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Research Advances in the Application of FlexSim: A Perspective on Machine Reliability, Availability, and Maintainability Optimization

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Abstract: This paper discusses recent research advancements in the use of FlexSim for machine reliability, availability, and maintainability (RAM) optimization of manufacturing companies in discrete event simulations (DESs). An extensive collection of relevant articles was gathered from the literature and reviewed to provide useful guidelines for companies in boosting their overall profits via FlexSim simulation. The main areas in which FlexSim has been used are spare parts inventory management, queue scheduling policy, task allocation, overall equipment effectiveness (OEE), process capability (PC), maintenance planning, and scheduling. The use of FlexSim has been very successful in these areas for efficient system reliability, availability, and maintainability optimization. Based on the findings in this work, FlexSim provides the basics for estimating the primary performance metrics of machines, such as mean time to failure (MTTF), equipment down time (EDT), and system availability values (Asys) for RAM analysis. The details derived from the study will allow management to determine a system's RAM needs. However, the current FlexSim DES in manufacturing industries is based on individual RAM analysis, with no studies on establishing the relationship among the RAM components. The goal of this research was to highlight the possible ways to establish relationships in RAM studies for higher performance on equipment and quicker decisions when it comes to a choice of maintenance applications, especially when using the FlexSim software for DESs. Hence, improving the efficiency of the simulation results for both practical and academic applications. The study also provides tables and data that are useful for FlexSim-related simulations on RAM in industrial processing.

Keywords: discrete event simulation, FlexSim, RAM analysis.

弹性模拟应用研究进展：机器可靠性、可用性和可维护性优化的视角

摘要：本文讨论了在离散事件模拟(DES)中使用弹性模拟对制造公司的机器可靠性、可用性和可维护性(内存)进行优化方面的最新研究进展。从文献中收集并审查了大量相关文章，为公司通过弹性模拟模拟提高整体利润提供了有用的指导。弹性模拟的主要使用领域是备件库存管理、队列调度策略、任务分配、整体设备效率(整体设备效率)、过程能力(个人电脑)、维护计划和调度。弹性模拟的使用在这些领域非常成功，可实现高效的系统可靠性、可用性和可维护性优化。基于这项工作的发现，弹性模拟提供了用于估计机器主要性能指标的基础知识，例如用于内存分析的平均故障时间(平均无故障时间)、设备停机时间(美东时间)和系统可用性值(系统)。从研究中得出的详细信息将使管理层能够确定系统的内存需求。然而，目前制造业中的弹性模拟DES是基于单个内存分析，没有研究建立内存组件之间的关系。这项研究的目的是强调在内存研究中建立关系的可能方法，以便在选择维护应用程序时，尤其是在使用DESs的弹性模拟软件时，提高设备性能并更快做出决策。因此，提高了实际和学术应用的模拟结果的效率。该研究还提供了对工

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业加工中内存上的弹性模拟相关模拟有用的表格和数据。

关键词：离散事件仿真、弹性模拟、内存分析。

Fig. 1 Graphical abstract

1. Introduction

Despite financial uncertainty, the productivity, flexibility, and efficiency of manufacturing companies rely on their performance. Companies must therefore govern their processes. In addition, maintenance managers need to understand the maintenance cycle and the efficiency of the plant in boosting production facility efficiency. One of the major issues that maintenance managers encounter is the adoption of the most effective maintenance plan [1]. However, due to the present nature of industrial processes, diagnostic systems and methods for decision-making have become a necessity, especially in the maintenance management process, which is characterized by costly sophisticated equipment and strict environmental requirements. Maintenance is a combination of both technical and associated administrative measures taken to sustain the operation of systems, in particular electromechanical equipment, in order to guarantee that systems can perform their intended functions as appropriate [2]. Traditionally, the focus of maintenance has been on equipment availability [3]. Modern repair activities concentrate on increasing the performance of facilities; that is, they ensure that equipment is both usable and capable of delivering high-quality goods. In addition, maintenance plays a major role in the overall production environment. However, a simple assessment will not provide adequate information for optimal decision-making [4]. However, the impact of maintenance on the performance of equipment is not clear, and, therefore, it is very difficult to measure. As a consequence, a simulation-based optimization approach is required to improve the reliability of production processes in order to assess the performance of industrial systems [5]. Simulation techniques using discrete event simulation (DES) have proven to be the best so far that can be used in addressing manufacturing system problems, such as enhancing efficiency, stability analysis, the design of manufacturing and production systems, and the design of transportation systems [6]. There are several DES technological applications allocated to the simulation of the manufacturing process, such as Arena, Enterprise Dynamics, FlexSim, Plant Simulation, Simio, Witness, etc. [7]. The key benefit of DES is its ability to run multiple modeling tests in a limited period. In addition, DES is also an important instrument for assessing and measuring the effects of various scenarios or enhancements on an existing production system [8]. DES is capable of offering solutions for modeling a real system by describing the relationships of all the elements of a system as an occurrence [9]. Ease of use is one of the main advantages of using FlexSim for DES. There are various easy-to-understand industrial applications available in the software, including ones with drag-and-drop components, the ability to include stochastic elements, and the ability to supervise specific system components and observe a variety of performance measurements for them.

