	Huang and Pan (2014)	Baykasoglu et al. (2017); Deros et al. (2011); Shikdar and Al-Hadhrami (2007); Fulder et al. (2005); Das and Sengupta (1996);
Number of Papers	6	3	1	5

Table 3. Effect of human differences factors on production system.

Effects from	Effects on	Authors	Number of papers
Skills			
Personal and professional capabilities including the workers' learning rate, experience, competency, speed, motivation, capability or any particular physical attribute	Task processing time / operation time	Chen et al. (2019); Liu and Yang (2019); Samouei and Ashayeri (2019); Digiesi et al. (2018); Fan et al. (2018); Gong et al. (2018); Moussavi, Mahdjoub, and Grunder (2018); Zhang, Tang, and Zhang (2018); Moussavi, Mahdjoub, and Grunder (2017); Oksuz, Buyukozkan, and Satoglu (2017); Rabbani, Akbari, and Dolatkhah (2017); Fattahi, Samoei, and Zandieh (2016); Li, Huang, and Niu (2016); Samouei et al. (2016); Folgado, Pecas, and Henriques (2015); Ramezanian and Ezzatpanah (2015); Sotskov et al. (2015); Öksüz and Satoğlu (2014); Denkena, Charlin, and Merwart (2013); Mutlu, Polat, and Supciller (2013); Zhang, Xu, and Gen (2013); Chen et al. (2012); Cheng and Chu (2012); Zhang and Gen (2011); Thongsanit, Boondisakulchok, and Tharmmaphornphilas (2010); Süer and Tummaluri (2008); Weng and Onari (2008); Iima, Karuno, and Kise (2005); Gallwey (1992)	29
	Cycle time / makespan time	Fichera, Costa, and Cappadonna (2017); Moussavi, Mahdjoub, and Grunder (2017); Oksuz, Buyukozkan, and Satoglu (2017); Liu and Wang 2016; Polat et al. (2016); Zacharia and Nearchou (2016); Ramezanian and Ezzatpanah (2015); Xin et al. (2015); Costa, Cappadonna, and Fichera (2014); Koltai, Tatay, and Kalló (2014); Costa, Cappadonna, and Fichera (2013a); Costa, Fichera, and Cappadonna (2013b); Koltai and Tatay (2013); Mutlu, Polat, and Supciller (2013); Araújo, Costa, and Miralles (2012); Koltai and Tatay (2011); Thongsanit, Boondisakulchok, and Tharmmaphornphilas (2010); Ikou, Yasuhiko, and Yong (2008); Weng and Onari (2008); Song et al. (2006); Bokhorst*, Slomp, and Gaalman (2004)	20
	Idle time	Osawa and Ida (2007); Wong, Mok, and Leung (2006)	2
	Cost	Dalle Mura and Dini (2019a); Hashemoghli, Mahdavi, and Tajdin (2019); Samouei and Ashayeri (2019); Hochdörffer, Hedler, and Lanza (2018); Martignago, Battaïa, and Battini (2017); Rabbani, Akbari, and Dolatkhah (2017); Fattahi, Samoei, and Zandieh (2016); Ramezanian and Ezzatpanah (2015); Denkena, Charlin, and Merwart (2013); Othman, Bhuiyan, and Gouw (2012a); Othman, Gouw, and Bhuiyan (2012b); McDonald et al. (2009); Moon, Logendran, and Lee (2009); Doerr, Klastorin, and Magazine (2000)	13

(*continued*).

Table 3. Continued

Effects from	Effects on	Authors	Number of papers
Skills			
Personal and professional capabilities including the workers' learning rate, experience, competency, speed, motivation, capability or any particular physical attribute	Cross Training cost	Chu et al. (2019); Lazzerini and Pistolesi (2018a, 2018b); Wu et al. (2018a); Niakan et al. (2016); Liu et al. (2013); Aryanezhad, Deljoo, and Mirzapour Al-e-Hashem (2009a); McDonald et al. (2009); Norman et al. (2002)	9
	Labor cost	Hashemoghli, Mahdavi, and Tajdin (2019); Salehi, Maleki, and Niroomand (2018); Niakan et al. (2016); Sungur and Yavuz (2015); Xin et al. (2015); Costa, Fichera, and Cappadonna (2013b); Zhang and Gen (2011); Moon, Logendran, and Lee (2009); Kuo and Yang (2007); Wirojanagud et al. (2007)	10
	Throughput / Productivity / output/ line efficiency	Méndez-Vázquez and Nembhard (2019); Digiesi et al. (2018); Wu et al. (2018b); Öner-Közen, Minner, and Steinthaler (2017); Fattahi, Samoei, and Zandieh (2016); Mossa et al. (2016); Bentefouet and Nembhard (2013); Asensio-Cuesta et al. (2012); Chen et al. (2012); Nanthavanij, Yaoyuenyong, and Jeenanunta (2010); McDonald et al. (2009); Nembhard and Shafer (2008); Wirojanagud et al. (2007); Song et al. (2006); Allwood and Lee (2004); Buzacott (2002); Norman et al. (2002); Shafer, Nembhard, and Uzumeri (2001)	17
	Workload balancing / smoothing	Lian et al. (2018); Sadeghi, Rebelo, and Ferreira (2018); Dalle Mura and Dini (2017); Zacharia and Nearchou (2016); Xin et al. (2015); Manavizadeh et al. (2013)	6
	Others: Energy expenditure, job safety, job satisfaction and workers' health	Dalle Mura and Dini (2019b); Asensio-Cuesta et al. (2012); Aryanezhad et al. (2009b)	3
Age			
	Cycle time; task processing time	Digiesi et al. (2018); Efe, Kremer, and Kurt (2018); Baines et al. (2004)	3
	Experience	Boenzi et al. (2015)	1
	Throughput / Productivity / output/ line efficiency	Digiesi et al. (2018); Efe, Kremer, and Kurt (2018); Börsch-Supan and Weiss (2016); Baines et al. (2004); Quintana, Leung, and Chen (2008)	5
	Physical workload capacity / Fatigue or discomfort	Efe, Kremer, and Kurt (2018); Botti, Mora, and Calzavara (2017); Peruzzini and Pellicciari (2017); Boenzi et al. (2015)	4
gender	Throughput / Productivity / output/ line efficiency	Efe, Kremer, and Kurt (2018); Garbie (2014)	2
	Task processing time	Efe, Kremer, and Kurt (2018)	1
	Physical workload capacity / Fatigue or discomfort	Efe, Kremer, and Kurt (2018)	1
Anthropometry	Throughput / Productivity / output/ line efficiency	Baykasoglu et al. (2017)	1
	Physical workload capacity / Fatigue or discomfort	Das and Sengupta (1996)	1
	Others: Energy expenditure, job safety, job satisfaction and workers' health	Dalle Mura and Dini (2019b); Huang and Pan (2014); Kara et al. (2014); Deros et al. (2011); Hanson et al. (2009); Shikdar and Al-Hadhrami (2007); Fulder et al. (2005)	7

can be used at the various levels of an organisation and in the analysis of various processes (Korytkowski 2017).

Some of the papers that we selected (i.e. Fattahi, Samoei, and Zandieh 2016; Chen et al. 2019) considered different levels of workers skill while some papers only distinguished between skilled and unskilled workers (i.e. Techawiboonwong, Yenradee, and Das 2006; Corominas, Pastor, and Plans 2008; Kim, Moon, and Moon 2018). It should be noted that the latter does not reflect personalisation and differences; hence, we did not consider such types of studies.

As mentioned earlier, workers' differences can impact production systems in terms of time, cost, productivity or even job safety. For example, as workers become more experienced and skilled in performing a specific task, their operation time may decrease and their work quality level may increase, resulting in different operating times and work quality levels depending on the workers' skills (Weng and Onari 2008; Battaïa and Dolgui 2013; Zhang, Xu, and Gen 2013). We discuss the possible impacts of this below.

3.1.1. Impacts of workforce skill differences on the production time

The traditional work measurement ignores the differences between individuals and treats work times as constant values. However, Gallwey (1992) showed that human physiology and psychomotor skills may result in different work times. Furthermore, Iima, Karuno, and Kise (2005) assumed that the operation time depends on the assigned worker's skill level. Öksüz and Satoğlu (2014), Samouei et al. (2016), Oksuz, Buyukozkan, and Satoglu (2017), Moussavi, Mahdjoub, and Grunder (2017) and Zhang, Tang, and Zhang (2018) explored this for the assembly-line-balancing problem. Moreover, Süer and Tummaluri (2008), Cheng and Chu (2012), Li, Huang, and Niu (2016), Rabbani, Akbari, and Dolatkhah (2017), Gong et al. (2018) and Liu and Yang (2019) considered work/worker assignment problems in production systems and maintained that the differences between workers in terms of skill level and proficiency can impact the task processing time. In line with this, there are studies that have applied the genetic algorithm to address the problem of workers' differences in terms of skill and experience in the context of the assembly-line-balancing and work/worker assignment problems (Weng and Onari 2008; Zhang and Gen 2011; Chen et al. 2012; Mutlu, Polat, and Supciller 2013; Zacharia and Nearchou 2016).

