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Effect of work-force availability on manufacturing systems operations of job shops

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Abstract

In manufacturing systems characterized by job shop architectures, long lead times, and multiple part types, operators are important resources of the system, because they supervise and actively support the technical operations of machines. However, Industry 4.0 tools, as digital twins of manufacturing systems, rarely consider the human aspect. As a consequence, the real impact of workforce on production performance cannot be assessed precisely. In this paper, the effect of work-force availability on manufacturing systems operations is shown, with a special focus on job-shop systems. Results show that there is a strong relation between the operators management and the short-term production planning. The method is applied and validated within a real industrial case in the aeronautics sector, characterized by high value-added complex parts.

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Keywords: Manufacturing systems; Workforce; Digital Twin; Operations management; Performance evaluation.

1. Introduction

The effect of manual workforce on production operations is utterly significant as workers are an essential part of it. Indeed, workers take care of the product handling in the shop-floor. They perform process operations which require manual execution (e.g., assembly operations and quality inspections), also they provide the services to the machines (e.g., set-ups and maintenance) [1]. Tasks that are assigned to operators should be consistent with their skills, therefore the overall system productivity depends also on the correct mix of skills among operators in the shop-floor and on the right training course for upskilling. In recent years, the increased level of automation has changed workforce operations. In fact, operators are mainly involved in process supervision, rather than actual process operations. This leads to workforce reduction, because one operator may supervise more than one machine in the shop-floor. However, when disruptions occur (e.g., machine failures, tool breakage, random stoppages in general), operators may suffer sudden workload from different machines [2], [3]. Consequently, the resumption of operations may be delayed, impacting, and propagating the delay to the downstream process stages which wait for the parts and affecting the overall system productivity.

Workforce costs represent a significant part of overall expenses for most businesses [4]. Therefore, their management and optimization are particularly relevant. Especially it is important in the time of economic difficulties, as the one they have recently experienced due to the global pandemic, as it is explicitly shown in paper [5] on the example of aviation sector. It is equally important to determine what workforce is needed in what amount and to organize the efficient schedule with meaningful assignments of the personnel according to their skills. Reasonable management of personnel under circumstances described above can be quite complicated. Researchers and practitioners

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have been focusing thoroughly on different aspects of such management to incorporate advanced strategies and achieve sufficient improvement of performance measure they consider in their works [6].

Availability of the workforce is the sufficient supply and appropriate stock of workers that possess the competences to match the production needs in performing required operations such that it is possible to reach aimed number of final products. Meanwhile, lack of worker means the lack of skill that is needed to satisfy the production demand in it.

This work presents an integrated method to evaluate the effect of workforce availability in complex manufacturing systems as job shops on the overall performance. The goal is to provide meaningful insights to allow an efficient operations management according to available workforce. The method combines a parametric Digital Twin (DT) based on a discrete event simulation model (DES) which is fed by a data gathering system of real production data, according to a specific data model. The DT returns a set of performance measures, which all together provide the effect of workforce availability on the overall productivity.

The remains of the paper are organized as follows: the following Section summarizes the state of the art; Section 2 describes the proposed methodology; in Section 3 a real case in the aerospace sector is presented and commented; Section 4 concludes the work and provides future developments.

1.1. Related works

Literature review was done in order to systematize and analyse existing scientific data about the role of workforce and its availability on the efficiency of the achieving aimed goals. Results of our findings has been aggregated into the Table 1. The works are classified according to the application sector, workforce skills, focus of research and configuration evaluation method.

In scientific literature authors address the issue of workforce availability through three aspects of human resource management (i) unavailability (ii) planning and (iii) workload:

(i) Unavailability in personnel management refers to the habitual non-presence of an employees at their job. However, it extends beyond what is deemed to be within an acceptable realm of days away from the office for legitimate causes such as scheduled vacations, occasional illness, and family emergencies [7].

(ii) Planning in personnel management refers to the many issues connected to the human resource management strategy of the company. In present research we understand this term through scheduling and assignment of workers [8].

(iii) Workload is a self-explanatory term. It is an important aspect that has significant impact on workforce performance and production goals achievement [9].

