A Digital Twin-based Approach to the Real-time Assembly Line Balancing Problem

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Abstract: The emergence of technologies linked to the Industry 4.0 paradigm is increasingly influencing the design and management of production systems. However, applications related to assembly lines are scarcely explored in the literature. Hence, in this paper, a Digital Twin-based approach to real-time assembly line balancing problem (ALBP) in the i-FAB learning factory of Università Carlo Cattaneo – LIUC is presented. The results show that the implementation of a Digital Twin (DT) can enhance the overall productivity of a manual assembly line to smooth the effects of disruptions.

1 INTRODUCTION & REVIEW OF THE STATE OF THE ART

The interest in the topic of Digital Twin (DT) in the literature presented a steady growth in the last few years. This strong rise in the study of DT-related themes can be attributed to the massive use of the technologies related to Industry 4.0 paradigm (Havard, Jeanne, Lacomblez, & Baudry, 2019). A DT can be defined as an integrated simulation technology, which aims at developing a model of the environment that has to be fed with real-time data, in order to provide high fidelity of the overall system (Saporiti., Cannas, Pirovano, Pozzi, & Rossi, 2020; Tao, Qi, Wang, & Nee, 2019). The real-time communication system that characterizes a DT represents one of the main issues of its implementation as well. As a matter of fact, in order to successfully implement and develop a DT, there is a relevant need for an intense gathering of data from sensors as well as a robust and fast computing system (Negri, Fumagalli, & Macchi, 2017).

A few works dealing with the interactions between DTs and human operators were proposed. Many of these works focus on the development of Human-Machine Interfaces to enable collaboration with robots (Segura et al., 2020). Other works related to DTs and manual operations face the problem of ergonomics by integrating a model of human operator (Greco, Caterino, Fera, & Gerbino, 2020). Moreover, a DT was developed to acquire data for monitoring human activities in manufacturing and to process them for improving ergonomics as well as to allow workstation reconfigurations (Nikolakis, Alexopoulos, Xanthakis, & Chryssolouris, 2019). In addition, the modeling of human behavior was considered to perform the optimization of the manufacturing processes (Bécue, Maia, Feeken, Borchers, & Praça, 2020). A DT for improving workers' ergonomics is discussed also in the work by Fera, which considers the monitoring of the balancing of the line as well (Fera et al., 2020).

From a system-oriented perspective, some methodologies were proposed integrating DT models of the operators to include them in the production control decision-making. Graessler and Poehler developed a self-controlling assembly system that integrates a real-time control approach based on a DT capable of replicating the behavior of the operator (I. Graessler & Poehler, 2018). Another work from the same authors dealt with matching operators with assembly tasks using a DT (Iris Graessler & Poehler, 2018)

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Looking at the background of the problem addressed in this paper, the relevance of the assembly line balancing problem (ALBP) in the manufacturing sector is well known and was subject to recent developments.

The problem of optimally dividing (i.e. balancing) the assembly tasks among the available stations in order to minimize or maximize one or more objective functions is known as ALBP (Scholl & Becker, 2006). In particular, Cakir developed a Simulated Annealing (SA) algorithm to deal with assembly line balancing considering a certain degree of stochasticity in the task times (Cakir, Altiparmak, & Dengiz, 2011).

Altekin and Akkan defined line rebalancing as the way to change the tasks and assignment of tasks to stations and proposed a model to cope with failures and recover performance losses (Altekin & Akkan, 2012). Yang stated that assembly line rebalancing has to consider not just performance improvements, but also the adjustment costs (Yang, Gao, & Sun, 2013). Often, assembly line rebalancing is performed due to variations of some parameters such as task times, cycle time, or even product features (Gamberini, Grassi, & Rimini, 2006).

Huo studied a fuzzy control logic for real-time assembly line balancing (Huo, Zhang, & Chan, 2020). The authors focused on machine health states to define triggers for rebalancing the line.

Despite the growing interest in DTs, and the relevance of the ALBP in the manufacturing engineering sector, to the best of our knowledge, no application to solve the ALBP based on the use of DTs is available in the literature.