Learning duration and learning ability also influence the task processing times (Thongsanit, Boondisakulchok, and Tharmmaphornphilas 2010; Öksüz and Satoğlu 2014; Liu and Wang 2016; Oksuz, Buyukozkan, and Satoglu 2017). The task processing time may vary because operators may have different levels of fatigue, experience, competency and motivation (Denkena, Charlin, and Merwart 2013; Sotskov et al. 2015). In this regard, there have been studies that applied the variable neighbourhood search (VNS) algorithm (Polat et al. 2016), data collection (Folgado, Pecas, and Henriques 2015) and a simulation model (Ikou, Yasuhiko, and Yong 2008) to indicate the task-processing variation among the workers in an assembly line that stems from the workers' aforementioned differences. In addition, Fan et al. (2018) showed that operators' cognition skills could largely impact their assembly performance in the cellular manufacturing system because the assembly tasks in this system are mainly cognitive tasks. Therefore, such researchers developed a model for measuring the human factors' complexity, and described the effect of the worker's cognition skills on the operation time of the human-based stations in the assembly line.

As workers employ a different ability depending on the set-up task that they perform, the makespan is strongly affected by the worker allocation issue (Costa, Cappadonna, and Fichera 2014). In this regard, Costa, Cappadonna, and Fichera (2014) proposed a mixed-integer linear-programming model to address the worker allocation issue for enhancing the performance of a manufacturing system. In their model, multiple skill levels of workers for each level of expertise are defined. They stated that the skill levels of workers depend on the experience they have earned over time using a given manufacturing equipment or a given technology. Costa, Cappadonna, and Fichera (2013a, 2013b) studied how the allocation of M differently skilled workers whose skill levels randomly vary in range (0.5, 1) to machines may affect makespan minimisation. In conclusion, they indicated that workforce skills may strongly influence the makespan minimisation for a parallel machine production system. Furthermore, Thongsanit, Boondisakulchok, and Tharmmaphornphilas (2010) and Fichera, Costa, and Cappadonna (2017) considered the makespan time for workforce assignment problems considering workers' varying learning abilities.

Koltai and Tatay (2011, 2013) and Koltai, Tatay, and Kalló (2014) defined different workers' skill levels in the mathematical programming constraints based on the workers' capabilities to indicate how they influence the optimal cycle time. In line with this, Ramezanian and Ezzatpanah (2015) applied a goal programming approach to solve the assembly-line-balancing and worker assignment problem. The general assumptions of their study were (1) the operators performing the assembly tasks have different skill levels; (2) the operating time for a task differs depending on the skill level of the operator performing it and (3) the operating cost of a task differs depending on the skill of the operator and the task condition. Moussavi, Mahdjoub, and Grunder (2018) proposed a multi-objective mathematical model for addressing the problem regarding integrating worker assignments and job rotation in the production domain by considering heterogenous workers, different task execution times for workers, the capability of the workers and the different workload levels of the jobs. Xin et al. (2015) formulated a mathematical model for assigning multi-skilled workers to each process in the assembly line. The aim of the model is to balance the workload of both the assembly station and the processes, and to minimise the total human cost. In their study, 'multi-skilled' had two meanings: (1) a multi-skilled worker has enough work skills and (2) different workers have different levels of work skills. Therefore, they constructed a new cycle time model considering the cooperation of multi-skilled workers so that the cycle time calculation results would be more accurate and closer to reality. Bokhorst*, Slomp, and Gaalman (2004) focused on the worker differences with respect to (1) their task proficiencies, (2) the number of skills they possess and (3) the loads of the work centres in which they can operate in manufacturing systems. They asserted that worker differences can be modelled in several ways, such as through differences in task proficiency or differences in the number of skills of workers, and a 'who rule' may affect the flow time performance only in those systems where the workers are not equal.

Besides the processing task time and cycle time, some studies have considered the effect of the workers' skill differences on the idle time to optimise the operator assignment and to solve the scheduling problem (Wong, Mok, and Leung 2006; Osawa and Ida 2007).

3.1.2. Impacts of workforce skill differences on the production cost

The differences between workers in terms of skill, including experience, proficiency, motivation, speed and learning level, can influence the total cost of the production system (Denkena, Charlin, and Merwart 2013; Li, Huang, and Niu 2016; Rabbani, Akbari, and Dolatkhah 2017). The cost can be defined as the training cost (i.e. the amount that should be invested in enabling the workers to learn new skills or to improve their existing skills) or as the labour cost (i.e. the workers' salary and the hiring or firing cost). The cost of training is higher the less experienced the worker is for the task assigned to him or her (Lazzerini and Pistolesi 2018a, 2018b). Regarding the labour cost, Doerr, Klastorin, and Magazine (2000) proposed optimal and heuristic algorithms for use in solving the problem of assigning tasks and workers of varying abilities to stations to minimise the expected sum of the regular and overtime costs. He believed that when the worker times are highly variable, it may be relatively more efficient to pay for overtime work than to hire more workers, which may result in even greater variability.

The training cost can be largely dependent on the workers' skill level differences. In the study by Aryanezhad, Deljoo, and Mirzapour Al-e-Hashem (2009a), training costs were incurred when some workers had to be trained to improve their abilities to operate higher machine levels. Norman et al. (2002), Liu et al. (2013) and Niakan et al. (2016) considered this matter with regard to the worker assignment problem. Moreover, McDonald et al. (2009) proposed a model that considers both the workers' skill depth level (each worker has an initial skill depth level for each task, reflecting how highly skilled the worker is for such task) and skill breadth level (reflecting the number of different tasks that the worker has been trained to do) to determine the amount of time needed for training each worker during each planning horizon. Based on the proposed model, it can be concluded that each worker requires a specified amount of time to be trained in the next skill depth level related to the given task, which incurs a training cost. Wu et al. (2018a) presented a novel mathematical programming model for addressing the worker assignment problem. In the proposed model, the training cost for each worker for each task depends on the task type and the worker's skill level. A higher skill level means that the worker requires less time to finish the assigned task, and the training cost increases when a worker with a lower skill level has to be trained so that he or she would attain a higher skill level. Therefore, the objective of the proposed model is to minimise the total skill training cost and the workload imbalance penalty cost. In addition, Chu et al. (2019) recently proposed a new mathematical programming model for addressing the worker allocation problem with cross-training influenced by the learning and forgetting levels.

The labour cost and a worker's wage, salary or employment cost can vary depending on the worker's skill and capability levels, which can impact the total cost of the production system (Ramezanian and Ezzatpanah 2015; Hashemoghli, Mahdavi, and Tajdin 2019; Samouei and Ashayeri 2019). For example, Kuo and Yang (2007) presented a mixed-integer programming formulation for optimising mixed-skill multi-line operator allocation problems, where the salary of each operator depends on his or her skill level. Moon, Logendran, and Lee (2009) developed a model for addressing the problems of selecting multi-functional workers with different salaries to match their skills and assigning tasks to a workstation when there are precedence restrictions among tasks. Martignago, Battaïa, and Battini (2017) presented a new balancing model for addressing the problem of total cost minimisation when different operator skills are involved at the same time (i.e. the work aim is cost minimisation by applying single-skill workers and trained, multi-skill workers). Hochdörffer, Hedler, and Lanza (2018) proposed the allocation model taking into consideration the workers' qualifications, the workplace's ergonomic exposure and the most recent allocations of each worker to determine the job rotation schedules for multiple rotation rounds. The objective of the presented model is to minimise the sum of individual penalty costs. Moreover, Sungur and Yavuz (2015) and Salehi, Maleki, and Niroomand (2018) indicated that the cost of performing each task mainly depends on the worker's qualification and skills (i.e. the more qualified the worker, the higher the wage cost). In this regard, there are other studies in the literature that have considered this matter in the assembly-line-balancing and worker assignment problems (Zhang and Gen 2011; Xin et al. 2015; Fattahi, Samoei, and Zandieh 2016). Similarly, other authors have indicated that labour cost variations stem from workers' differences in terms of general cognitive abilities (Wirojanagud et al. 2007) and workers' personalities and motivation levels (Othman, Bhuiyan, and Gouw 2012a; Othman, Gouw, and Bhuiyan 2012b).

3.1.3. Impact of workforce differences on productivity/throughput

Another important impact of workers' skill levels is related to the productivity of the system in which they operate. In reality, there is tremendous variability in workers' individual capabilities. Buzacott (2002) studied the impact of worker differences on the production system because individual differences can result in substantial losses in throughput. Norman et al. (2002) considered the different technical skill levels of workers and examined how these differences affect the manufacturing cell. They indicated that the work quality and worker productivity are lower when the tasks are performed by workers with lower skill levels. They claimed that when the worker has a higher skill level, the work quality increases by at least 20%. The productivity coefficients are generated in a similar manner. In this respect, McDonald et al. (2009) and Chen et al. (2012) indicated that the skill level of the worker performing a task affects the worker's productivity in relation to such task and the quality of the task output. Productivity is also related to the cost incurred by poor task quality. As workers have different skill levels, the worker productivity in relation to the same tasks will vary significantly (Wu et al. 2018b). For this reason, Wu et al. (2018b) proposed new mathematical models for assigning suitable workers to tasks to maximise the throughput and to balance the workload of workers by considering the task time and the workers' different skill levels.

