Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 107 (2022) 966–971

www.elsevier.com/locate/procedia

55th CIRP Conference on Manufacturing Systems

Evaluation of Material Shortage Effect on Assembly Systems Considering Flexibility Levels

Oleksandr Melnychuk[a]*, Jonas Rachner[b], Lea Kaven[b], Amon Göppert[b], Robert H. Schmitt[b], Tullio Tolio[a]

[a]*Department of Mechanical Engineering, Politecnico di Milano, via La Masa 1, 20133 Milano, Italy*
[b]*Laboratory for Machine Tools and Production Engineering (WZL), RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, German*
[c]*Fraunhofer Institute for Production Technology (IPT), Steinbachstraße 17, 52074 Aachen, Germany*

* Corresponding author. Tel.: +39 388 487 1143. *E-mail address:* oleksandr.melnychuk@polimi.it

---

Abstract

The global pandemic caused delays in global supply chains, and numerous manufacturing companies are experiencing a lack of materials and components. This material shortage affects assembly systems at various levels: process level (decreasing of the resource efficiency), system level (blocking or starvation of production entities), and company level (breaking the deadlines for the supplying of the products to customers or retailers). Flexible assembly systems allow dynamic reactions in such uncertain environments. However, online scheduling algorithms of current research are not considering reactions to material shortages.

In the present research, we aim to evaluate the influence of material shortage on the assembly system performance. The paper presents a discrete event simulation of an assembly system. The system architecture, its behavior, the resources, their capacities, and product specific operations are included. The material shortage effect on the assembly system is compensated utilizing different system flexibility levels, characterized by operational and routing flexibility. An online control algorithm determines optimal production operation under material shortage uncertain conditions. With industrial data, different simulation scenarios evaluate the benefits of assembly systems with varying flexibility levels. Consideration of flexibility levels might facilitate exploration of the optimal flexibility level with the lowest production makespan that influence further supply chain, as makespan minimization cause reducing of delays for following supply chain entities.

Keywords: Material Shortage; Discrete Event Simulation; Flexible Assembly; Production planning; Production control.

---

1. Introduction

The global pandemic is causing various problems for the industrial production sectors around the globe [1]. One of the most significant issues for industrial companies has arisen in the logistics area, i.e., material and components shortage [2]. International logistics chains have been broken or damaged due to travel restrictions and economic issues in the suppliers' companies. The automotive assembly production sector is particularly struggling from the component shortage. This happens due to the adoption of the just-in-time concept in most of them [3]. The lack of materials and components influences production systems on various levels [4]: (i) process level; (ii) system level; (iii) company level.

On the process level, the lack of the materials and components causes a drop in the individual resources' overall efficiency. In some cases, it means postponing the process that requires the component's material. In other cases, alternative materials or components might be used. In case when the material has to be substituted, adjustment of the process has to be done, e.g., due to the set-up with new process parameters. Latter means elongation of the processing time and increase of

10.1016/j.procir.2022.05.093

the non-conformances probability.

On the system level, the lack of material and components might cause product flow blocking or starvation. The system level contains whole production flow, its management is complex and utterly important for manufacturing.

At the company level, lack of material and component frequently causes breaking of the deadlines for supplying the products to customers or retailers. Often this means substantial penalties and fees.

The issue of material and component shortage frequently arises in the assembly systems. Multiple works consider these issues in the supply chain , particularly assembly of automotive sector [5], [6], [7]. Mainly, a prospective area for production performance improvement is the system level management (e.g., production planning) of an assembly production system. Indeed, system level adjustments play one of the key roles in manufacturing improvement as they connect the process level and company level.

In the present research, we aim to evaluate the effect of material shortage on assembly systems in the automotive sector, using flexibility levels of the production systems. This paper exposes the effect of material shortage from upstream on the downstream link of the supply chain, considering optimization of the production makespan in the manufacturing facility. Here, upstream means the previous supply chain link (e.g., supplier of raw material or component) and downstream means the following after considered manufacturing link of the supply chain (e.g., product buyer, retailer.).