Table 1 reports multidisciplinary nature of the workforce availability effect on the system service level. There are two works addressing the heterogeneous skilled workforce availability issue in manufacturing sector [10], [11]. Most of the researchers concentrate on the scheduling and assignment issue addressing them through mixed-integer linear programming (MILP), meanwhile topic of unavailability is not considered so broadly [11]; a few of reviewed works are completely concentrated on unavailability mitigation and its

Table 1. Classification of relevant works related to the effect of work-force availability on systems operations.

Author	Focus of research			Application sector	Workforce skills	Evaluation method
	unavailability	planning	workload			
Bard and Purnomo [18]		X		medicine	homogeneous	MILP
Easton and Goodale [12]	X	X		service sector	heterogeneous	MILP
Whitt [25]		X		service sector	homogeneous	queueing model
Easton [14]	X	X		general application	heterogeneous	DES
Krishnamoorthy et al. [22]		X		general application	heterogeneous	MILP
Smet et al. [24]		X		general application	heterogeneous	hamming distance model
Green et al. [13]	X	X	X	medicine	homogeneous	analytical model
Lapègue et al. [23]		X	X	medicine	heterogeneous	MILP
De Bruecker et al. [20]		X	X	manufacturing	heterogeneous	DES
Ingels and Maenhout [15]	X	X		general application	heterogeneous	DES
Gross et al. [21]	X	X		medicine	heterogeneous	MILP
Dantan et al. [2]		X	X	manufacturing	homogeneous	DES
Steenweg et al. [11]	X	X	X	manufacturing	heterogeneous	DES
Becker [19]		X		general application	homogeneous	MILP

management, such as last minute assignment, precious findings were made in medicine area [12], [13]. Papers in which multiple stage optimization is utilized are of great interest as they use simulation as configuration evaluation method, consequently methods used in those articles provide relevantly precise results and allow easily incorporate stochasticity in established models [14], [20], [15], [11]. Interesting findings were done in [2], as authors made a clear distinction of the manufacturing equipment's behaviour, from the human resources. Analysis of the interactions between the human behaviour (fatigue, learning, etc.) and the production system behaviour (productivity, quality) allowed to quantify the impact of a design decision on the production system performance and the human factors. Authors explore the influence of workers fatigue not only on throughput, but also on the quality aspects of the manufacturing process through human related errors and consequently to the rejection rate. In the paper is highlighted the difference in the results of production goals achievement according to the designed system configuration. Crucial aspect that was considered in the research is the level of process automatization: more manual work provokes more fatigue that leads to the human related errors or often worker breaks.

This view opens a discussion about the operation modes influence on production rates. As well as in other considered papers, [2] uses DES as configuration evaluation method.

In this context, DT may result as quite useful, since they ground on sensor data and historical data for mirroring one or more real systems [16], [17].

2. Methodology

2.1. Overview of the approach

The proposed methodology integrates a DT based on a parametric (DES) model which is continuously updated by data coming from the real system, Fig. 1. The DES model has

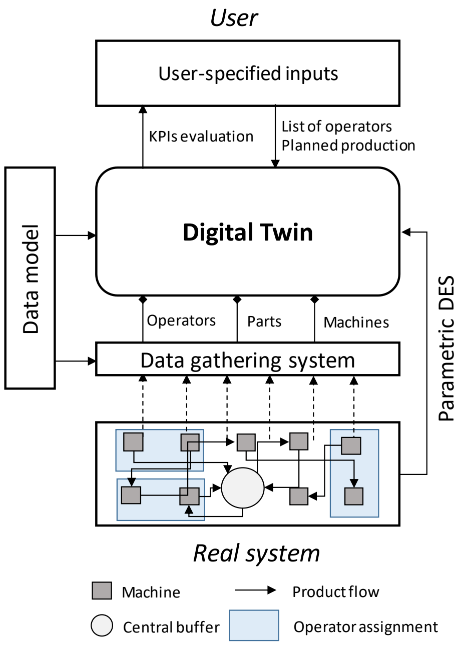

Fig. 1. Overview of the proposed approach.

been designed in Siemens Tecnomatix Plant Simulation [27].

Data are fed to the DES of DT according to specific data model, which includes information regarding operators (i.e., skills, tasks, and assignment), machine data (i.e., machine dynamics in terms of operations, processing times per operation, failures, set-up etc.), product data (i.e., product type, routing for each product type), part status and buffer status. The DT returns to the users a set of Key Performance Indicators (KPIs) that are used to understand the effect of workforce availability on the productivity performance.