The way that workers with different capabilities and speed are placed in the production line can influence the production line efficiency. Öner-Közen, Minner, and Steinthaler (2017) developed different scenarios to test the impact of an inhomogenous workforce in terms of experience and speed in assembly line design. In their study, paced and unpaced assembly lines were compared to determine the guidelines that suggest which line configuration is the best under which production circumstances. Based on their study, in a paced line, the inexperienced worker should be placed at the first station of the line to minimise efficiency losses, while in an unpaced line, an inexperienced worker should be placed in the middle of the line. Workers capable of speed-up should be placed in the middle of the line in both line types. Song et al. (2006) stated that a worker's efficiency varies in different operations. It is not stable even when the worker is carrying out the same task due to human factors such as the worker's emotions, motivation, skill level and experience, or other uncertainties, such as machine breakdowns. Different workers may also have different levels of efficiency in the same operation. For this reason, Song et al. (2006) proposed an optimal worker allocation solution for solving assembly-line-balancing optimisation problems considering the worker efficiency variance. Three indices were proposed for use in measuring and evaluating the impact of worker allocations on assembly line balancing, to determine the optimal solution with the lowest operation efficiency variance, the highest line efficiency and the least total operation efficiency waste.

Although job rotation can help enhance workplace safety by reducing the workers' exposure to occupational hazards, it can reduce the system productivity if the workers' competencies in performing their tasks are not considered. For example, Nanthavanij, Yaoyuenyong, and Jeenanunta (2010) presented a safety—productivity workforce-scheduling model for assigning the right workers to the right tasks considering their competency levels. They scored workers' competency levels from 1 to 5, with 1 representing the lowest competency level and 5 the highest. Thus, both the safety and productivity objectives can be concurrently achieved. Asensio-Cuesta et al. (2012) employed a multi-criteria genetic algorithm to generate job rotation schedules considering the workers' competency levels for optimising the company's production performance and improving the company's benefits. In their study, the workers had different competency levels, and each job demanded certain competencies at different levels. Mossa et al. (2016) defined different skill levels (i.e. high, medium and low) in a work environment with repetitive tasks to find the optimal job rotation schedules. They indicated that the maximum output of the assembly stations (due to technical constraints) could be obtained by assigning the most skilled workers to each workstation. Allwood and Lee (2004) proposed the job rotation model for improving the worker problem-solving skills in light of the variation in worker skill levels. They indicated that the throughput can be improved by the workers with a higher learning rate. However, the simulation results indicate that job rotation does not improve the overall problem-solving skill and productivity of the workers. Moreover, Shafer, Nembhard, and Uzumeri (2001), Nembhard and Shafer (2008), Bentefouet and Nembhard (2013) and Méndez-Vázquez and Nembhard (2019) indicated that workers' learning rate differences affect productivity in production systems. Additionally, Wirojanagud et al. (2007) applied a general cognitive ability metric to model the effects of individual differences in efficacy on worker productivity. They indicated that the workers' differences should be considered in planning and managing the workforce because these can impact productivity.

3.1.4. Impacts of workforce skill differences on workload balancing/smoothing and job safety

Some of the selected papers considered the effects of the workers' differences on workload balancing. Lian et al. (2018) proposed a mathematical model considering the differences in workers' skill sets and proficiency level in the context of the seru production system for solving the multi-skill worker assignment problem. They analysed the impact of the differences in workers' competency on workload balance. In summary, they asserted that homogenous workers could help bring about a high level of inter-worker workload balance whereas heterogenous workers with diversified competencies perform well in balancing inter-seru workload. Manavizadeh et al. (2013) solved the problem of balancing a mixed-model U-line in a just-in-time production system by using the simulated annealing algorithm. The research also proposed a labour assignment policy considering workers' skill levels to balance the workload. Moreover, other authors took into consideration the impact of workers' skill level differences on workload smoothing (Zacharia and Nearchou 2016; Sadeghi, Rebelo, and Ferreira 2018), weighted smoothness (Fattahi, Samoei, and Zandieh 2016) or balancing workload (Xin et al. 2015).

Finally, other studies considered the effect of human skill differences on job satisfaction (Asensio-Cuesta et al. 2012), safety (Aryanezhad et al. 2009b) or energy expenditure (Dalle Mura and Dini 2019a). For instance, Aryanezhad et al. (2009b) developed a new model for job rotation design, in which workers are classified according to their skill levels. The aim of their study was to find the best pattern of assigning workers to job categories according to their skill level. Dalle Mura and Dini (2019a) proposed a genetic algorithm for addressing the assembly-line-balancing problem in the case of human–robot collaborative work to minimise the energy load variance among the workers on the basis of their energy expenditure.

3.2. Age

The workforce-ageing phenomenon is currently affecting most of the Organisation for Economic Co-operation and Development member countries, forcing them to raise the average retirement age of their workforce due to the general ageing of their population (Calzavara et al. 2020). If most people retire at around 66–67 years of age, the European labour force will shrink by around three million per year over the 2020–2035 period, as reported by the European Agency for Safety and Health at Work (Börsch-Supan, Härtl, and Ludwig 2014; De Looze et al. 2016). Besides, the companies in developed countries are facing an ageing-workforce trend in their assembly systems. Although ageing workers are more experienced than young workers, they may have problems with carrying out high-pressure manual tasks and engaging in highly repetitive and short-cycle operations. For this reason, Peruzzini and Pellicciari (2017) cited the need for adaptive manufacturing systems, which they defined as manufacturing systems that are able to adapt to ageing workers' needs considering their reduced workability due to physical and cognitive functional decrease, with the final aim of improving the human–machine interaction and the workers' well-being. In the literature, there are two different theories regarding ageing workers: one asserting that an ageing workforce has a positive impact on human performance because it provides the workers with a higher level of expertise, and the other one recognising the negative impact of an ageing workforce on the workers' functional capacities due to an increment in their fatigue and physical limits. To the best of our knowledge, there have been only two studies that considered both these aforementioned aspects in relation to manufacturing systems, those by Quintana, Leung, and Chen (2008) and by Boenzi et al. (2015). Boenzi et al. (2015) considered both the functional decline and experience aspects of age according to the compensation theory (i.e. ageing workers use their experience to compensate for the decline in their physical capacities). They developed an age-related integer linear mathematical programming to find the optimal job rotation schedules in work environments characterised by low-load manual tasks with a high frequency of repetition (e.g. assembly lines). Quintana, Leung, and Chen (2008), on the other hand, examined and quantified the effect of workers' ages and years of experience on yield and productivity in manual electronics assembly. The results of the study indicated that age and years of experience have interaction effects and that these effects exert asymmetric influences on manual electronics assembly process yield and assembly time. That is, a higher degree of yield due to greater experience and a greater capacity to learn does not necessarily lead to a shorter assembly time because of ageing.

Functional problems can be categorised into physical and health problems or cognitive disorders. In assembly line positions and other occupations, workers can experience pain and discomfort associated with long periods of standing. Digiesi et al. (2018) proposed a mixed-integer nonlinear programming model for assigning the workforce to the workstations of a line, balancing productivity and the ergonomic goal considering differently aged and skilled workers. In the proposed model, the standard operation time of the workstations increases by a worker productivity factor, with higher values for low-skilled and aged workers. Hanson et al. (2009) considered both the age and the physical characteristics of workers on the assembly line work. The results indicate that age significantly affected all the test parameters and is thus an issue that developers should consider, along with anthropometric variables like stature. The study by Baines et al. (2004) was founded on the assumption that human variations lead to a large percentage of variance between simulation predictors and real-world performance. The study thus aimed to improve the accuracy and reliability of simulation prediction by incorporating human factors into manufacturing simulation. The study results indicated that the age model increases the cycle times in the simulation by up to 35% and hence causes a large decrease in throughput. Botti, Mora, and Calzavara (2017) developed a bi-objective mathematical model for designing activity schedules for aged workers exposed to the risk posed by repetitive tasks. The developed model has two objectives: (1) to reduce the ergonomic risk posed by repetitive work and (2) to assign to workers tasks that better fit their capabilities, abilities and skills. Efe, Kremer, and Kurt (2018) analysed six different age categories in a textile firm to assess the impact of age and gender on physical workload capacity. Their study mainly focused on productive workload differences with respect to the age and gender of workers to minimise the number of workstations for the assembly line worker assignment and balancing problems. The results of their study showed that advancing average age increases the number of stations, and this situation triggers a reduction in the line efficiency and physical workload capacity utilisation ratio. The study by Börsch-Supan and Weiss (2016) showed that that older workers are not less productive than younger workers in an assembly plant of a truck manufacturer. They illustrated that the productivity of a worker in a large-car manufacturing firm does not decline until at least up to age 60. The aim of this study was to relate labour productivity to age.