Furthermore, we aim to provide valuable insight for handling the lack of material and components issue. Latter will be done by researching optimal scheduling algorithms that might be applied at various flexibility levels of the production system

1.1. Related works

In the work of Boysen and Bock (2011) [8] the issue of job scheduling in mixed-model assembly lines is examined. The paper reflects internal scheduling in the production facility that is studied as an industrial case. The authors emphasize the harmful effect of the line stoppage and off-line repair costs as well as due dates violation on the whole production system. The authors strive to avoid internal material shortage that non-optimal logistics of material might cause at the stage of its delivery from the company storage to the shop-floor. Specifically, the research is concentrated on the study of optimal scheduling algorithms for material supply facilitated by the transportation system. The research considers only existing production system with the flexibility level it has. The paper does not take into account material shortages caused by suppliers.

Another paper, of Awate (1990) [7], which considers the material lack, exploits a flow-shop scheduling algorithm to minimize company loss. The material shortage is seen in the paper as a result of the non-optimal scheduling policy. A pull-type component inventory control mechanism is considered. A production dispatching policy is established for the assembly facility. It is based on a pre-established flow-shop heuristic algorithm scheduling. Firstly, the authors balanced each station load in the production assembly system. Then, the cyclic loading strategy was implemented as a scheduling policy to minimize a time-separation necessary between assembly and component shop. It was established on a short-time horizon. Finally, the established scheduling was extended to a mid-time term strategy.

The robustness of a supply network is considered in the paper of Petrovic *et al.* (2021) [9]. It copes with procurement logistics. Evaluation of its robustness is done by measuring its sensibility to the changes in customer demand. To tackle the material shortage, depending on the time of the order, two main strategies of material ordering are represented: (i) ordering from the standard supplier (cheap option) or (ii) order from emergency supplier (expensive option). A model with fuzzy multi-objective optimization is presented in the paper to study the optimal supply strategy, where the optimum is a trade-off between cost and robustness of the supply chain. Nevertheless, the paper considers only the logistics aspect of the efficient material supply managing demand to avoid material shortage. Production system flexibility is not considered in the research.

In the paper of Zhou *et al.* (2020) [6], the uncertain capacity and random yield of electronic devices are considered simultaneously for different suppliers. The paper copes with procurement logistics. The authors aimed to formulate the optimal conditions of material ordering under the uncertainty to avoid component shortage and formulate components ordering decision model. Indeed, the optimal component ordering strategies are characterized for the considered assembly system. Specifically, two types of uncertainty were taken into account and an optimal ratio of various components order was found. Nevertheless, the dependency between the system flexibility and optimal supply of the assembly components is not considered as it is done in work Göppert *et al.* (2020) [10].

In their work Petitjean *et al.* [5], the authors model the supply chain for an automotive production facility. The paper considers logistics links of the production chain and the effect of the latter's disruption at different stages. The paper does not consider the flexibility issues that might be useful for decreasing the negative effect of material shortage, but it provides a valuable insight to a global supply chain management from the logistics point of view.

Based on the discovered lack of joint consideration flexibility and scheduling in the issue of materials and components shortage, we decided to establish such an approach in this paper. The flexibility concept is defined and measured by various authors in different ways [11], [12], [13]. We aim to adopt a classification and the view on flexibility formulated in the paper Sethi and Sethi (1990) [14]. Particularly, in the present paper we consider four levels of production system flexibility, relevant for assembly of automotive components: (i) flow-shop [15]; (ii) flow-shop with parallelization (i.e., a flow shop with parallel station or stations [16]; (iii) job-shop [17]; (iv) flexible job-shop [18]. There are two types of flexibility corresponding to those flexibility levels, i.e., operation and routing flexibility. The operation flexibility enables change of the operation sequence in the process plan, meanwhile the routing flexibility facilitates operation performance on different servers (i.e., machines, assembly stations, etc.). Those flexibility types correlate to component and system flexibility correspondingly [14].