This is necessary since workforce availability may change abruptly from shift to shift, due to unpredicted circumstances. Hence, re-assignment of operators is possible only if the current production scenario in terms of planned parts to be produced and machine status is integrated with the workforce availability information. Therefore, a DT-based approach is required since it provides decision support for the production manager according to the actual system condition.

2.2. Data model

The data model combines the formal description of static data, as machine, operations, buffers, and product types, as well as dynamic data, as operators assignment, machine status, parts status, and buffer status. The first-level Entity Relationship Diagram of the data model is shown in Fig. 2. Each Entity is further defined by multiple levels of details according to the actual data gathering and definition.

As it can be noticed from the Fig. 2, each operation is

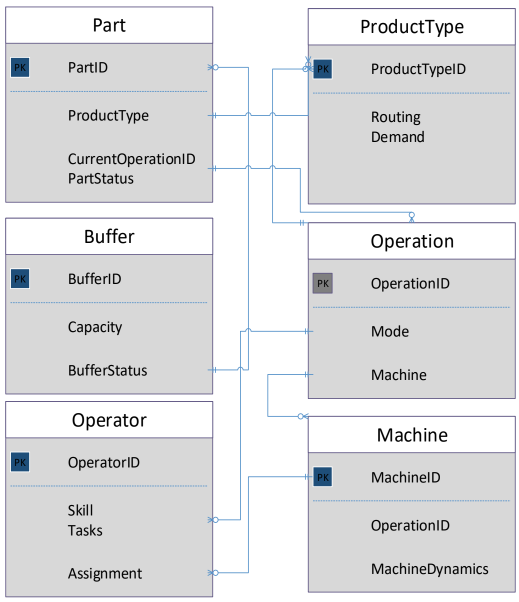

Fig. 2. The first-level Entity Relationship Diagram.

described by a mode. A mode defines how often an operation requires manual intervention. In particular:

(i) the operator is working on the part by hand or with hand tools, hence the operation is completely manual and the operator is constantly busy during operation processing time;

(ii) the operator is mounting and dismounting the part in a machine, in this mode operator does not need to work manually on the part, but still he is busy during all processing time of operation as s/he is obliged to monitor the part while it is in the machine;

(iii) the operator is mounting and dismounting the part in a machine, and the operation can be unsupervised but predefined (or pre-set) stops should be performed for checks or alignment of the part during the machining. If the operator is not there, the machine can not keep on processing the part.

(iv) the operator is mounting and dismounting the part in a machine, the operation is unsupervised hence the operator can perform other jobs.

Table 2 summarized how modes can be distinguished with respect to the operation sequence of actions.

Table 2. Operation modes.

Mode	Name	Set-up	Processing	Predefined stops
i	Manual	X	X	
ii	Semi-manual	X	X	X
iii	Semi-automatic	X		X
iv	Automatic	X		

Therefore, by means of the operation modes, operators modelled in the DT may be available of performing assigned tasks, as in shared capacity problems. The added value brought by this formalization is that for companies becomes quite easy to provide the initialization of this information, and therefore the generalization of the DT is increased.

2.3. Key Performance Indicators (KPIs)

In this paragraph, the Key Performance Indicators that can be evaluated by the proposed approach are introduced. The goal of these KPIs is to assess the effect of the workforce availability on the overall manufacturing systems. In fact, usual KPIs, as system throughput, cannot be alone an efficient performance indicator, especially when lead times are quite long. Therefore, these KPIs rather focus on how much production has advanced in a certain time frame, as the week, which is consistent to usual workforce schedule.

- Throughput (TH): the system throughput represents the number of parts that each time period that are completed by the production system and leave it.

- Throughput Variance (VarTH): the variance of throughput represents the dispersion of the throughput along the time frame.

- Total Number of Performed Operations (TNPO): this KPI is used as proxy of the advancements in the part completion. It is particularly relevant when parts are processed without a FIFO logic, therefore routing and dispatching have both a strong effect on system performance.