FlexSim is a complete collection of tools for the development and compilation of simulation applications. In the FlexSim environment, there are three phases of use: the compiler, the developer, and the function items. The FlexSim environment is fully integrated with the C++ compiler and uses FlexScript (a pre-compiled C++ library) or C++ directly. All the animation uses OpenGL, which features amazing virtual reality. The animation can be viewed in a tree view, 2D, 3D, and virtual reality. Two views may be seen at the same time during the model creation or run process. Because of this, most manufacturing maintenance-related companies use FlexSim for simulations [10]. FlexSim is a valuable tool that provides a view and information on the dynamic flow system approach described by complexities and inconsistencies utilizing DES, because a system can only be enhanced if the components' interactions are understood [11]. Hence, this technology is typically used for designing, evaluating, and optimizing production systems.

The FlexSim software has been used in the industrial sector as an analytical method for process reconstruction, plant configuration planning, production preparation, etc. Moreover, the FlexSim software has also been utilized in the warehouse and logistics industry. Also, FlexSim is one of the most advanced simulation software systems that offers 3D visualization capabilities and interoperability with other applications [12]. Practitioners and researchers have paid attention to these features, and a few of them have established interesting applications by combining FlexSim with other software and hardware.

Because FlexSim DES research related to manufacturing maintenance is ongoing and at an initial stage with limited studies, it is necessary to evaluate the current research progress to provide deeper insight into its application and methods. In consideration of this, a holistic literature review of all the areas of maintenance studied with the use of the FlexSim simulation software would be useful in developing guidelines and pathways for effective maintenance management and optimization for manufacturing and industrial productivity. In this review paper, an attempt has been made to discuss the application of FlexSim DES evaluation on the maintenance of manufacturing plants to increase overall productivity. The paper also provides a detailed theory of FlexSim software and its maintenance methods related. Almost all papers in the literature that applied FlexSim in maintenance analysis have been critically reviewed to discuss the efficiency of using FlexSim to increase the overall efficiency of manufacturing processes for maintenance management. Relevant tables on FlexSim simulation parameters, such as elements, objects, operators, flow item, source, queue, processor, conveyor, rack, sink, workstation, dispatcher, etc., have been provided in this article. The findings in this work will provide better information on the use of FlexSim software, especially in the maintenance-related manufacturing area, and more insight on how to use the software to solve and increase the effectiveness of manufacturing organizations and to adequately evaluate the industrial systems' performance, thereby adding to the productivity of the whole operation, achieving maximum economic performance or reducing total working time. This makes it quicker and simpler for businesses to boost their job performance, identify bottlenecks and vulnerabilities in their systems, increase staff wellbeing, minimize prices, working time, and other similarly critical considerations.

2. Discrete Event Simulation

Discrete Event Simulation (DES) is the most commonly used approach for the development of simulation systems. The system elements are modeled as attribute objects [13]. Object states shift in response to particular events at random, and multiple events may occur simultaneously [14]. The key benefits of DES are the ease of use, the ability to include stochastic elements, monitor specific device components, and take multiple performance steps [15]. The term DES refers to a modeling procedure in which only changes in the system states are depicted. Fundamentally, it generates a line of occurrences that influence the status of the scheme [16]. Such activities are scheduled according to their scheduling. The simulation then passes through these events and applies the device adjustments without modeling the time between any two events. Instances of these occurrences in a standard production system include the introduction of separations, the beginning and end of cycle periods on equipment, and the incidence of breakdowns. It is also a complex simulation technique where changes to the structure are represented over time [17]. The core features of conventional DES applications include modeling heterogeneity in statistical or scientific distributions and fast modeling by offering built-in modules that speed the modeling process. In addition, the traditional DES program allows interactive visual simulation where device adjustments are animated, and users can interact during the simulation process. Digital virtual simulation benefits include a deeper understanding of the model through visualization, virtual testing, increased connectivity to all stakeholders, and promoting model verification [18].

