The Application of Simulation in Facility Layout Design of an Industry 4.0 Factory

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Abstract. Facility layout planning (FLP) is one of the most discussed industrial topics that affects the performance of a manufacturing system. Conventional approaches have extensively focused on quantitative analyses with a primary focus on cost minimization. The recent technological development in computer-based simulation has provided powerful tools to better visualize and test different layouts in an easier way. In this study, a graphical simulation package is used to showcase the design of a cellular production plant, where the design principle is based on the flexible manufacturing system. The proposed virtual factory demonstrates the possibility of solving FLP challenges under intra-logistics factors in an intuitive and interactive manner. The proposed approach can be highly beneficial for manufacturing companies, especially small-and-medium-sized enterprises (SMEs).

Keywords: Virtual Technologies, Facility Layout Planning, Simulation, Smart Manufacturing, Virtual Factory

1 Introduction

The manufacturing industry has experienced significant improvements throughout the last decades, and the role of technological development has become increasingly important. The emergence of new customer demands and cutting-edge methodologies makes today's manufacturing process and production management become more complicated. While these improvements have generally favored organizations to increase their responsiveness to demand fluctuations and other sorts of uncertainties, the effec-

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tive implementation of new technologies is still under investigation. Among other operational factors, facility design is substantially crucial for the overall performance of manufacturing systems both in the short-term and in a long run [1]. Given material handling as a key driver, extensive research has been carried out to minimize the time and/or expenses associated with facility design [2]. Although various quantitative methods have been introduced to address this target, less attention has been paid to other logistical indicators of the facility layout planning (FLP) [3, 4]. Thus, a more intuitive and interactive method may be used to better achieve cross-functional platforms and reliable decisions [5, 6]. Thanks to the latest technological advancements of the fourth industrial revolution, namely Industry 4.0, several virtual technologies, i.e., simulation, augmented reality (AR), and virtual reality (VR), have been substantially developed to serve a wide range of industries and public sectors with viable digital solutions [7].

The application of the latest virtual technologies in FLP is, however, still in its infancy, and more efforts are required to achieve a concrete and systematic approach that facilitates the real-time evaluation of various system configurations and logistical drivers. This purpose can, however, hardly be achieved with traditional mathematical methods that suffer from a lack of powerful result visualization and interactivity. Thus, this research aims at investigating the FLP with a cutting-edge simulation package, and the result is shown through the development of a tailored virtual Industry 4.0 factory.

The rest of the paper is organized as follows. A literature review is conducted in section 2, which highlights the conventional approaches of FLP and investigates the recent digital solutions. Section 3 proposes the digital model and elaborates the practical steps to establish the facility layout. In section 4, the advantages, potentials, and current limitations of this approach are discussed. Section 5 concludes the paper and sheds light on further research directions.

2 Literature Review

2.1 Facility Layout Planning in Manufacturing Systems

FLP is one of the key elements of manufacturing logistics, which has a significant impact on the overall performance of a company. Various definitions have been given, and it is mainly referred to as a decision-making process that seeks the optimal design and arrangement of the equipment to increase efficiency [8, 9]. FLP involves several drivers, i.e., the adjacency of facilities, the distance between facilities, etc. [2]. However, there is a strong consensus on the material handling system (MHS) as one of the most influential factors in this context. Depending on the significance of other cost drivers, the MHS could constitute up to 50% of the operating cost and 70% of the total cost of a produced item [1].

Facility design decisions vary accordingly to minimize the key cost drivers, i.e., transportation, inventory on hand, etc. In this regard, cellular layout, product layout, process layout, and fixed product layout are the most investigated arrangements [10]. Making such decisions needs to consider the trade-off between production quantity and variety, by which one seeks to optimize the material handling cost, work-in-process (WIP), manufacturing lead time, and other indicators. For instance, in cellular layout or cellular manufacturing system (CMS), machines and equipment are grouped such that each department is responsible for processes corresponding to an individual part family [11]. Additionally, FLP must align with today's competitive market to facilitate agile and adaptive production, which is one of the profound features attributed to a small-scale intelligent manufacturing system (SIMS) [12]. Given flexibility and reconfigurability as two of the core criteria of SIMS [13], the role of recent manufacturing paradigms, i.e., flexible manufacturing systems (FMS), reconfigurable manufacturing systems (RMS), etc., becomes even more magnified. Although the outlined manufacturing paradigms benefit from novel technologies, e.g., industrial robots, CNC machines, etc., their success can be substantially influenced by the equipment configuration, and therefore, decisions in this regard are cross-functional.