In order to find optimal production planning under the uncertain conditions of material shortage we study scheduling algorithms that may be applied for different levels of flexibility. The scheduling issue is a research topic that is studied for various types of manufacturing systems with various levels of flexibility, such as single machine systems, parallel machine systems, flow shops and job-shops [19].

Typically, a flow-shop is characterized only with one job type [15], therefore all jobs to be done possess the same process plan. However, the complexity of flow-shops and job-shops is constantly growing with recent innovative technologies that expand their flexibility range. In latterly mentioned production systems, the products to be proceeded are considered as jobs that have sub-attributes, such as number of items to produce, product type, etc. In order to complete each job a set of operations has to be preceded. Within job-shop scheduling, the flexibility of the operations to be proceeded is defined with a precedence graph. The issue of scheduling in job-shop systems was considered in many papers(e.g. [17], [20], [21]). Commonly, the job-shop system has a limited routing flexibility level compared to the flexible job-shop system. The goal of the job-shop scheduling is finding the solution to a sequencing problem to reach the optimal level of pre-defined Key Performance Indicators (KPIs), mainly makespan, i.e., the maximum completion time of all jobs.

The flexible job-shop apart from the extended routing flexibility compared to the job-shop also possesses the operational flexibility [18]. As it was mentioned before, operational flexibility enables changes in the sequence of operations to be performed to complete the product. This flexibility significantly increases the agility and robustness of the production system under the conditions of high uncertainty. However, it also increases the complexity of decision support in such systems due to the growing number of decision options, their consequences and interaction between them.

Scheduling issues in flexible job-shop [22] might be solved (i) statically and (ii) dynamically. In the first case all the data regarding decision making in scheduling is available in advance and no unplanned events are taken into account. Meanwhile, in the second case disrupting events, such as machine breakdowns, job cancellation and material shortage are considered. To handle material shortage events a dynamic scheduling performed online during processing is needed.

Based on the literature analysis we conclude that there is a research deficit in the issue of estimation of material lack effect through the supply chain regarding the flexibility levels of the manufacturing facilities. Some research papers regarding material shortage and components shortage focus on procurement logistics [9], [6] or scheduling in their production facility [8], [7] , other evaluate the whole logistic chain without the consideration of intralogistics of some production system [5]. However, the extensive estimation of material lack effect on the supply link, that goes next after the manufacturing facility, is missing in the literature.

The flexibility levels and their types for assembly systems relevant for present research are defined in the paper. In order to manage the issue of material lack in assembly systems state-of-art scheduling algorithms should be implemented, studied, and extended. This work aims to address the issues mentioned above by estimating the production makespan in the assembly systems considering various flexibility levels. To sum up, the material and component lack should be considered as a three-stage issue: (i) upstream (i.e., insufficient supply), (ii) manufacturing (i.e., production planning, e.g., scheduling), (iii) downstream (i.e., makespan estimation). Using the latter prospective increase of tardiness and deadlines breakage might be presumed.

A set of experiments shall be performed in a discrete event simulation environment. This way its outcome may be integrated in existing frameworks regarding production planning issues, e.g., digital twin optimization for production scheduling [23] and ongoing research that considers other aspects of manufacturing disruptions [24].

2. Methodology

In order to define an optimal makespan in an assembly production system with corresponding flexibility levels a discrete event simulation (DES) model was developed. Schematic representation of the considered flexibility levels is given in Fig. 1, there: (a) flow shop, (b) flow-shop with parallelization, (c) job-shop, (d) flexible job-shop.