This paper proposes the implementation of a working DT in i-FAB, the learning factory of Università Carlo Cattaneo – LIUC is presented (Figure 1). In i-FAB, a series of production activities aimed at enhancing the knowledge of university students, as well as company employees and managers, about the themes of Lean Manufacturing and Industry 4.0 paradigm, are carried out. As a matter of fact, in i-FAB the operators perform complex assembly tasks, representing, therefore, an assembly line that could be considered as fully manual.

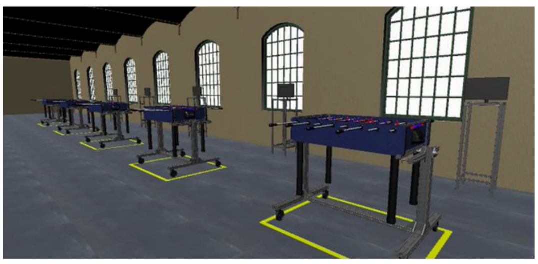

Figure 1: i-FAB: learning factory of LIUC.

The learning factory developed by LIUC presents a series of workstations that allows to fully perform an assembly of different kinds of complex products and to deliver the final product to the quality check department. The number of workstations is variable, the layout is flexible, and the main goal is to enable a production that respects the takt time set in advance.

For the purposes of this work, the number of workstations was set to five and they were arranged in a line. The layout of the assembly line is sketched in Figure 2.

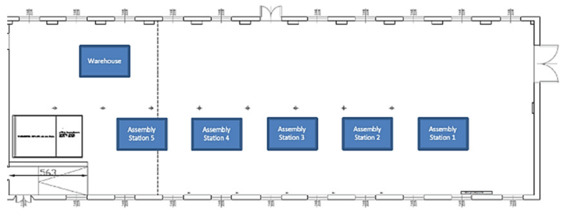

Figure 2: i-FAB layout.

A DT model has been built in order to enhance the overall productivity of the manufacturing system, thanks to a real-time balancing of the assembly line.

In this context, this work aims at answering the following research questions:

- What is the impact of a DT in an ALBP?
- What are the advantages of a DT in a human-intensive assembly line?

This paper is structured as follows. Firstly, the research design is presented, and therefore, gaps and objectives of the research are discussed (section II). Secondly, the research approach is described by presenting the adopted modeling methodology (section III). Thirdly, the main findings of this work are presented (section IV). Finally, a discussion on the results as well as on limitations and future research directions of the paper is carried out (section V).

2 RESEARCH DESIGN

2.1 Gaps

From an analysis of the literature, some gaps emerged which are to be tackled by this work. Indeed, these gaps are relevant to drive the development of the work.

- Only a few papers face the issue of real-time line balancing problem, although this could be of great potential to maintain high system performances in case of disruptive events.
- No author has studied the interrelationships between line balancing problems and DTs,

even though these appear relevant issues, in light of the importance of the ALBP in the manufacturing engineering, on one hand, and of the potential due to the synchronization with field operations favored by the use of DTs, on the other hand.

- DTs considering operators under a system perspective are scarcely found in the literature. Nevertheless, it is interesting to study the effects of local variability induced by the operators on the performances at a system level, i.e., the line. This is not a novelty per se, its innovativeness lies in the context of a DT-based approach and real-time assembly line balancing.

2.2 Objectives

The main objective of this work is to develop a DT of a human-intensive assembly line to improve overall system performances. In order to achieve this, a new methodology for real-time ALB based on DT will be defined. Moreover, this will assist in the exploration of the potential of DTs in fully manual assembly systems.

3 MODELLING METHODOLOGY

3.1 Hypotheses & Mathematical Model

Hereafter, the mathematical model of the problem addressed by this work is presented. Task durations are expressed in seconds [s].

i,h=1:n tasks index

G=(i,h) directed acyclic graph

k=1:m station

ξ scenario, it includes the various errors states that could happen to the assembly line (error states are adopted to represent the disruptions, deeply described in section 3.2)

t_i average task duration [s]

t_i^{ξ} average task duration under a scenario ξ [s]

$$x_{ik} = \begin{cases} 1, & \text{if task i is assigned to station k} \\ 0, & \text{otherwise} \end{cases}$$

$\forall$ i=1,…,n; $\forall$ k=1,…,m

We define the workload on a certain station as:

$$w_k^{\xi} = \sum_{i=1}^{n} t_i^{\xi} x_{ik} \ [s] \quad (1)$$

Cycle time is assumed as the maximum value among stations workloads:

$$C^{\xi} = \max w_k^{\xi} \ [s] \quad (2)$$

In addition, we define the Smoothing Index (SI) as:

$$SI^{\xi} = \sqrt{\sum_{k=1}^{m} \left(C^{\xi} - w_k^{\xi}\right)^2} \quad (3)$$

SI is a relative index commonly used for measuring the balancing of an assembly line, accounting for the differences in the workload of the stations. Hence, it allows the comparison between different system configurations.