2.1.1 Facility Layout Approaches

The decision about the equipment arrangement is treated differently concerning the uncertainty. Given material flow as one of the key drivers of FLP, many researchers dealt with this challenge by making one assumption: the absence of modifications during the analysis. This perspective, known as static facility layout problem (SFLP), is a deterministic approach that optimizes the shop floor design without considering the variable factors during the planning horizon, e.g., production volume, changes in the product design, etc. [14]. On contrary, the dynamic facility layout problem (DFLP) attempts to incorporate the potential changes and approaches this challenge as a series of static problems [3]. The DFLP seeks to minimize the aggregate material handling and rearrangement costs according to a set of probabilities during the forecasted periods [15]. While several advantages are delivered through these methods, the role of the randomness of other logistical drivers, e.g., customer demand, etc., are disregarded, and thus, a stochastic approach could lead to more realistic inferences. Extensive research works have been carried out to address this problem through developing new models and metaheuristics, e.g., quadratic assignment problem (QAP), mixed integer programming (MIP), graph theory (GT), etc. [16]. However, a thorough survey reveals that more efforts are required to incorporate other logistics goals into such problems, i.e., the design of the working cells, etc. [4]. These concepts are interconnected and can impact the decisions of the equipment arrangement. For instance, mobile robots and conveyor systems have significant differences in terms of flexibility, capacity, versatility, etc., which impact the production performance and the decisions related to facility design. Hence, an interactive environment that enables dynamic visualization and real-time evaluation of the design alternatives is highly preferred to increase the reliability of the decision-making [5, 6].

2.1.2 Digital Solutions

Digital solutions have favored FLP with new methods, which may not only provide a dynamic and interactive environment but also incorporate other aspects of production and logistics. Simulation is one of the most powerful digital solutions and versatile platforms, which can be used to perform thorough analyses of dynamic systems and examine various scenarios. One study argues about the use of simulation as a means of a post-design study to analyze the associated configuration performance. For that purpose, the computer-aided design (CAD) file of the facility layout is incorporated into a discrete event simulation (DES) environment [17]. The graphical representation uses static images of the respective machines and equipment, while the flow of materials is the dynamic element. Recently, simulation and graphical modules have experienced considerable improvements with significant leap in virtual technology. In one research, virtual reality (VR) is utilized to assist the facility design process in an interactive manner [18]. However, several limitations are pointed out, including the integration with other design aids and the technical drawbacks in terms of software performance. Thanks to the hardware and software improvements, this approach is recently further developed to assist the design modification and appraisal of an existing workstation [19]. By integrating CAD files with the virtual environment, this research replicates the facility layout using 3D scanner and uses various platforms for demonstration, i.e., desktop system, wide-screen projection, and immersive VR system.

The studies discussed above depict an increasing trend in using advanced virtual solutions in facility design and FLP. These research works attempt to demonstrate the technical aspects of using novel methodologies and tools; however, it is of significance to highlight the various policies one can benefit from to best tackle the existing challenges. In this regard, a general framework is proposed, which encompasses two different ways of utilizing simulation for FLP [20]. The first perspective considers the facility layout decisions before the simulation studies, which is more suitable for deterministic problems with a limited focus on MHS cost. The latter, however, makes the layout decisions in the post-simulation stage to best deal with the uncertainties by modifying the production system.