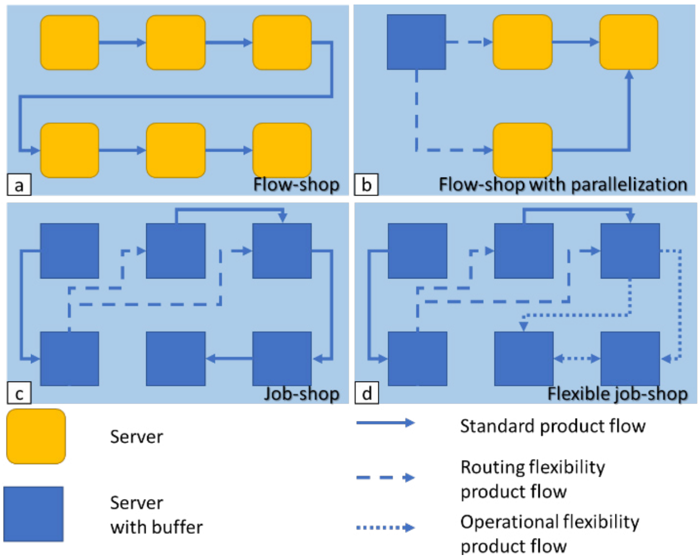

Fig. 1. The flexibility levels of the assembly system.

Afterwards, the DES model was integrated with a scenario analysis tool that facilitates the initialization of experiments with different parameters [25]. In Fig. 1, regarding the production flow, routing flexibility means the possibility to choose an alternative server to proceed the operation (alternative choice), meanwhile, operational flexibility means the possibility to change the sequence of operations that have to be proceeded (sequential choice). The difference between considered flexibility levels in the model are cumulated in Table 1.

The simulation model of the production assembly system was developed in Tecnomatix Plant Simulation [26]. Positioning of the solution (e.g., DES supported by scenario analysis tool) regarding the supply chain is given in Fig. 2.

A production plan for a given period is considered in the model. The production plan contains the set of jobs to be done. The jobs might be defined either numerically or proportionally, as a jobs distribution in the production plan. Each job has a set of sub-attributes, i.e., product type and number of items. Moreover, every job can be operated (assembled) and transported by various servers, i.e., by various assembly stations and automated guided vehicles (AGVs) or workers.

Table 1. Production system flexibility levels.

Production system	Buffers status	Flexibility	
		Routing	Operational
Flow-shop	No buffers		
Flow-shop with parallelization	Buffers at parallel stations	X	
Job-shop	Buffer at each station	X	
Flexible job-shop	Buffer at each station	X	X

In order to generate the replications and to obtain statistical relevance the random seed can be set for the overall system. Processing time of each item depends on the product type, process type and processing resource. The sequence of the operations to be proceed in order to complete each item is defined in a precedence graph of each product type. The product types might have different precedence graphs with various levels of flexibility, i.e., routing flexibility and operational flexibility. Each assembly station in the system has its process capabilities and is given availability defined with the mean time between failure (MTBF) and mean time to repair (MTTR).

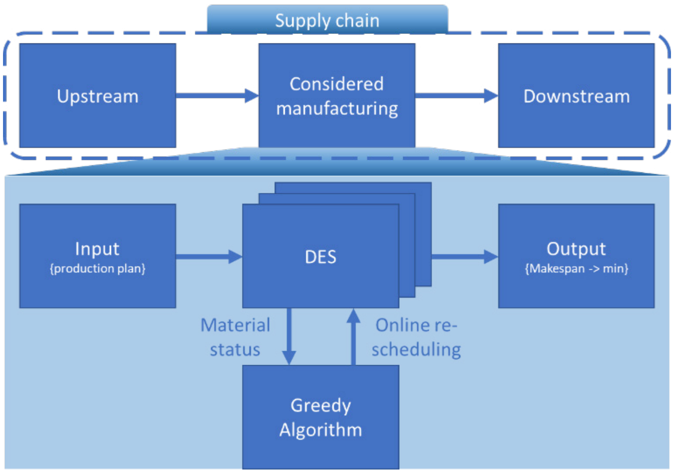

Fig. 2. Positioning of the solution regarding the supply chain.