A quick analysis of the literature on discrete-event simulation (DES) reveals that its usage for maintenance program optimization is remarkably below anticipated. In this context, Yang et al. [19] adopted a genetic algorithm-based optimization technique by using discrete events to estimate the financial impact of the maintenance plan. The goal of Schutz and Rezg [20] was to build numeric and simulation models for the management of leased equipment in order to minimize and to solve the maintenance-scheduling issue for a fleet of aircraft in such a way that the model could optimize the availability of the equipment and reduce deviations. A discreet event simulation was used to describe flight operations, maintenance schedules, and equipment failures. Azadeh et al. [13] developed a model for a comparative assessment of condition-based, corrective and preventive maintenance applications. Assid [21] aimed to develop a discreet continuous model for joint production management, implementation, and preventive maintenance. Alrabghi and Tiwari [16] conducted a discreet event simulation to optimize the maintenance strategies of complex systems holding non-identical units where condition-based, preventive, and corrective maintenance may be appropriate. Alrabghi et al. [22] have optimized the maintenance policies of a tire reprocessing plant and a petrochemical plant with a discreet simulation model by analyzing multiple strategies. Martinod et al. [23] considered preventive block-and age-type part replacements and corrective maintenance in a discreet setting when determining appropriate maintenance strategies for ropeway systems.

It is noted from the literature that the optimization of maintenance policy content using discrete event simulation is limited. In addition, most papers have overlooked the inclusion and comparison of multi-work packages in creating an effective maintenance strategy with financial and functional performance. The review of field surveys shows several specific research weaknesses in the modeling of maintenance systems. These include modeling the maintenance system in exclusion of other essential and interrelated processes, such as manufacturing and spare parts management, modeling different maintenance techniques and policies simultaneously, and making oversimplifying assumptions that result in a paradigm that cannot be applied in real-world systems. These assumptions involve good maintenance/audits, immediate maintenance activities, and a single unit network. Thanks to the versatility of DES, the proposed solution allows for the development of different maintenance systems based on models that exist in the literature. Classic examples include perfect/imperfect maintenance, perfect/imperfect inspection, asset dependence, the impact of maintenance on product quality and production speed, different approaches to modeling asset deterioration, and inclusion/exclusion of maintenance resources such as maintenance equipment, spare parts, and technicians [8].

3. FlexSim Simulation

FlexSim is commercial software developed by FlexSim simulation Software Production Company (US). It is a mixture of modeling, artificial intelligence, 3D computer image analysis, and data processing technologies [24]. FlexSim has a rich object model library, where the object parameters can be represented in almost all actual physical objects, allowing FlexSim to simulate several real physical models [25]. With a strong analytical capability, FlexSim can be conducted according to various simulation research needs to tackle resource supply chain management systems and key optimization parameters. It is also a low-cost, quick and reliable way to help decision-making. Simulation has been widely used as an important tool for system analysis and testing in many fields. Production of modern logistics system simulation through the simulation aims to understand various statistics and dynamic performance which the material transport and stored dynamic process [26]. The FlexSim platform is simple to use and compatible with other software applications. The basic steps involved in FlexSim software are defining the model's layout and logistic procedure, setting the parameters, compiling and running the model, generating results, and analyzing the output. The FlexSimsimulation is mainly used in many fields, such as logistics, warehouses optimization, and design [27].

Flexible production systems (FMS) are dynamically programmed and computerized production procedures. Flexibility requires the capability of the machine to manage a variety of types of components [27]. Consequently, a scalable production environment will adapt quickly to industry trends and achieve different goals, such as reducing production times, improving process performance, increasing product quality, and decreasing intermediate stock prices [28]. An efficient manufacturing system consists of a series of workstations, a stock, tool, and component transport system connecting the workstations, as shown in Fig. 2. Each unit can perform several automated tasks with the help of computer instructions which monitor the mechanical devices on the workstation and the automatic tool-changing mechanism [28]. The mechanical conveyance system conducts the movement of components employing automation technology or some other mechanism (conveyors, etc.). All conclusions regarding the transport, handling, and entrance of parts into the system will be made via a flexible manufacturing system regulator [29]. This section briefly describes the class of FMS that can be simulated using FlexSim. Simulation is essential to the plan and operation of the flexible manufacturing system. Therefore, this modeling method, called FlexSim, was developed as a computer-assisted design and assessment device for FMS systems. In addition, it is built on an innovative concept of the interconnectivity amongst the catalog illustration model for the FMS method and its simulation model. The simulation model helps the designer study the FMS in depth and forecast its output through high accuracy [30]. FlexSim does not use prevailing simulation packages such as SLAM, MAP/1 or GPSS, to sustain the maximum probable notch of flexibility [27]. In this way, FlexSim can also support the designer of the real FMS database system to build a proper choice of the database following performance considerations. However, where necessary actual FMS database previously exists, the data it comprises may be transferred to the FlexSim database. FlexSim performs the resulting functions [25].