2.2 Industry 4.0 and Virtual Factory

The manufacturing industry has witnessed and benefited from substantial developments in technology throughout the globe, particularly within the last decade. These improvements in production and operation management have led to the advent of Industry 4.0 (I4.0). This exquisite paradigm shaped many research directions according to two main concepts [21], namely intelligent analytics and cyber-physical systems (CPS). While the former has a concrete focus on novel methodologies in statistics, analytics, optimization, and so forth, the latter has a predominant role in achieving the goals set by I4.0 according to a comprehensive structure that depicts the significance of connectivity and intelligence in every layer of a production plant [22]. This framework is further elaborated through the projection of the involving steps onto a bilateral correlation between intelligence and automation, with an emphasis on the pure digital components of I4.0 [23, 24]. Given simulation and augmented reality (AR) as the core elements in this regard, the concept of virtual technologies (VT) was put forward, which provides an in-depth modelling platform to perform analysis of or ideate a manufacturing plant [24]. The versatile and profound structure of such digital solutions has proven promising performance by utilizing the VR from three major perspectives: design, operation management, and manufacturing processes [25]. Although establishing the connection between the virtual environment and the real world is still in its infancy, the advancement in digital solutions and their impact is inevitable. For example, one preliminary research depicts the advantages of a virtual factory with a robotic additive manufacturing (AM) process, and the potential effects on the production are discussed. However, the layout design is less focused on [26]. This approach has a key role to investigate feasible solutions at the shop floor level. In this regard, the results of a recent survey, conducted among 100 manufacturing decision-makers in the United Kingdom, highlight some of the major mistakes committed in implementing robotics and automation solutions, which might be avoided by using VTs [27]. The wrong focus point in bottleneck recognition and robot reachability are among the top five factors that novel digital tools can resolve.

2.3 Literature Gap and Scientific Contribution

Facility design and FLP are the key factors that affect the overall performance of a manufacturing plant from both financial and operational perspectives. Based on the expenses, limitations, and complexity associated with the rearrangement of equipment, important decisions need to be made. This is inherently a dynamic issue because companies are required to expand or change their equipment for several reasons, i.e., market fluctuations, changes in the production capacity, technological improvements, etc. The development of VT has provided new opportunities. However, some of the tools such as VR fail to provide an efficient interactive environment or incorporate operational aspects of the manufacturing system into the model [4]. Thus, in this paper, we use a state-of-the-art simulation package to develop a dynamic and interactive virtual Industry 4.0 factory, which provides powerful visualization of the manufacturing process and can be used to test different configurations. The features of the virtual Industry 4.0 factory are discussed as follows:

- Designing a cellular layout in an interactive environment and leveraging the routing flexibility.
- Proposing pragmatic solutions to logistics problems, i.e., bottleneck, queue accumulation, etc.
- Demonstrating the human interaction with the equipment and processes within the manufacturing plant.

3 Modeling and Methodology

Tailoring specific requirements of a manufacturing system for the influencing factors, e.g., market demand, product type, production volume, etc., impact the production performance. A well-designed layout may reduce potential expenditures and assists companies to better cope with future uncertainties. Considering the I4.0 features, this section presents a graphical simulation to model a production plant. The layout configuration is first conducted concerning the principles and attributes of FMS and I4.0 [23].

In this study, a cellular layout is put forward to examine various arrangements by leveraging the MHS and to process grouping as the key drivers of FMS [28, 29]. The proposed manufacturing plant constitutes the production and assembly of engine blocks and pistons, which are delivered in the final package for either large-scale or single sale. Some of the challenges in the design phase are related to investigating the possible approaches of MHS, minimizing the fixed structures for material flow as a means of flexibility, logical grouping of operations, discovering the potential bottlenecks, visualizing along with resolving equipment collisions and conflicts, and so forth. The production flowchart is depicted in Fig. 1.

The Visual Components 4.2.2 simulation package is used in this research, which provides a comprehensive 3D environment including more than 2,700 components, i.e., parts, robots, machines, equipment, etc. The operations and dynamic features are coded with python programming, which helps to establish customized connections between equipment and workstations and material flows in an intelligent virtual production system. Besides, the software is also well-adapted to import 3D objects as CAD files. In this study, the manufacturing parts are selected from the internal database with minor adjustments of the orientation of their origin coordination frame. The production cells create three family parts including engine block, piston head, and piston rod. The engine block is fabricated by the sand cast method, while the piston rod and head are manufactured by machining processes from the blocks of raw material. Since the engine production emits hot air, the area allocated to this unit is not as congested as the other manufacturing cells. Each individual production unit is equipped with several machines that are operated in parallel to increase productivity and throughput. An intelligent robotic system is designated in each unit to load and unload the machines using the latest available technologies to minimize the occupied space by each work cell. Production cells are followed by quality control (QC) stations; however, the engine blocks require post-processing before the QC stage. The QC units are organized in an automated manner except for the piston rod, where two human workers interact with machines and parts to accomplish the QC tasks. The unqualified parts are labeled in order to filter