The online scheduling is realized through a Greedy algorithm, taking the current system status into account. As an input, the discrete event simulation provides information about the station status (processing, waiting, idle, blocked, queue length) and the product (precedence graph, realized process steps). Additionally, the material status for all assembly steps is communicated. The Greedy includes the matching (which stations offer the capability for potential following process steps) and the routing (which station is selected for the next assembly step) for one product and is triggered after every completion of an assembly step. If a material type is not available at the moment, no assembly step using this material type is included in the matching decision. The routing decision optimizes the overall makespan by choosing the next station based on the minimized transportation and waiting time (see (1)). The transportation time is calculated based on the Euclidean distance of stations and the transport system velocity. The waiting time depends on the current queue length of the chosen station.

$$min\, t\_transport\ + t\_waiting \tag{1}$$

As it was mentioned above, the scenario analysis tool is an additional tool that extends the capabilities of the simulation model. Particularly, the tool facilitates the co-dependency of the system variables and parameters. System considerations, such as layout, product variety, complexity, flexibility of the assembly system as well as their variation levels might be used as input parameters for the tool. After entering the input into the tool, a full factorial experiment plan is created. Using a random seed, the number of replications is defined, thus scenarios with different para random values are generated. This way simulation files for each experiment are generated and executed. The results of the experiments are combined in a single report file and evaluated right after the programmed series of the experiments is performed. Relevant KPIs, e.g., flow time, makespan and utilization, are used for the results evaluation.

The scenario analysis includes online matching and scheduling of each process step to the next station (only considering the data available at this time (e.g., breakdowns, new orders, etc.). The scheduling in the tool is done by a greedy algorithm that minimizes the overall makespan. The material presence in the model is defined stochastically with a normal distribution. When material is not available, a specific process step referring to a specific product type cannot be processed. In both systems, flow-shop and flow-shop with parallelization, the process steps before the station that has no material, cannot continue to work, as product flow is blocked. In the job-shop, products requiring missing material block the buffer exit of a specific station.

Particularly, the product waits in the buffer until material is available. Meanwhile, other stations can still perform process steps not requiring the material. In the flexible job-shop the product that requires some material, but missing it, can be processed on other stations, when some process steps are possible regarding the constraints of the precedence graph. In the best scenario of the latter there is no blocking of the production flow at all. However, when no other process steps are allowed due to the precedence restrictions, the same method as in a job-shop applies to the flexible job-shop.

3. Evaluation with industrial case-study

The developed methodology was applied to an automotive assembly system use case. The model was first adapted to the four flexibility levels. The servers, their buffers, and corresponding capabilities were derived (see Table 2).

In Table 2 the list of technologies is given according to the product and server number. Additional technologies are marked differently for various flexibility levels: (i) bold numbers, marked with blue colour are for flow-shop with parallelization; (ii) underlined numbers, marked with yellow colour are for job-shop and flexible job-shop.

Table 2. Matching of server technologies to product variants based on flexibility levels.

Server number	Product					
	1	2	3	4	5	6
1	1, 2	11, 12	1, 12	11, 2	1, 12	2
2	1, 2	11, 12	1, 12	11, 2	1, 12	2
3	3, 4	13, 14	4	3, 4	3, 14	3, 14
4	3, 4	13, 14	4	3, 4	3, 14	3, 14
5	5, 6	15, 16	5	16	5, 16	15, 6
6	5, 6	15, 16	5	16	5, 16	15, 6
7	7, 8	17, 18	17, 8	7, 18	7, 18	7, 18
8	7, 8	17, 18	17, 8	7, 18	7, 18	7, 18
9	9, 10	19, 11	9, 11	19, 10	9, 11	9, 10
10	10, 9	11, 19	11, 9	10, 19	11, 9	10, 9
11	**3**	**13**		**3**	**3**	**3**
12	**8**	**18**	**8**	**18**	**18**	**18**

The production program contained 500 products in 6 variants evenly distributed. Variants differ in the amount of needed assembly steps (8 - 10) and the required duration per assembly step. Moreover, the process time is statistically normally distributed with a mean of 5 min and a standard deviation of 0.1 min. Within the Flexible Job-Shop System, an operational flexibility of 30%, 60% and 90% was examined. Here, the routing flexibility refers to the number of assembly steps that can be changed in their order, while respecting the precedence graph. Each simulation run was repeated 3 times with different random seeds to insure statistical validity.