The objective of the optimization problem is to minimize the SI:

$$\min SI^{\xi} = \sqrt{\sum_{k=1}^{m} \left(C^{\xi} - w_k^{\xi}\right)^2} \quad (4)$$

The constraints of the problem must ensure that any task is assigned to one and only one station:

$$\sum_{k=1}^{m} x_{ik} = 1 \,, \ \forall i=1,\dots,n \quad (5)$$

Besides, precedence constraints must be respected:

$$\sum_{k=1}^{m} k x_{hk} \leq \sum_{k=1}^{m} k x_{ik} \quad \forall (h,i) \quad (6)$$

3.2 Solution Method

The proposed solution method for the ALBP is depicted in Figure 3 and relies on a DT-based methodology including a SA algorithm.

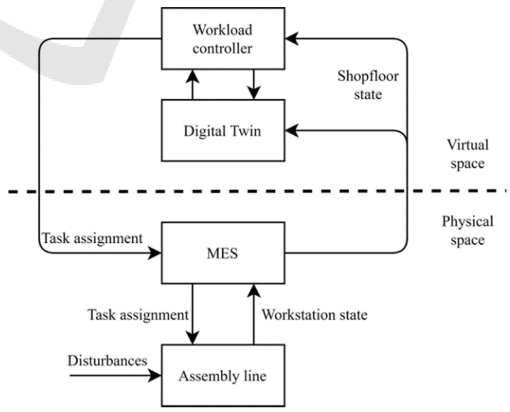

Figure 3: Solution method for ALBP.

The physical assembly system in the lower part of the block diagram is provided with local computers connected to the Manufacturing Execution System (MES). This allows communication between each workstation and the centralized information system. The MES is the connection point between the physical and the virtual domain: here the DT and the real-time line balancing module (designated as workload controller in the figure) lie. The former consists of a Discrete Event Simulation (DES) model which is connected to the MES to gather information related to the current situation of the shop floor. The latter collects just the data related to eventual error states to be addressed in order to improve the workload balance. Furthermore, workstation state may represent either proper functioning state or any error state.

In fact, the whole system remains silent until it is triggered by the MES, which is responsible for detecting errors states related to three main causes:

- Lack of materials, which does not allow the execution of a certain assembly task for which a specific material is required;
- Lack of equipment, which does not allow the execution of any assembly task for which a given tool is necessary;
- Lack of operators, which does not allow the execution of the tasks strictly requiring two operators. Moreover, this increases the completion time of all the other tasks by 50% on average, due to the lack of parallelization of part of the work.

The recovery from a given error state is considered as a trigger itself.

The workload controller solves the ALBP thanks to the SA algorithm (Figure 4) and tests the solution on the DT of the line. The behavior of the system considering the new assignment of the tasks is compared to the present one: only in case a significant performance improvement is detected, the new solution is implemented. The decision is then feedbacked to the MES, which is responsible for actuating eventual changes in the task assigned to each workstation.

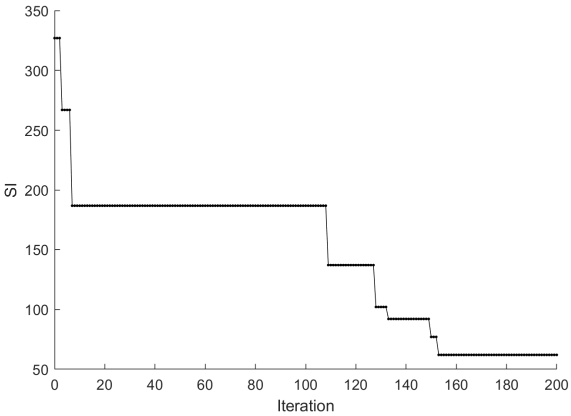

Figure 4: Simulated Annealing algorithm.