- Verification of the inclusiveness and accuracy of the FMS requirement provided by the designer of the FMS framework and applied by the user to FlexSim; the designer of the FMS and the operator of FlexSim may be the indistinguishable individual or cluster of persons.
- Providing quantifiable data like production capacity, machine utilization, production constraints, buffer capacity as a function of design variables.
- Recognizing and recording unwanted conditions, like buffer hindering, time delays, etc.
- Examining the consequences of adjusting the parameters of the physical structure and the capacity.
- Trying and enhancing various output methods. Diverse hypothetical situations can be explored through the exploitation of FlexSim with acting on the storage space at the workplaces, the number of devices, the distances amid the workstations, the grouping of the component and the sort, the operation disciplines of the input and output buffer queues at the workstations, the routing order of the part categories, etc.

3.1. FlexSim's Physical Structure

The class of measured FMS variables usually comprises existing workstations and a transport scheme designed to process a collection of workpieces or components. This segment outlines FlexSim's standards for the several elements of the FMS systems considered. These constraints are not fundamental in contrast with the universal solution. They are simply the limits of the implementation of FlexSim that are defined. The workstations contain computer-controlled industrial machinery, local equipment storage, a component management system, or a robot that moves parts and tools to local services. Every workstation has an input buffer and a finite capacity output buffer. The first one collects parts for manufacturing, while the other holds parts pending for another destination. Other stations are also available, such as loading/unloading (LU) stations, washing stations, or inspection stations, as shown in Fig. 2 [27]. Meanwhile, the material transportation system carries parts and equipment from one station to another [31]. It is presumed that all tools required to produce parts on machines are kept locally such that we do not need a transport tool in the current version of FlexSim. The component transport mechanism described is a nonlinear closed loop that requires pallets to carry parts and transfer them around workstations. Pallets can be of various types depending on the parts they manage [27].

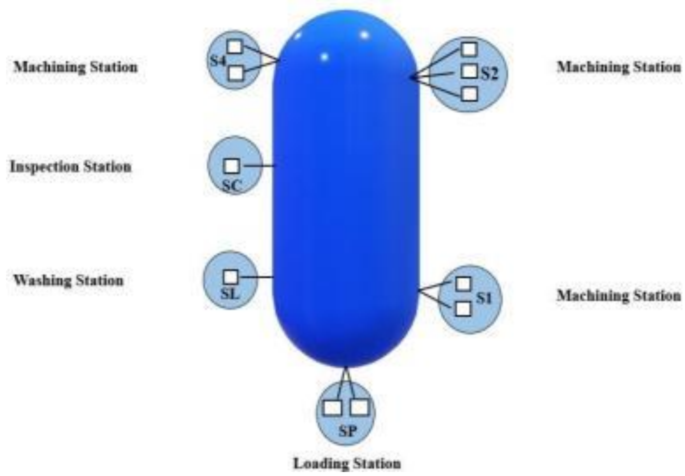

Fig. 2 Flexible manufacturing system transportation loop [27]

3.1.1. *Properties of the Parts*

Each input part is installed on a pallet at the LU station, allowing a number of operations to be carried out, which may necessitate rotation of certain components within the device [32]. As this is achieved at the LU station, during the production process, many different forms of pallets can be used. Each type of pallet is assigned to a single-part type, and each component type is processed in a hypothetically uniform series of main phases. Thus, one form of pallet is allocated to a single workstation at which a series of operations is performed during each phase [33]. For this purpose, an appropriate computer-controlled tool is employed, along with a software component module comprising a series of program macrocalls stored within. Although, processing each component form requires a set of bespoke phases, the first and the final phase typically involve loading and unloading, respectively. Thus, any component that enters the system must comply with the order of these phases [34]. The main issues that can arise during this production approach stem from the need to substitute one main phase with another that is deemed more suitable for a particular component, or can expedite system loading or output. In such cases, all operations are carried out on an alternative workstation [27].

3.1.2. The Control System

A scalable software development system requires a control system that is typically implemented as a number of distributed controllers responsible for monitoring the release of individual parts tothe system at the LU station, guiding the parts to the appropriate workstations, redirecting them to alternative workstations when any issues (such as temporary bottlenecks) arise at specific stations, and sending the parts to the LU station for eventual departure from the system. All system's controllers are integrated through a local communication network, as shown in Fig. 3 [27].