Material availability was examined at 90%-100%. Based on the industry use case, it was assumed that the missing material is available after equally distributed 15 - 45 minutes. As shown in Fig. 3, increasing of operational flexibility allows better reactivity in case of short-term material failures while machine flexibility doesn't influence it. In particular, with a material availability of 90%, the makespan influence of all jobs in the system decreases with increasing flexibility.

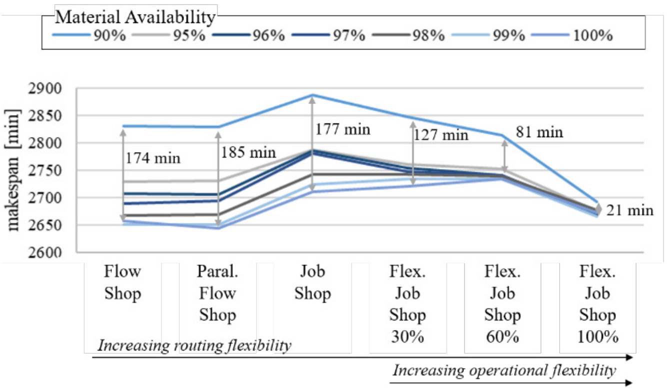

Fig. 3. Makespan based on material availability and flexibility levels.

The flexible job-shop model with 100% operational flexibility only increased for 21 min compared to the makespan with 100% material availability. In contrast, the makespan in a flow-shop increased for 174 min. Thus, an operational flexibility allowed for a 12% better reaction regarding the makespan. This can be explained by the fact that the assembly processes order can be changed dynamically in a flexible job-shop with online scheduling due to the flexible priority graph.

Hence, the time spent waiting for missing material can be replaced by productive time. In addition, the inherent flexibility of the multi-purpose stations and the connected buffers allows the use of a station for another process step for which the material is available. In contrast, a shortage of material in a flow shop blocks the station and thus interrupts the upstream material flow. The change from a flow-shop to a job-shop with no alternative process sequences has no influence since the product has no alternative routes when the material for the needed process is not available.

4. Conclusions

Regarding different levels of production system flexibility, a set of experiments has been performed in order to define the effect of material shortage on the supply chain. It was defined in the work that the change from flow-shop to job-shop has no positive influence regarding material shortage. From the results of the experiments, it is clear that a flexible job-shop has a high resilience in terms of material shortage because of the operational flexibility (i.e., processes without available material can be skipped).

In conclusion, assembly processes should be designed keeping in mind the operational flexibility (i.e., modularization of product for flexible precedence graph) to enable resilience regarding material shortage. Indeed, production systems should be flexible (job-shop) to facilitate better reaction to increasing supply chain problems.

Further evaluation regarding the reason why the job-shop increases the makespan in the given scenario, and the flexible job-shop helps to compensate material shortage while decreasing the makespan is required.

Future work should focus on different types of material shortage (short and long term) and different optimization KPI (e.g., due dates, tardiness, smoothness of the production). Moreover, advanced algorithms for online scheduling should be investigated for production systems with different flexibility levels. Latter should be done in order to cope better with the complexity of production planning issues, that grows along with increasing of system's flexibility.

Acknowledgements

This work is part of the research project "AIMFREE" that is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the indirective on a joint funding initiative to fund research and development in the field of electromobility (funding number: 01MV19002A) and supported by the project management agency German Aerospace Center (DLR-PT). The authors are responsible for the content.

References

[1] Coutiño A, Zandi M. Global loss of production capacity caused by the COVID-19 pandemic. J Policy Model. Epub ahead of print 27 April 2021. DOI: 10.1016/j.jpolmod.2020.07.003.

[2] Paul SK, Chowdhury P, Moktadir MA, et al. Supply chain recovery challenges in the wake of COVID-19 pandemic. J Bus Res 2021; 136: 316–329.

[3] Swanson CA, Lankford WM. Just-in-time manufacturing. Bus Process Manag J 1998; 4: 333–341.

[4] Cohen MA, Lee HL. Strategic Analysis of Integrated Production-Distribution Systems: Models and Methods. https://doi.org/101287/opre362216 1988; 36: 216–228.