The nervousness of the system is mitigated by the introduction of an ad-hoc heuristic in the workload balancing module. This function allows preventing changes in the assignment of the tasks in case the improvement does not reach a certain threshold. Indeed, the DT predicts the system behavior in the following 15 minutes simulating both the current and the proposed solutions to the ALBP, which consist of the allocation of tasks to workstations.

To accept the new assignment, for each task moved from a station to another one there must be a significant improvement in the lead time of an assembled product (i.e., a job) completed in the DT prediction window. The lead time of a job is computed as the difference between its enter and exit times.

It has to be remarked that, for the development and testing phases of the proposed methodology, a physical twin of the assembly line was realized, according to the definition by Ait-Alla (Ait-Alla, Kreutz, Rippel, Lütjen, & Freitag, 2020). The physical twin consists of a DES model which replicates the behavior of the physical system.

3.3 Software/Tools/Languages

In order to develop the DT model, two main software tools has been exploited, i.e., MATLAB® and R/RStudio.

The former has been used as a computing system. As a matter of fact, Simulink has been used to develop the simulation model of i-FAB. In this sense, the model has been built as a simulation meta-model, based on the number of active assembly workstations on the shopfloor.

The latter has been exploited in order to integrate the MES system of i-FAB with the newly developed DT. Hence, the MES itself of i-FAB has been developed in RStudio, and in particular as a ShinyApp. However, several code changes in the main body of the MES were needed. These were aimed at performing two main tasks. Firstly, RStudio has been used as an interface to the real physical part of the factory in order to gather data and to rearrange them in the best form. RStudio monitors mainly two kinds of information. Firstly, there is a constant check of the overall condition of the factory, as every piece and every activity are tracked from the very start to the delivery of the finished product. Secondly, R/RStudio and therefore the MES itself monitor a series of events that are reported by the operators as errors. The gathered and reworked data constitute the input of the simulation performed on Simulink. Secondly, after that the simulations have been performed, R/RStudio gathers the results and transmits the data to the MES of i-FAB. Subsequently, the MES pushes the information about the balancing of the assembly line directly to the shopfloor, thanks to the monitor that is embedded in every workstation in the factory. Therefore, the operators are constantly updated about the next activities to be performed. As depicted in Figure 5, the joint use of R/RStudio and MATLAB allowed closing a double data loop that connects the real world to the virtual one.

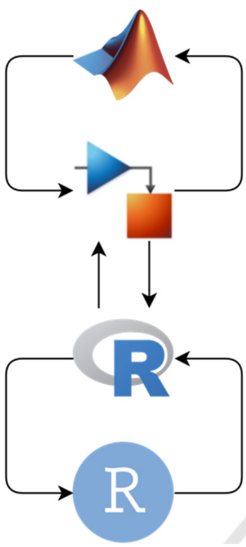

Figure 5: Software architecture data loop.

Hence, data first flow from the physical shopfloor to R/RStudio and then to the MES. Afterward, data are elaborated and simulations are performed by Simulink. Finally, results flow back to the physical world thanks to the use of monitors to communicate with the operators on the workstations.

4 FINDINGS

The proposed methodology allows the exploitation of the DT paradigm on a system constituted of a manual assembly line. As a matter of fact, it is possible to control the line by assigning tasks to the workstations in real-time after (re)-balancing the workload.

The architecture developed permits to effectively use a DT to solve the real-time ALBP. The workstations have been modelled considering nondeterministic assembly times due to the performance of the operators, allowing to provide more robust solutions.

From a system performance viewpoint, the proposed work is able to grant some improvements.

An experiment was performed considering the following conditions. An error state induced by the lack of an operator in a workstation was in action for 45 minutes (i.e., 2700 seconds). The error occurred after 45 minutes from the beginning of the experiment.

The results of the performed test are two-fold as they entail both workstations utilization and lead time of the assembled products.

The utilization of the workstation where the error occurs increases drastically with respect to its normal operating condition. In fact, as depicted in Figure 6, its value approaches the upper limit of utilization, i.e., one. On the other hand, when the DT is active, in the same situation it is possible to remarkably mitigate the effects of the error on the utilization level. As a matter of fact, the increment of this value is limited to approximately 0.15, thus reaching a maximum value of nearly 0.8.