According to the investigated studies, age can have an impact on both the experience and physical/cognitive capacity of workers. Therefore, the most critical option for an ageing workforce is to apply the approach of balancing these two aspects to give aged workers a chance to stay longer in the workplace instead of applying for early retirement. This can be achieved by identifying the capabilities of individual ageing workers and assigning to them the most appropriate tasks for them. Alternatively, some relevant policies and strategies from companies or governments can be adopted to make workplaces more age-friendly.

3.3. Gender

Gender, as well as biological sex, can affect work activity through (1) gendered job and task assignments; (2) the biological differences between women and men influencing the interface between work activity and the physical environment; (3) gendered human relations at work, including sexual stereotyping, sexism and sexual relations between workers and between workers and management or clients; and (4) manifestations of work—family articulation (Messing, Lefrançois, and Saint-Charles 2018). Moreover, gender differences are considered in abilities, in terms of working memory capacity, processing speed, spatial abilities and intelligence (Hirsch, Koch, and Karbach 2019). In the present review, gender differences are considered only in terms of biological, physical and general worker ability (i.e. working memory capacity, processing speed, spatial abilities and intelligence) and the performance differences between male and female workers in the production context. For example, Garbie (2014) built a regression model via experimental investigation to measure the worker performance in assembly workstations considering the gender. The main objective of the proposed model is to investigate the effect of ergonomically designed assembly workstations on worker performance. To achieve such objective, ten college students were randomly assigned to one of three experimental factors or parameters (i.e. table-adjustable, chair-adjustable and gender) to perform the assembly task. The performances of the participants assembling a product were worker productivity (units/hour), worker satisfaction (degree of comfort) and worker health (headache). The results showed that the female subjects were more productive and were healthier than the male subjects, but had lower work satisfaction. The effect of gender differences especially in the assembly line was also studied by Efe, Kremer, and Kurt (2018).

3.4. Anthropometry

Anthropometry, which refers to measurements of the human body, plays an important role in job design and in manufacturing system (Das and Sengupta 1996) and human-centred design (Lee 2006; Huang, Yang, and Chu 2012). Anthropometric data have played a fundamental role and have been highly valued in a vast range of design fields, including workstation design, product design and interactive design for service systems. Anthropometric data are influenced by various factors, such as gender, age, culture, nutrition, social development and population. Due to the diverse human-body characteristics, it is imperative for each country or population to build its own anthropometric database (Lee, Chen, and Lee 2019). Considering the human-body measures of workers, such as height, weight, strength and body shape, can be very effective for assigning the most appropriate task to the right worker and designing the workstation in such a way that it fits the workers. The contribution of this factor to a production system is that it can ensure that the workplace design addresses the workers' ergonomic concerns (Yusof et al. 2019).

Das and Sengupta (1996) proposed a systematic ergonomics approach to industrial workstation design considering human variability in size and capability. An objective of industrial workstation design is to ensure that the majority of the intended user group can be comfortably accommodated, without having to assume any harmful posture. In the said study, for the physical design of industrial workstations, the four essential design dimensions were considered: (1) work height; (2) normal and maximum reaches; (3) lateral clearance and (4) angle of vision and eye height. An engineering/structural anthropometry approach was used in determining the workstation dimensions.

One weakness of the approach proposed by Gunther, Johnson, and Peterson (1983) is the researchers' assumption that the number of calories needed to accomplish a particular task is the same for all workers. The truth is workers have different attributes, such as age and body size. It is known that considerable variations may occur in the energy expenditure of homogenous individuals (Finco et al. 2019b). Therefore, before balancing an assembly line, the number of calories needed to accomplish a particular task should be separately determined for every worker (Kara et al. 2014). For this, Kara et al. (2014) proposed an integrated model for single-assembly-line-balancing problems under ergonomic and posture restrictions. The proposed model is human-oriented as it considers the physical and psychological strains caused by different tasks. Furthermore, the researchers mentioned that the number of calories needed per task depends on the worker assigned to perform the task, and the main determinants of the daily energy expenditure of a person are body size and physical activity.

Dalle Mura and Dini (2019b) recently proposed a model for solving the assembly-line-balancing problem on the basis of worker technical skills and worker physical capabilities. Worker task assignment is based on the workers' physical capabilities and limits, evaluated according to their anthropometric and physiological characteristics. In their paper, various individual characteristics, such as age, gender, skill level and physical measures like height and weight, were considered to calculate the energy expenditure for each task performed by a particular worker. In fact, the researchers asserted that the energy expended to perform a task may vary from person to person on the basis of the individual characteristics, such as gender, age and weight.

Baykasoglu et al. (2017) proposed a systematic approach to designing an assembly system and solving the workplace layout problem to achieve efficient production. They considered the interrelation between technological variables such as time and methods, and environmental variables such as workers' physical attributes and ergonomics evaluations. Fulder et al. (2005) presented an ergonomically and economically designed workstation to optimise worker productivity and the total system and to ensure the workers' physical and mental well-being and job satisfaction and safety. In such study, the workstation was adjusted based on the workers' bodies, body sizes and body movements. The worktable was flexible, with the different height indications of the work area. The designed and optimised workstation contributes to the realisation of lower psychological loads and prevents inappropriate physiological body postures and partial loads. Shikdar and Al-Hadhrami (2007) designed and developed a smart workstation for performing industrial assembly tasks. Flexibility in workstation setup can eliminate the anthropometric and ergonomic problems of fixed workstations and can boost the workers' performance.

Huang and Pan (2014) presented an ergonomic job rotation strategy in a manufacturing line based on individual anthropometric measurements. They determined job assignment decisions according to the predicted human dimension of each worker. To assign appropriate jobs to workers, anthropometric measurements were used as job assignment criteria to reduce the workers' discomfort caused by working in a workstation unsuited to themselves. This method was designed to guarantee operational safety and to reduce the incidence of work-related musculoskeletal disorder. The results of the study indicate that the proposed system can effectively and significantly reduce the average risk and decrease the number of workers experiencing either a high- or medium-level risk. Deros et al. (2011) presented a case study conducted at an assembly workstation in a manufacturing company. The case study showed that the assembly workers had to assume awkward postures while working at an unergonomically designed workstation. Therefore, to ensure worker health and safety by eliminating the possible mismatches between the workers' anthropometric characteristics and the tasks they are performing, designing an appropriate workstation is very critical. In summary, workstation design needs to incorporate workers' physical characteristics and work capabilities and limitations. Hanson et al. (2009) considered both the physical characteristics (e.g. stature) and age of assembly line workers and found that stature significantly affected such workers' joint angle distribution and joint angle velocity distribution. Stature, however, was found not to have an effect on the time to perform ingress movements or on the ingress technique employed.

4. Results and discussion

The following study results were derived from the presented literature review and from the papers' classification reported in section 3.

4.1. Publication trends by year

As can be seen in Figure 1, there has been an upward trend in the number of relevant papers over the recent years. Furthermore, the given chart illustrates that 14% of all the papers that were found in the Scopus database were published in 2018, which indicates that the importance of and interest in this topic emerged only recently. However, in the early years, particularly from 1992 to 2005, only 11 studies gave attention to the issue of the effects of workforce differences on manufacturing systems.

Besides Figure 1, we developed another graph using VOSviewer, as shown in Figure 2. In such graph, the co-occurrence of keywords is shown to have been limited to the keywords selected for the search in the Scopus database (also shown in Table 1) to understand how the sets of applied keywords are connected with one another in the selected papers. Moreover, the resulting map was visualised according to the year of publication to demonstrate how the interest in the different related topics has evolved. Here, it can be seen that most of the earliest publications are related to assembly line and manufacturing systems (as shown by the darker circles) while most of the recent publications focus on assembly line problems, assembly line balancing and worker assignment. Moreover, the keywords referring to human and individual factors such as skill, ageing workforce and heterogenous workers are related to the most recently published papers (as shown by the lighter circles).

4.2. Keywords co-occurrence network analysis

The importance of the selected keywords and how they overlap and are connected to one another are shown in Figure 3. As shown in Table 1, two sets of keywords were selected: those relating to the differences between workers and those relating to the problem under study. To analyse the co-occurrence of all the keywords of the selected papers and to determine the importance of each keyword, VOSviewer was used in this study. The VOSviewer software helped us visualise bibliometric networks and create a map of the 100 papers that we selected for this study, as shown in Figure 3. Here, each keyword is represented by a node, and each relation between the keywords is represented by a directional arrow. To determine the importance of each keyword, the size of each node was made proportional to the number of its occurrences in the network. The minimum number of occurrences of a keyword to be shown in the graph was

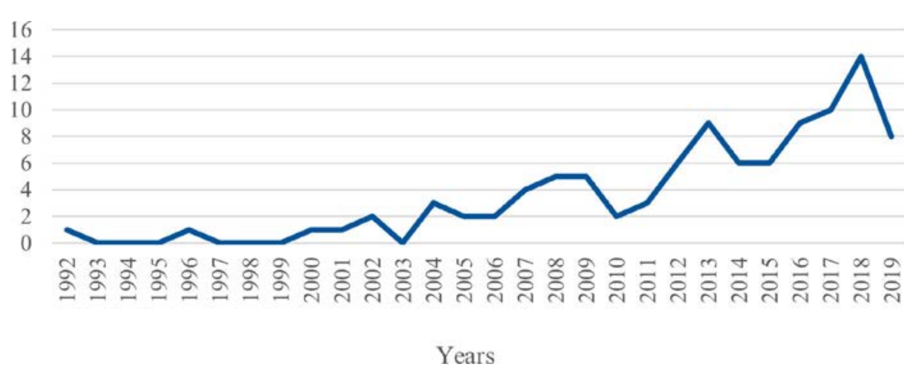

Figure 1. Distribution of studies by publication year.