[5] Petitjean F, Charpentier P, Bron J-Y, et al. GLOBAL MODELLING OF AN AUTOMOTIVE INDUSTRY SUPPLY CHAIN APPLIED TO PRODUCTION MANAGEMENT DECISION-SUPPORT. IFAC Proc Vol 2007; 40: 415–420.

[6] Ji Q, Zhou S, Li B, et al. Component ordering strategies in assembly systems with uncertain capacity and random yield. Appl Math Model 2020; 88: 715–730.

[7] Awate PG. A case study in cyclic assembly planning and dynamic coordinated component shops' loading in a locks manufacturing plant. Eng Costs Prod Econ 1990; 19: 115–123.

[8] Boysen N, Bock S. Scheduling just-in-time part supply for mixed-model assembly lines. Eur J Oper Res 2011; 211: 15–25.

[9] Petrovic D, Kalata M, Luo J. A fuzzy scenario-based optimisation of supply network cost, robustness and shortages. Comput Ind Eng 2021; 160: 107555.

[10] Göppert A, Rachner J, Schmitt RH. Automated scenario analysis of reinforcement learning controlled line-less assembly systems. Procedia CIRP 2020; 93: 1091–1096.

[11] Chryssolouris G, Georgoulias K, Michalos G. Production Systems Flexibility: Theory and Practice. IFAC Proc Vol 2012; 45: 15–21.

[12] Beach R, Muhlemann AP, Price DHR, et al. A review of manufacturing flexibility. Eur J Oper Res 2000; 122: 41–57.

[13] Garavelli AC. Performance analysis of a batch production system with limited flexibility. Int J Prod Econ 2001; 69: 39–48.

[14] Sethi AK, Sethi SP. Flexibility in manufacturing: A survey. Int J Flex Manuf Syst 1990 24 1990; 2: 289–328.

[15] Lechleiter I. Maschinenbelegungsplanung in der Variantenfertigung. Maschinenbelegungsplan der Var. Epub ahead of print 1999. DOI: 10.1007/978-3-322-93421-5.

[16] Askin RG, Zhou M. A parallel station heuristic for the mixed-model production line balancing problem. http://dx.doi.org/101080/002075497194309 2010; 35: 3095–3106.

[17] Zobolas GI, Tarantilis CD, Ioannou G. Exact, Heuristic and Meta-heuristic Algorithms for Solving Shop Scheduling Problems. Stud Comput Intell 2008; 128: 1–40.

[18] Özgüven C, Özbakir L, Yavuz Y. Mathematical models for job-shop scheduling problems with routing and process plan flexibility. Appl Math Model 2010; 34: 1539–1548.

[19] Ouelhadj D, Petrovic S, Ouelhadj D, et al. A survey of dynamic scheduling in manufacturing systems. J Sched 2008 124 2008; 12: 417–431.

[20] Wang L, Hu X, Wang Y, et al. Dynamic job-shop scheduling in smart manufacturing using deep reinforcement learning. Comput Networks 2021; 190: 107969.

[21] Wang ZY, Lu C. An integrated job shop scheduling and assembly sequence planning approach for discrete manufacturing. J Manuf Syst 2021; 61: 27–44.

[22] Chaudhry IA, Khan AA. A research survey: review of flexible job shop scheduling techniques. undefined 2016; 23: 551–591.

[23] Magnanini MC, Melnychuk O, Yemane A, et al. A Digital Twin-based approach for multi-objective optimization of short-term production planning. IFAC-PapersOnLine 2021; 54: 140–145.

[24] Magnanini MC, Colledani M, Melnychuk O, et al. Effect of work-force availability on manufacturing systems operations of job shops. Procedia CIRP 2021; 103: 152–157.

[25] Grahn L, Rachner J, Göppert A, et al. Framework for Potential Analysis by Approximating Line-Less Assembly Systems with AutoML. 2022; 423–430.

[26] Plant Simulation and Throughput Optimization | Siemens Digital Industries Software, https://www.plm.automation.siemens.com/global/en/products/manufacturing-planning/plant-simulation-throughput-optimization.html (accessed 21 July 2021).