Figure 6: Comparison Utilization DT/Standard.

Furthermore, in Figure 7 the comparison between the lead time of the jobs in the standard situation (without the use of the DT) versus the one using the DT is provided.

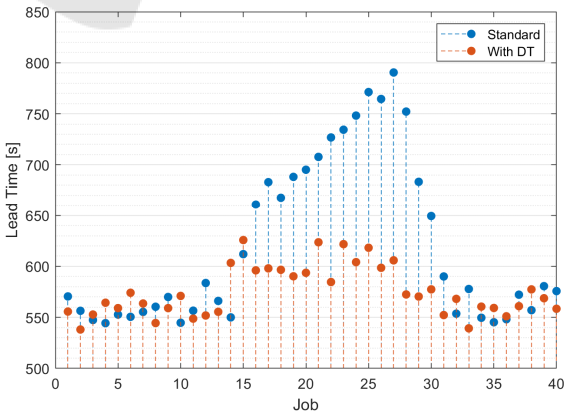

Figure 7: Comparison Lead Time DT/Standard.

As it can be noticed, the DT grants a remarkable improvement in the lead times when the error state arises. In the standard situation, the occurrence of an error implies a relevant increase in the lead time of the jobs, whereas, in the case of the use of DT, this increase in time is far lower. On average, the lead time of the jobs affected by the error state is 113 seconds lower with respect to the case without the DT. Indeed, we can notice an improvement of 16.0% in the overall system performance under the error condition.

Hence, the DT can represent a valid instrument in order to enhance the solutions of an ALBP.

As a matter of fact, the reactivity of the system is strongly enhanced as assembly tasks are re-assigned by the DT as soon as some error state is identified on the MES.

The centralized control of the system leads to an overall increased autonomy of the manual assembly line. In this sense, the DT permits the system to self-optimize its behavior, according to the analysis of the current state of the line and to the predictions provided.

Finally, the proposed methodology is also capable to cope with the discussed errors through line rebalancing but avoiding any nervousness of the system.

5 CONCLUSIONS

This research presents an introductory model of a DT aimed at approaching a real-time balancing problem in the learning factory of Università Carlo Cattaneo – LIUC, i.e., i-FAB. The results show that the use of a DT can be highly beneficial for the entire manufacturing system, even in the case of a manual assembly line. Indeed, the DT can be exploited in order to dynamically enhance the line balancing on the workstations with respect to the different error states that could possibly happen on the shopfloor. Hence, the use of a DT can lead to a remarkable reduction of the increase in the lead time of the jobs and in the utilization of the station in which the error occurs.

However, several limitations can be found in this study. Firstly, the number of experiments performed in i-FAB on the DT could be greatly increased. As a matter of fact, inthis work, only a few experiments were performed, mainly aimed at validating the features of the DT as well as the right flow of data and information from and to the field.

Secondly, in this model, the operators are permanently assigned to their initial workstation. Indeed, operators are not allowed to move from a station to another one no matter the event/error states that occur, even if this could lead to improvements to the overall performance. However, this limitation is quite representative of the real behavior of the operators in i-FAB. Hence, in the learning factory operators generally are not allowed to move to another workstation unless in very particular situations.

Additionally, some future research directions can be derived from this research that could be addressed in upcoming works.

First of all, in future work, a larger experimental campaign should be held with a twofold purpose. Firstly, deeper data gathering could be exploited in order to fine-tune the main parameters of the model. This could lead to higher reliability of the overall DT. Secondly, a larger experimental campaign could be a valid tool to enhance the validity of this research.

Furthermore, in future works, it could be of high interest to perform tests on different manufacturing systems. It could be interesting to consider the interaction with co-bots, AGVs as well as the application of the DT model to semi-automatic lines. This could represent major future applications to research on; this would give a context where tasks assignment may be considered with various levels of flexibility due to the available resources, being concerned also of different levels of skills and roles for the operators. Closely related, another future research direction could lay on the possibility to include the mobility of the operators among the workstations on the shopfloor. Indeed, this feature could represent a relevant enhancement of the validity of the model, as well as a resolution for a limitation of this research.

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