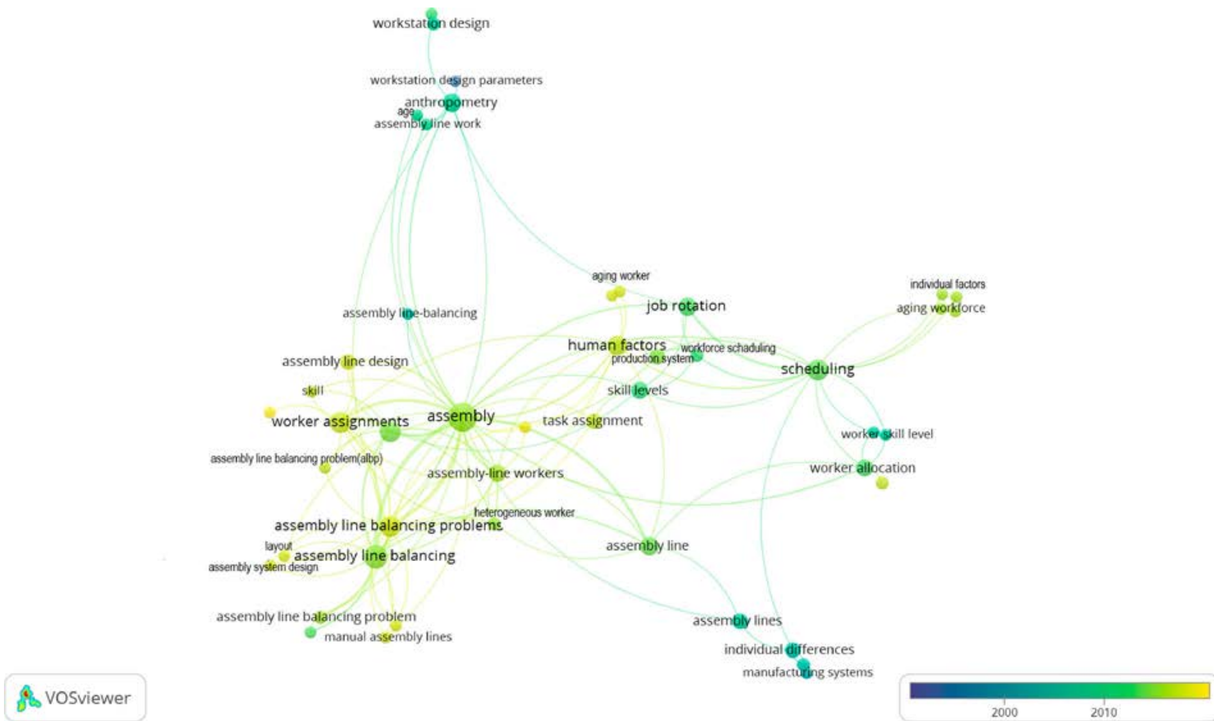

Figure 2. Co-occurrence of the keywords used in the search according to the year of publication.

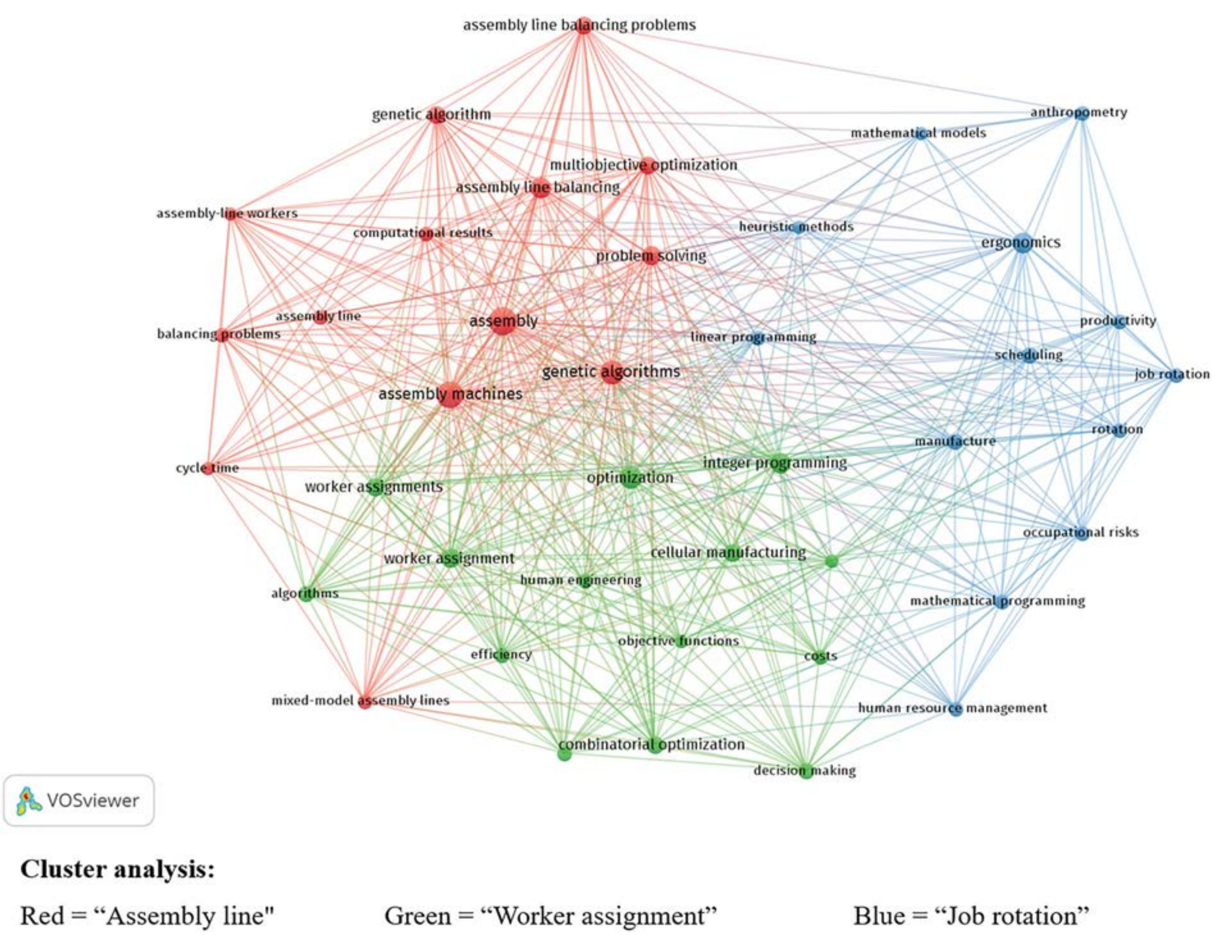

Figure 3. Co-occurrence keywords network of the 100 selected papers.

set to five. According to the given figure and by deepening the analysis of the network, three main clusters were identified:

(1) Group 1 (red colour): keywords focused mainly on 'assembly' issues;
(2) Group 2 (green colour): keywords focused mainly on 'worker assignment'; and
(3) Group 3 (blue colour): keywords focused mainly on 'job rotation'.

Based on the given map and according to the classification of the literature, it can be concluded that the focus of the existing contributions is mainly on the assembly line considering individual worker differences, which lead to cycle time, cost and productivity variances. In addition, there are notable contributions for worker assignment and job rotation, respectively, while no attention is given to workstation design, as also shown by Table 2, on which the related studies are rare (fourth column).

Additionally, some parts the clusters overlap with one another, indicating the similarity of the keywords of some studies. For example, a wide range of studies refer to both the assembly line and worker assignment. On the basis of the sizes of the nodes and the connections, it is possible to conclude that the differences between workers were mostly investigated in the context of assembly line balancing and worker assignment, followed by job rotation, and rarely in the context of workstation design. This outcome is completely consistent with what can be seen in Table 2. Furthermore, on the basis of the nodes in Figure 3, it can be concluded that optimisation methods are mainly used to solve the workforce differences problem in production systems.