2.4. Relation among KPIs and workforce availability in job-shop production systems

In job-shop production systems characterized by combinations of manual and automatic operations, workforce availability and expertise combination are crucial for the effective system operations. Indeed, the following aspects should be considered:

- If operators have vertical expertise, i.e., are extremely specialized, the lack of one operator leads to the impossibility of performing specific operations. However, the re-assignment of operators to other tasks is easier since constraints are very well specified. The effect of this aspect on KPIs cannot be known a priori since it depends on the level of completion of parts planned for production.

- If operators have horizontal expertise, i.e., are not specialized, the lack of one operator can be solved more easily since his/her activities can be replaced. However, operators reassignment is more complex, and is strongly inter-dependent with the planned parts. The effect of this aspect on KPIs cannot be known a priori, as it depends on the reassignment reactivity.

3. Industrial case-study

3.1. Case description

The case study refers to a production system in a real industrial company from the aerospace sector. It produces large-size critical mechanical components with extremely high-quality requirements. They produce hollow shafts for aero turbines. Hollow shafts are high added value parts, production process of which is long and complex, mainly because of technological issues and quality aspects. Considered manufacturing is characterized with a steep price of machine failures and human connected errors.

Therefore, efficient resource management is required to reach the defined production goals.

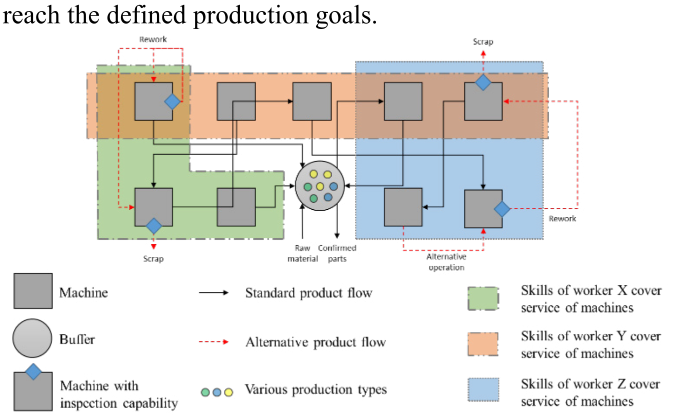

Fig. 3. Graphical representation of the production system at GAN.

The production system consists of a job shop, as depicted in Fig. 3. Operation plan of each unique part is created according to the technological sequence that depends on part product type. There are standard and alternative operations in operation plans of part types and each rework may cause a sub-cycle of different operations. In such conditions it is vital to form efficient working groups in shifts where every worker contributes into skills pull to cover the service's demand of each machine. Also, each operation might be performed in different mode, modes define the level of operation process automation, consequently the level of the operator involvement, and the required time of his presence at the server station.

Complex routing of operation plans for each part production changes dynamically according to the planning and quality issues and establishes particular and non-stable demand of the workforce skills pool to serve the machines on the shop floor.

Workforce skills are of heterogeneous nature. Therefore, it is a challenge for production manager to form proper worker teams for the shift assignments in which skills of each worker would complement each other and cover the demands for station service of machines that are required to perform a given production plan in a required timeframe. This task becomes extremely complicated in crisis times, such as global pandemic, when planning problems become harder to solve because of workforce unavailability. Problem of workforce unavailability causes the issues that might be solved in efficient way only considering it jointly with planning and workload aspects, because with absence of some workers previous planning cannot be proceed and workload balance changes. In this way we consider all aspects of workforce availability.

When some workers are unavailable, especially those who are the most saturated and consequently do the much of work, other workers with their mix of skills have to substitute the required set of skills of unavailable workers. It is vital to possess a strategy of worker skills substitution in order to maintain production rates level or at least not to pass quality level and delivery on time level thresholds, where penalties for passing those thresholds might be critical for the economic condition of manufacturing company.

3.2. Numerical results

In this application, the relation between availability workforce in terms of skills and production performance has been investigated.

In particular, the following cases have been tested on the proposed DT:

- Case 1: workers possess homogeneous skills; operations are done in manual (i) and semi-manual (ii) modes;
- Case 2: workers possess heterogeneous skills; operations are done in manual (i) and semi-manual (ii) modes;
- Case 3: workers possess homogeneous skills; operations are done in manual (i) and semi-automatic (iii) modes;
- Case 4: workers possess heterogeneous skills; operations are done in manual (i) and semi-automatic (iii) modes.