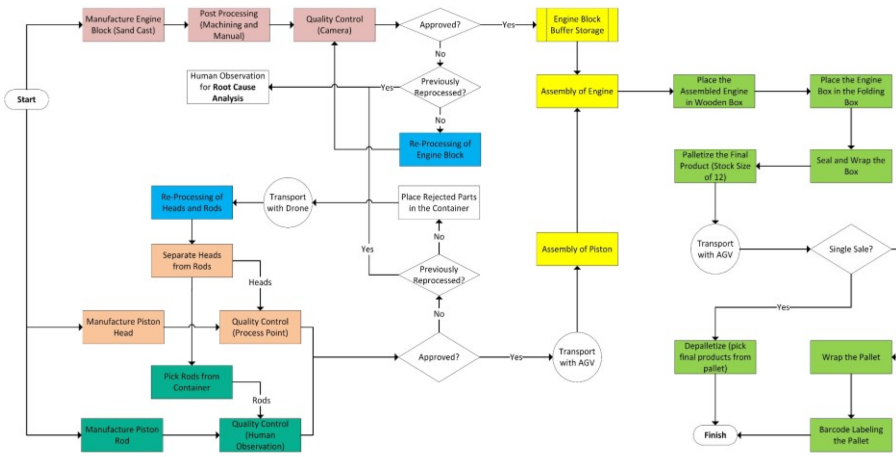

Fig. 1 Manufacturing flowchart

them out in the successive stage. This idea can be implemented by RFID technology or QR codes in practice so that robots or automated processors can read and perform the necessary task accordingly. A reprocessing department is designated to fix the defects of the rejected parts and reduce the production waste. This workstation is adjacent to the engine block production department to minimize the transportation time and cost associated with this heavy item. On contrary, the unqualified piston rods and heads are accumulated in a box and transferred by a drone, which is a helpful method to reduce the complexity of the internal logistics system and to increase flexibility. In case that the reprocessed parts fail to satisfy the QC qualifications, they are transported to the quality assurance department for root cause analysis experiments. The assembly of manufactured parts takes place afterward, where eight pieces of piston rod and head are assembled and then installed inside the engine block. Regardless of the engine block, which is relatively heavy and transported by conveyor, the other parts are transported by automated guided vehicles (AGVs). To resolve the observed bottleneck within the assembly department, two policies are implemented. Firstly, the engine blocks are stored inside an automated storage and retrieval system (ASRS) upon arrival and individually released once eight pistons are assembled and transferred to the final assembly position. To increase productivity, an optical sensor is used, which sends a signal to retrieve an engine block after counting eight assembled pistons. Secondly, the AGVs load eight pieces of each part for the piston assembly to eliminate any unnecessary movements. It is worthwhile to mention that this approach has a direct positive impact on the production flexibility by adjusting the workload and task schedule of mobile robots according to the changes in the product batches. For instance, producing engine blocks with various volumes, which bears a difference in the required number of pistons. This policy enables the effective adaption of the MHS. Another flexibility policy is applied where the assembly department is equipped with another workstation, which is responsible for 10% of the assembly tasks. The robotic design and low utilization rate of this unit provide significant opportunities for production capacity flexibility or routing flexibility. Transporting piston components to this assembly cell is accomplished by an AGV, which transports 16 components. Assembled products are then packaged and transported by pallets in the batch size of 12 using a dedicated AGV. Automated and adaptable palletizing along with the utilization of mobile robots not only is consistent with capacity adjustments but also, more importantly, shapes the ground for further modifications within the packaging department by occupying the least amount of area for MHS. The packaging departments in manufacturing enterprises are highly prone to alterations during the planning horizon in order to adjust their capacity, and contingency policies are therefore of significant advantages. In the final step, product packages may follow two routes according to the sales schedule; the major route is designated for large-scale delivery where the pallets are wrapped and labeled with barcodes to be placed inside the lorries using a forklift. Alternatively, the individual packages are depalletized to be transferred to the sales department for a single sale.

4 Advantages and Limitations

Different from conventional quantitative techniques, this computer-based simulation model provides powerful graphical visualization (see Fig. 2 and Fig. 2), which seeks to address the design challenges in an intuitive, pragmatic, and interactive manner (link: https://youtu.be/alTxdfz8wyk). The proposed production plant is designed concerning the axioms of cellular manufacturing layout and flexible production. The devised departments are engine block production, piston head production, piston rod production, reprocessing, assembly, packaging, and delivery, quality assurance, as shown in Fig. 4. Colored circles represent the QC stations that are adjacent to their respective production cells.