4.3. Consideration of workers' differences in production systems

Much evidence from the papers found in the Scopus database indicates that the majority of the studies reported in such papers focused on workers' differences in terms of skill (83 papers) while few studies investigated other individual human factors. Therefore, it can be concluded that skill is the most investigated factor in the production domain, and particularly in assembly line systems, and that the importance of other human factors, such as age and anthropometry, is to date underestimated, and gender and anthropology are completely neglected as individual factors considered in a model. For example, although the word ***anthropology*** was included in the set of search keywords in this study, no related papers were found in the context of this study's topic. In some cases, the anthropology factor can be important, such as to consider the wide range of variations between humans with different cultural and environmental determinants, which can impact workers' abilities and performance (Robey 1974), or in terms of anthropometric body dimensions, which can vary in different countries, such as in different Asian populations (Lee, Chen, and Lee 2019). As far as the gender factor is concerned, it was not often considered by itself in the analysed literature. The reason for this is probably that there is no specific need to consider it as a separate factor because gender is already often coupled with skills evaluation, physical capability and ergonomic risk assessment by managers and industrial engineers (e.g. Dalle Mura and Dini 2019b). Similarly, workers' differences in terms of age and anthropometry are not modelled as much as skills are, although considering workers' differences in a model can help decision managers assign the most appropriate workers to the suitable workstation and improve their productivity (Asensio-Cuesta et al. 2012; Zhang, Tang, and Zhang 2018). Therefore, most of the studies that were found herein did not consider the workers' ages as a challenge, and put more emphasis on the analysis of workers' skills and fatigue. Moreover, most of the studies on ergonomics in manufacturing focused on the development of new ergonomic assessment methods by considering the 'mean human worker' without differentiating the ergonomic risk analysis with respect to the workers' ages (i.e. Battini et al. 2017). Finally, the very recent literature review conducted by Calzavara et al. (2020) clearly demonstrated that when the ageing factor becomes relevant, both the level of workers' capacities (cognitive and physical) and the level of workers' experience need to be carefully investigated and taken into consideration.

On the basis of the investigated sample (100 papers), it can be concluded that there have been very few studies that simultaneously considered two human factors in their studies, and no study that considered more than two human factors together was found. There were only four papers (around 4% of all the selected papers) that concurrently considered two individual differences in their model and design: the paper by Digiesi et al. (2018), which concurrently considered skill and age; the paper by Dalle Mura and Dini (2019b), which concurrently considered skill and anthropometry; the paper by Efe, Kremer, and Kurt (2018), which concurrently considered age and gender; and the paper by Hanson et al. (2009), which concurrently considered age and anthropometry. The other 96 selected papers focused only on one human factor, mainly skill.

As can be seen in Table 2, a wide range of previous studies focused on the workforce differences in assembly line balancing (58 papers) and the worker assignment problem (74 papers) because workers' differences lead to a problem called assembly line worker assignment and balancing problem, which needs to be resolved to improve the line efficiency and productivity (Miralles et al. 2007). However, the job rotation and the workstation design problem considering workers' differences seem not to have been largely considered in the selected literature. Moreover, there is no variety in working space design and facility layout according to the differences in workers' physical attributes, such as body index, strength and height or skill and age. This issue is also understandable, as can be seen in Figure 3, which indicates that most of the keywords that co-occurred were related to assembly line and worker assignment.

The classification in Table 3 shows that there are compelling evidences that workforce differences can largely impact the task processing time (Sotskov et al. 2015) and consequently the cycle time (Moussavi, Mahdjoub, and Grunder 2017) and cost, including the total cost (Martignago, Battaïa, and Battini 2017) and training cost (McDonald et al. 2009), and the throughput (Bentefouet and Nembhard 2013). Many of the selected papers acknowledge that time and cost are largely influenced by the differences between workers, particularly in terms of skill. For instance, the higher the workers' ability, speed and motivation, the shorter the task processing time. In addition, skilled workers with a high level of functional capacity are paid more, but the training cost can be decreased significantly by the workers' high capacity for learning how to perform their tasks. Besides time and cost, line efficiency and unit productivity are also highly influenced by workforce differences, but there have been very few studies that considered the effect of workers' differences on job safety, job satisfaction and health (Fulder et al. 2005) and energy expenditure rate (Kara et al. 2014; Dalle Mura and Dini 2019b). The reason for this could be that the latter factors are more difficult to measure and that the decision problems that we considered are usually based on quantitative measures of factors.

5. Future research agenda

On the basis of the literature analysis that was conducted in this study, this section identifies some areas that deserve further research attention and proposes the future research agenda for the consideration of workforce differences in production systems. Therefore, the aim of this section is to address the third research question so that the aforementioned research gap can be addressed to some extent by the future research.

5.1. Development and application of models for considering workers' age in the production system

As mentioned in section 3.2 of this paper, the European manufacturing industry is entering a new era of an ageing workforce. The EU has thus set strategy objectives to increase the labour market participation of older workers. However, practical limits arise, and a complete rethinking of operation management strategies and manufacturing systems design and management is needed (Battini et al. 2011; Aiyar and Ebeke 2017; Calzavara et al. 2020).

The current theory on manufacturing systems design and management, however, was not conceived and designed on the basis of age-oriented paradigms (Bogataj et al. 2019; Calzavara et al. 2020). Older workers may experience various age-related changes, such as increased weight; reduced flexibility, mobility and strength; deteriorating vision and hearing; a possible reduction in cognitive abilities; and in some cases, health-related complaints or issues. If these are not taken into consideration and companies do not respond appropriately, the aged workers may experience increased injuries and reduced productivity (Bures and Simon 2015). This matter indicates the importance of analysing the phenomenon of ageing in production systems. To cite an example, the German automaker BMW is determined to proactively face the challenges of an ageing workforce. To identify potential difficulties and devise ways to mitigate these, the company (1) set up new equipment such as special ergonomic facilities, (2) devised and implemented a job rotation scheme across workstations to minimise worker fatigue and (3) developed special stretching exercises for their workers to prevent them from experiencing physical strain during work hours or to minimise their physical strain. The company has achieved impressive results with only a minimal investment. They indicated that their 'older' production line has the same level of productivity as their other lines and had actually achieved even better quality than the comparable lines (Bures and Simon 2015).

Therefore, it is strongly recommended that the future research integrate the age differences between workers as an influential factor in the new models to enable the theoretical development of new age-oriented models and methods for manufacturing systems design and management, and to validate such models through real-case applications, applying a multi-disciplinary point of view. For example, worker age can be considered in a model through the following: implementing different execution times of manual and heavy tasks (older workers having higher times); considering a constraint in the assignment of operators to stations (some stations could not be suitable for aged operators); or effecting a change in the availability of the workers, which can for example be estimated through their energy expenditure (older workers are less available; Finco et al. 2019b) or in the scheduling, incorporating different rest times (older operators need more time to rest or recover).

Furthermore, as mentioned in section 3.2, the ageing-workforce issue has two main aspects: workers' experience and expertise can be increased by age and workers' physical and cognitive capacities may be reduced by ageing. To balance these two aspects, it is suggested that the future research not only consider the ergonomic indices that model the general posture of workers but do not appropriately consider workers' ages, but also apply quantitative or qualitative indices taking into account the workers' ages in the model. In fact, the ergonomic indices mainly concern workers' well-being from the point of view of ergonomics and posture whereas indices and methods such as REFA-Method, ATS and check age (quantitative indices) and WAI and WAS (qualitative indices) adjust effort, energy expenditure and all the activities in response to the worker's age (Katiraee et al. 2020). For example, in the WAI qualitative index, all the workers are made to answer the given questions. Then, depending on the score obtained by the workers from their self-assessment, their ability, health status and other aspects can be evaluated. However, among the indexes here presented and all the others which consider the age factor, most of them do a general age differentiation only between elder workers and younger ones and only few of them consider operators' heterogeneity, especially for what concerns the link between individual age and operator's abilities and skills (Wolf and Ramsauer 2018).

Age-differentiated or individualised work evaluation can help managers and decision makers have a mental image of their workers, which can help them manage and design the production systems with regard to their workforce status. Therefore, the age problem in production systems can be addressed to some extent through the following measures:

- applying indices and methods concerned with the ages of the workers in production systems; and
- considering the personal needs and priorities of the ageing workers (i.e. approving their preferred work shifts, offering them a flexible time schedule, and changing the workstation design into a human-centred one to prevent physical problems from arising) to help them stay longer in the workplace instead of applying for early retirement.

Therefore, for the future research, it is recommended not only that the human factors be incorporated into production systems but also that each individual worker be considered in the production system to ensure that all the workers are correctly managed.

The final aim of this paper is to help manufacturers and decision makers investigate their ageing workforce needs and requirements and ageing workers' disruption areas in modern production and assembly systems so as to provide them with appropriate equipment and safe/ergonomic working conditions. In addition, the results of this study can help managers understand how they can distribute and manage their workers in the different parts of their production system according to their ages to improve their companies' system productivity and their workers' health simultaneously.