Results of test are shown on the Fig. 4 and Fig. 5.

On the figures, cases where workers possess homogeneous skills are marked with red colour, meanwhile cases where workers possess heterogeneous skills are marked with blue colour.

Fig. 4 shows the clusters of results for the Total Throughput TH with respect to the TNPO.

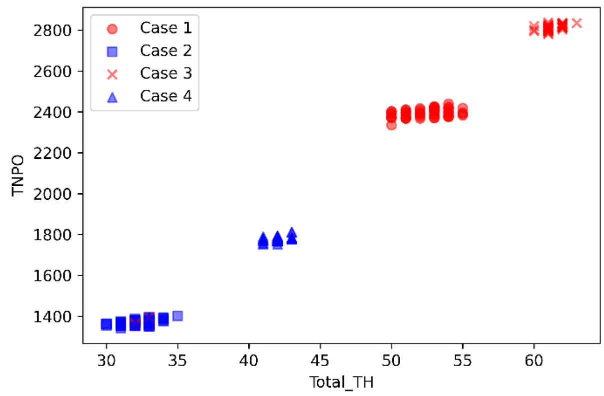

Fig. 4. Total TH and TNPO.

In Fig., the weekly throughput variance VarTH and total number of performed operations TNPO are shown, in relation to the overall system throughput TH, for the cases described above.

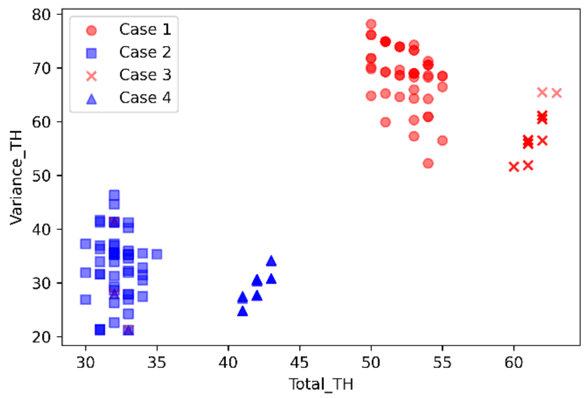

Fig. 5. Total TH and Variance TH.

It can be noticed that each of the tested cases provides insights on the relation between the production strategy and the workforce availability. For instance, when operators have horizontal capabilities (Cases 1 and 3), the overall productivity benefits from it because as soon as an operation is required, all operators can attend it. On the other hand, variance increases because operators work alternatively on parts which are almost close to completion, and on parts which are still at the beginning of the process chain. In this context, variance does not represent a negative aspect of the production system. However, given the workforce availability, the production strategy should be optimized in order not only to satisfy the required weekly throughput, but also to minimize the expected variance.

When the workforce availability is based on vertical skills, i.e., dedicated, and specialized expertise (Cases 2 and 4), the so-called 'interference problem' might occur: as soon as a specific operation is required, the operators who could attend it are busy elsewhere, and therefore the part must wait, and time is lost. Indeed, both TH and TNPO is always smaller than in the other two cases. However, this does not hold for the expected variance VarTH. In fact, given the lead times longer than one week, VarTH depends strongly on the production strategy. Therefore, according to the specific production plan, the minimum VarTH can be obtained with vertical (Case 4) or horizontal competences (Case 3).

This would suggest the further analyses should be conducted on the effect of the planned production status on the operator assignment. Indeed, different workforce availability may lead to alternative production plans for effective production operations.

4. Conclusions

In this work, a methodology for the evaluation of the effect of workforce availability is presented. The methodology formalizes the modelling of operators and operators' tasks in a manufacturing system within a Digital Twin. The innovative aspect is given by the general data model which is used by the DT to integrate information about the workforce availability and current production status about planned production. The method is implemented in a real case of the aerospace sector, which includes a job-shop production system and operators characterized by different skills. Results show that the proposed Key Performance Indicators capture quite well the effect of workforce availability on the overall manufacturing system. Also, the close relation among production planning and workforce availability is proved in the industrial case study.

Future research will be related on how this method can be used by companies to understand which skills are crucial for efficient production operations, as well as how to use the proposed approach as optimization kernel for a joint production planning and operators assignment problem, in order to maximize the service level on the medium and long term..

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