Fig. 2 Assembly of engine and piston

Fig. 3 AGV transportation of piston components

One of the advantages of this approach is the possibility of monitoring the robot motions in its working envelope and detecting any potential collisions or unreachable target points to ensure effective design. In addition, the rich catalog of industrial robots provides many alternatives to explore the best solutions for the expected operations, which highly affects the costs and operational efficiency of the system. For instance, several pick-and-place tasks associated with the reprocessed parts are performed by Scara Robots that require less rotational movements. On the other hand, the packaging department is equipped with specialized robots for carrying heavy parts and palletizing

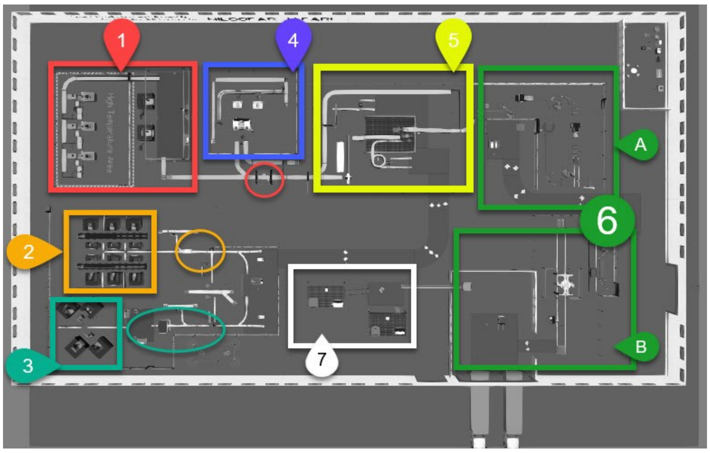

Fig. 4 Facility layout of the proposed manufacturing plant

purposes. Furthermore, production bottlenecks can be intuitively discovered. In our experiment, some alternatives were investigated to tackle the bottleneck in the assembly department by adding a buffer or adjusting the operation. The former is implemented by embedding a spiral conveyor and an ASRS unit in a synchronized and intelligent manner to prevent the accumulation of parts. The latter is, however, performed on mobile MHS that increases the routing and expansion flexibility. Moreover, this approach is strikingly beneficial to conduct studies regarding human interactions with the environment, i.e., efficiency, ergonomics, safety, etc.

The model forms the ground for further analytical studies of the manufacturing performance, e.g., machine utilization, throughput, and waiting time of parts in the queues, etc. However, performing these evaluations with this approach requires comprehensive model enhancement and a high level of hardware capacity, i.e., RAM, GPU, and CPU. To solve such challenges, discrete event simulation (DES) is an extensively used method, which should be operated under the same logic [30]. Although there is a compromise in the modeling time, the virtual factory could serve as a profound production plant for data collection in order to perform more detailed analyses within the DES environment. Another limitation is the modeling of the customized production processes, where some specialized equipment is not available within the software library. In such a case, the CAD file of the corresponding object could be incorporated into the simulation environment to interact with other components. For this purpose, the various characteristics and essential properties of the equipment must be defined manually, i.e., coordination frames, joints, color, material, etc.

5 Conclusion

This paper presents the application of advanced computer-based simulation in FLP of a virtual factory, which considers several logistics drivers of an Industry 4.0-enabled FMS. The production system can be visualized, and dynamically and interactively modified to solve the design challenges. The simulation model takes into account the principles of cellular manufacturing layout with a major focus on process grouping and optimizing the MHS. Several feasible options are investigated to better model the real-world system, such as using optical sensor technology, RFID, and so forth. In addition, the human interactions with the production system are considered to further evaluate ergonomic, labor utilization, as well as other factors related to the human's role in manufacturing.

This research illustrates the effectiveness of digital tools and simulation in FLP. As suggested by a survey [27], while almost 40% of the interviewed industrial sectors suffer from ineffective facility and automation design, their opinion on using simulation platforms is controversial. The majority of feedbacks reveal that their available solution neither is used efficiently nor satisfies the enterprise requirements. This is mainly due to the lack of expertise among the industries. In this regard, this research provides a more easy-going solution to help manufacturing companies, especially SMEs, with their FLP in the Industry 4.0 era. Moreover, combined with advanced analytical tools, e.g., DES, several key performance indicators can be measured to yield more comprehensive insights into the manufacturing process.

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