5.2. Consideration of the impacts of human factors on human health, job safety and job satisfaction

Individual differences, particularly in terms of age and anthropometric measures, can influence the health and job safety and satisfaction of the workers in production systems. For example, using an RGB-D camera system, Huang and Pan (2014) applied anthropometric measurements as job assignment criteria for each worker to reduce the discomfort experienced by the workers from working in a workstation unsuited to them. This method was designed to guarantee operational safety and to reduce the incidence of work-related musculoskeletal disorder. Then the researchers calculated the fitness of the workers for their jobs according to the corresponding human dimensions estimated. On the other hand, Aryanezhad et al. (2009b) considered workers' skill levels in designing job rotation schedules to minimise the workers' back injuries. However, as can be seen in Table 3, very few studies have considered workers' differences in their model for investigating the effects of such differences on the job safety and human health of workers, while most studies have maintained that time and cost are mostly influenced by human differences factors. Here, it is important to emphasise that the lack of consideration of workforce differences in a model can lead to a low level of job safety and/or job satisfaction in the workplace because workers may be assigned to an inappropriate task in terms of physical demands or skill level. To reduce the risk of incurring injuries and to increase worker satisfaction, a possible option could be applying a job rotation scheme so that workers can be switched to the tasks most appropriate for them in terms of the work demand and the workers' differences (Botti, Mora, and Calzavara 2017).

Another possible action is using methods such as the NASA-TLX subjective method to assess the perceived task demand and workload for each worker. This index is sensitive to task variety and can thus be practical for some parts of production systems with high task variety (i.e. assembly lines). This index can be helpful in determining the level of mental demand, physical demand and effort of each worker for each task. The workers are individually involved in this qualitative index. Applying these types of methods can address workers' differences problems because they match the workers' capabilities and the task difficulty. Consequently, these measures can impact workers' health and job safety and satisfaction because workers will be assigned to the tasks appropriate for them based on the scores that they obtained and their capabilities. However, according to our findings, there has been no study in this area that connected these types of methods to production systems and assembly line workers. The NASA-TLX method is applied more in other areas, such as in the construction or healthcare fields (i.e. Costa and Sartori 2007).

5.3. Giving more attention to workstation/layout design problems considering workforce differences

In the selected papers, very few (8 papers) took into account variety in human-centred and working space design according to human differences factors. The differences between workers, particularly in terms of age and anthropometric measures (e.g. body height, weight, strength, hand dimension and length) can influence decisions regarding human-centred workplace design and workspace characteristics (Battini et al. 2018). Moreover, the proper consideration of workforce variety can impact the equipment required for a certain workstation, according to the worker who has to work in it (Finco et al. 2019a). From a modelling point of view, workers can be seen as specific cases of 'differently skilled' workers; therefore, the existing methods considering skills diversity can be easily adopted for workers who have special physical, perceptual and/or mental needs. Moreover, not only proper work balancing and scheduling are important; creating an individualised/customised design solution for each individual should also be considered. Therefore, it would be interesting to increase the involvement of the worker in the design of workstations and in the choice of workstation equipment, which would be tantamount to a human-centred approach.

Therefore, future research is required to incorporate the human differences factors in terms of age, physical dimensions and skills characteristics into layout design techniques to create suitable human-centred assembly and production workspaces for the available workforce by researching on and advancing productivity, quality and safety paradigms. This issue can be addressed by introducing smart and configurable workstations that are able to adapt to workers' needs and capabilities, and that can be estimated using relevant methods and indices (e.g. NASA-TLX, WAI Index or BORG scale). Moreover, the design of workstations should also include the design of the tools and equipment to be used therein, which should conform to the recognised worker needs and differences to reduce the physical damage to the workers. A possible solution can also be based on the use of virtual-reality devices and of appropriate software to support this new design approach.

5.4. Collection and analysis of new real data concerning the effects of human differences on manufacturing systems

Even if a good number of the presented studies concern real cases (46 studies, as can be seen in Table 2), there is still a need to conduct studies with higher statistical samples, new statistical data, field studies and real measurements to better understand and measure human variability factors and to validate future human-oriented models (Börsch-Supan and Weiss 2016). This can also be achieved through the adoption of proper technologies, such as those for tracking workers and getting feedback on their performance and for quickly measuring their personal characteristics and behaviours. The suitable devices for this can be inertial sensors to be placed on workers' bodies, heart rate monitors, motion capture systems and/or cameras (Battini et al. 2018; Calzavara et al. 2018). The availability of real data will enable the proper validation of mathematical models and methods. Furthermore, the new data can lead to the development of new time measurement methods (e.g. MTM and MOST) that can better reflect workers' differences.

6. Conclusion

This paper has presented a systematic literature review focused on the studies that have considered and integrated the workforce differences in models related to assembly line balancing, work/worker assignment, job rotation and workstation/layout design problems. Starting from the definition of the research questions and of the appropriate keywords that were used, the search for papers led to a sample consisting of 100 relevant papers. These papers were read and analysed to deepen the understanding of the most investigated differences between workers in production systems to date, and how these factors could generally affect a production system. The analysis of the selected papers revealed that the skill differences between workers is the most investigated factor to date while other factors (e.g. gender, age) have been rarely considered in production models (RQ1).

Moreover, cost, time and productivity turned out to be the parameters most influenced by workers' differences (RQ2).

The classification of the papers and the main findings of this study were also made the bases of the research agenda proposed for future studies. The future studies in this direction should take advantage of new technologies to obtain real on-the-field data, reflecting the actual differences between workers. Such information is useful for developing more accurate mathematical models and testing these, which will effectively support designers and managers in both systems design and balancing and human resources management (RQ3).

Some limitations of this study need to be mentioned. The study mainly focused on manual tasks in production systems considering workers' differences. Therefore, the workers' differences in other sections of industry, such as warehousing and order picking, were not considered. Furthermore, although we were aware that disability is a factor that can differentiate workers' task performance, we did not consider it in our study and decided to just focus on workers' main characteristics, particularly their skills, age, gender and physical aspects. As worker disability can be caused by workplace accidents or can be a congenital or birth defect, disability cannot be considered a main worker feature. Besides, although disability can impact workers' skills, determining the disability levels of workers in production systems is somewhat impossible as workers are generally just classified into two groups: disabled or not disabled (0,1).

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Appendix

Table A1.

Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Source type: Scopus	Source type: Snowball
Chen et al. (2019)	Journal of Manufacturing Systems	×	×			×				Time	×	×	
Chu et al. (2019)	Computers and Industrial Engineering		×			×				Cost		×	
Dalle Mura and Dini (2019a)	CIRP Annals	×	×			×				Cost		×	
Dalle Mura and Dini (2019b)	CIRP Journal of Manufacturing Science and Technology	×	×			×			×	energy expenditure	×	×	
Hashemoghli, Mahdavi, and Tajdin (2019)	Scientia Iranica		×			×				Cost	×	×	
Liu and Yang (2019)	International Journal of Computational Intelligence Systems		×			×				Time		×	
Méndez-Vázquez and Nembhard (2019)	Computers and Industrial Engineering		×			×				Throughput		×	
Samouei and Ashayeri (2019)	Applied Mathematical Modelling	×	×			×				Time & cost		×	
Digiesi et al. (2018)	International Journal of Industrial Engineering and Management	×	×	×	×	×	×			Time & throughput		×	
Efe, Kremer, and Kurt (2018)	International Journal of Industrial Engineering: Theory Applications and Practice	×	×				×	×		Time, throughput & physical workload capacity	×	×	
Fan et al. (2018)	Human Factors and Ergonomics In Manufacturing	×				×				Time	×	×	
Gong et al. (2018)	Journal of Cleaner Production		×			×				Time		×	
Hochdörffer, Hedler, and Lanza (2018)	Journal of Manufacturing Systems	×		×		×				Cost	×	×	
Lazzerini and Pistolesi (2018a)	IEEE Transactions on Systems, Man, and Cybernetics: Systems		×			×				Cost	×	×	

(*continued*).

Table A1. Continued

Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Source type: Scopus	Source type: Snowball
Lazzerini and Pistolesi (2018b)	IEEE Systems Journal		×			×				Cost	×	×	
Lian et al. (2018)	Computers and Industrial Engineering	×	×			×				Workload balancing / smoothing	×	×	
Moussavi, Mahdjoub, and Grunder (2018)	IFAC-PapersOnLine	×	×	×		×				Time	×	×	
Sadeghi, Rebelo, and Ferreira (2018)	Computers and Industrial Engineering	×	×			×				Workload balancing / smoothing	×	×	
Salehi, Maleki, and Niroomand (2018)	Applied Intelligence	×	×			×				Cost	×	×	
Wu et al. (2018a)	Mathematical Problems in Engineering		×			×				Cost	×	×	
Wu et al. (2018b)	Industrial Management and Data Systems		×			×				Throughput		×	
Zhang, Tang, and Zhang (2018)	ICIC Express Letters	×	×			×				Time		×	
Baykasoglu et al. (2017)	Human Factors and Ergonomics In Manufacturing	×			×				×	Throughput	×	×	
Botti, Mora, and Calzavara (2017)	IFAC-PapersOnLine		×	×			×			physical workload capacity		×	
Dalle Mura and Dini (2017)	CIRP Journal of Manufacturing Science and Technology	×				×				Workload balancing / smoothing	×	×	
Fichera, Costa, and Cappadonna (2017)	International Journal of Industrial Engineering Computations		×			×				Time	×	×	
Martignago, Battaïa, and Battini (2017)	IFAC-PapersOnLine	×				×				Cost		×	
Moussavi, Mahdjoub, and Grunder (2017)	International Journal of Production Research	×	×			×				Time	×	×	
Oksuz, Buyukozkan, and Satoglu (2017)	Computers and Industrial Engineering	×	×			×				Time	×	×	

(*continued*).

Table A1. Continued

												Source type	
Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Scopus	Snowball
Öner-Közen, Minner, and Steinthaler (2017)	Computers and Industrial Engineering	×	×			×				Throughput		×	
Peruzzini and Pellicciari (2017)	Advanced Engineering Informatics				×		×			physical workload capacity	×	×	
Rabbani, Akbari, and Dolatkhah (2017)	Management Science Letters		×			×				Time & cost	×	×	
Börsch-Supan and Weiss (2016)	Journal of the Economics of Ageing	×					×			Throughput		×	
Fattahi, Samoei, and Zandieh (2016)	International Journal of Engineering, Transactions B: Applications	×	×			×				Time, cost & throughput		×	
Li, Huang, and Niu (2016)	Computers and Industrial Engineering		×			×				Time	×	×	
Liu and Wang (2016)	International Journal of Computational Intelligence Systems		×			×				Time		×	
Mossa et al. (2016)	International Journal of Production Economics			×		×				Throughput	×	×	
Niakan et al. (2016)	Journal of Manufacturing Systems		×			×				Cost		×	
Polat et al. (2016)	International Journal of Production Research	×	×			×				Time	×	×	
Samouei et al. (2016)	Applied Mathematical Modelling	×	×			×				Time		×	
Zacharia and Nearchou (2016)	Engineering Applications of Artificial Intelligence	×	×			×				Time & workload balancing / smoothing		×	
Boenzi et al. (2015)	IFAC-PapersOnLine			×			×			Experience & physical workload capacity		×	
Folgado, Pecas, and Henriques (2015)	Journal of Manufacturing Systems	×				×				Time	×	×	
Ramezanian and Ezzatpanah (2015)	Computers and Industrial Engineering	×	×			×				Time & cost		×	

(*continued*).

Table A1. Continued

Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Source type: Scopus	Source type: Snowball
Sotskov et al. (2015)	Computers and Industrial Engineering	×				×				Time		×	
Sungur and Yavuz (2015)	Journal of Manufacturing Systems	×	×			×				Cost			×
Xin et al. (2015)	Assembly Automation	×	×							Time, cost & workload balancing / smoothing	×	×	
Costa, Cappadonna, and Fichera (2014)	International Journal of Production Research		×			×				Time		×	
Garbie (2014)	International Journal of Industrial and Systems Engineering	×			×			×		Throughput	×	×	
Huang and Pan (2014)	Journal of Manufacturing Systems		×	×					×	Job safety & workers' health	×	×	
Kara et al. (2014)	International Journal of Computer Integrated Manufacturing	×	×						×	Energy expenditure		×	
Koltai, Tatay, and Kalló (2014)	International Journal of Computer Integrated Manufacturing	×	×			×				Time	×	×	
Öksüz and Satoğlu (2014)	Proceedings of the Global Conference on Engineering and Technology Management	×	×			×				Time	×		×
Bentefouet and Nembhard (2013)	International Journal of Production Economics		×	×		×				Throughput		×	
Costa, Cappadonna, and Fichera (2013a)	International Journal of Advanced Manufacturing Technology		×	×		×				Time		×	
Costa, Fichera, and Cappadonna (2013b)	International Journal of Operations and Quantitative Management		×	×		×				Time & cost		×	
Denkena, Charlin, and Merwart (2013)	Production Engineering		×			×				Time & cost	×	×	

(*continued*).

Table A1. Continued

												Source type	
Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Scopus	Snowball
Koltai and Tatay (2013)	Optimisation and Engineering	×	×			×				Time		×	
Liu et al. (2013)	International Journal of Advanced Manufacturing Technology	×	×			×				Cost		×	
Manavizadeh et al. (2013)	Computers and Industrial Engineering	×	×			×				Workload balancing / smoothing	×	×	
Mutlu, Polat, and Supciller (2013)	Computers and Operations Research	×	×			×				Time		×	
Zhang, Xu, and Gen (2013)	Procedia Computer Science	×	×			×				Time			×
Araújo, Costa, and Miralles (2012)	International Journal of Production Economics	×	×			×				Time		×	
Asensio-Cuesta et al. (2012)	International Journal of Advanced Manufacturing Technology		×	×		×				Throughput & job satisfaction	×	×	
Chen et al. (2012)	Expert Systems with Applications	×	×			×				Time & throughput	×	×	
Cheng and Chu (2012)	International Journal of Advanced Manufacturing Technology		×			×				Time	×	×	
Othman et al.(2012a)	Computers and Industrial Engineering		×			×				Cost		×	
Othman, Gouw, and Bhuiyan (2012b)	Journal of Industrial Engineering and Management		×			×				Cost		×	
Deros et al. (2011)	American Journal of Applied Sciences	×			×				×	job safety & workers' health	×	×	
Koltai and Tatay (2011)	Periodical Polytechnical Social and Management Sciences	×	×			×				Time		×	
Zhang and Gen (2011)	Journal of Intelligent Manufacturing	×	×			×				Time & cost		×	

(*continued*).

Table A1. Continued

												Source type	
Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Scopus	Snowball
Nanthavanij, Yaoyuenyong, and Jeenanunta (2010)	International Journal of Industrial Engineering: Theory Applications and Practice		×	×		×				Throughput		×	
Thongsanit, Boondisakulchok, and Tharmmaphornphilas (2010)	Engineering Journal	×	×			×				Time	×	×	
Aryanezhad, Deljoo, and Mirzapour Al-e-Hashem (2009a)	International Journal of Advanced Manufacturing Technology		×			×				Cost		×	
Aryanezhad et al. (2009b)	International Journal of Advanced Manufacturing Technology			×		×				job safety & workers' health		×	
Hanson et al. (2009)	International Journal of Vehicle Design	×					×		×	job safety, job satisfaction and workers' health	×	×	
McDonald et al. (2009)	International Journal of Production Research		×	×		×				Cost & throughput	×	×	
Moon, Logendran, and Lee (2009)	International Journal of Production Research	×	×			×				Cost		×	
Ikou, Yasuhiko, and Yong (2008)	European Journal of Industrial Engineering	×				×				Time		×	
Nembhard and Shafer (2008)	International Journal of Production Research	×				×				Throughput	×		×
Quintana, Leung, and Chen (2008)	International Journal of Productivity and Performance Management	×					×			Throughput	×	×	
Süer and Tummaluri (2008)	International Journal of Production Research		×			×				Time	×		×
Weng and Onari (2008)	Journal of Japan Industrial Management Association	×	×			×				Time		×	
Kuo and Yang (2007)	Computers and Industrial Engineering		×			×				Cost		×	
Osawa and Ida (2007)	IEEJ Transactions on Electronics, Information and Systems		×			×				Time		×	

(*continued*).

Table A1. Continued

Authors (Year)	Source title	Assembly line balancing and design	Work / worker assignment	Job rotation and task switching	Working space design and layout design	Skill	Age	Gender	Anthropometry	Effect on	Applying case study	Source type	
												Scopus	Snowball
Shikdar and Al-Hadhrami (2007)	International Journal of Industrial and Systems Engineering	×			×				×	job safety, job satisfaction and workers' health	×	×	
Wirojanagud et al. (2007)	International Journal of Production Research		×			×				Cost & throughput	×		×
Song et al. (2006)	Computers and Industrial Engineering	×	×			×				Throughput	×		×
Wong, Mok, and Leung (2006)	International Journal of Advanced Manufacturing Technology	×	×			×				Time	×	×	
Fulder et al. (2005)	International Journal of Simulation Modelling				×				×	job safety, job satisfaction and workers' health		×	
Iima, Karuno, and Kise (2005)	IEEJ Transactions on Electronics, Information and Systems	×				×				Time		×	
Allwood and Lee (2004)	International Journal of Production Research			×		×				Throughput		×	
Baines et al. (2004)	Simulation Modelling Practice and Theory	×					×			Time & throughput		×	
Bokhorst*, Slomp, and Gaalman (2004)	International Journal of Production Research		×			×				Time		×	
Buzacott (2002)	International Journal of Production Economics		×			×				Throughput			×
Norman et al. (2002)	International Journal of Production Research		×			×				Cost & throughput		×	
Shafer, Nembhard, and Uzumeri (2001)	Management Science	×				×				Throughput			×
Doerr, Klastorin, and Magazine (2000)	Management Science	×	×			×				Cost & throughput		×	
Das and Sengupta (1996)	Applied Ergonomics				×				×	Physical workload capacity / Fatigue or discomfort	×	×	
Gallwey (1992)	International journal of industrial Ergonomics	×				×				Time		×	
100 Selected papers		58	74	15	8	83	9	2		9	46	91	9