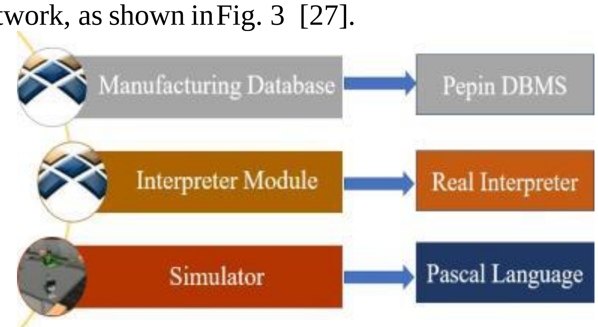

Fig. 3 The FlexSim simulation tool structure [27]

3.2. Environment Compiler

FlexSim is a highly advanced simulation modelling and landscape tool [35] benefitting from a versatile simulation application compiler that allows development of bespoke simulation software, including special graphical interface, object libraries, and a wide range of configurations, making it ideal for deployment in niche markets. In that sense, FlexSim is not a simulation software package, but rather a robust development environment, equipped with powerful design tools for creating visualization operating systems based on object-oriented concepts, as FlexSim uses the C++ compiler and the Flex-Script (C++ feature library) for programming purposes [25]. Each application is completely integrated with 2D and 3D virtual reality animation, and the resulting graphics are presented in real time using FlexSim's sophisticated virtual reality graphics engine, which maximizes simulation animation and has video game realism and graphics consistency. All graphics used in FlexSim products are industry-standard artefacts such as 3D.DXF, WRL, and STL images, thus ensuring that C++ libraries and functions can be used to construct applications. As a result of this particular approach, FlexSim simulation applications are extremely scalable and provide a user-friendly modelling environment [15]. In addition, third-party software such as Professional Suit, Opt Quest and VISIO can be combined with the package to provide additional functionality. FlexSim can also be added to any ODBC database (such as Oracle or Access), data structure (text, Excel, or Word files) and nearly any hardware system [27].

3.3. Environment Developer

The FlexSim creator is being used to build simulation applications and to customize the basic function of the FlexSim simulation program. FlexSim Developer offers tools and interfaces that permit developers to easily build simulation objects, such as queues, workstations, conveyors, etc., for use in the software. Applications in the d program are used to creatediscreet event simulation models using the simulation engine, artifacts, and interfaces [7]. Fig. 4 depicts that the FlexSim applications are stand-alone products that may have various names. The new FlexSim architecture includes FlexSim GP for general-purpose simulation, FlexSim Fab for semiconductor processing, FLEXSIM Port for maritime container terminal simulation, and FlexSim SANS for the simulationof shared access network storage networks [25].

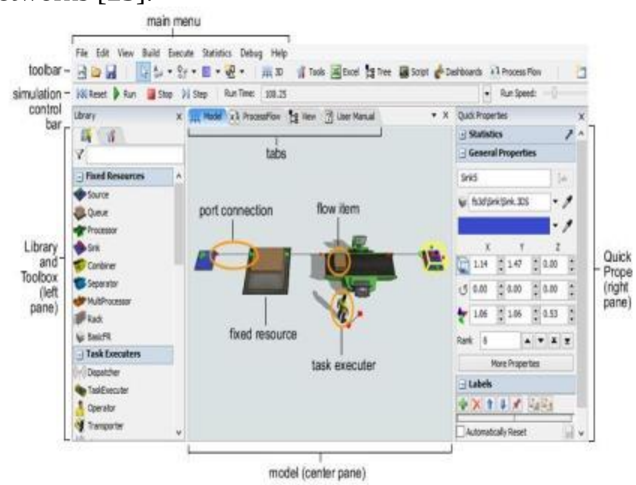

Fig. 4 Elements used for simulation [25]

3.4. FlexSim Model Development

There are five basic steps for creating a model with FlexSim: developing a layout, linking artifacts, detailing objects, running the model, and testing the performance. Three elements make up the FlexSim simulation study. [36]. The first study concerns the time of production and the frequency of blocking. It is represented in parts per minute. Meanwhile, the second report reveals the number of pallets used during the simulation and their delivery. The mean number of parts in the system and the distribution of parts among finished, discarded, and blocked parts are also given. Eventually, the third report includes statistical statistics on the queues in the virtual system, such as the mean length of the queues upstream and downstream of the workstations [10].

4. Reliability, Availability, and Maintainability (RAM)

Assessing the reliability of systems is a crucial feature of proper maintenance execution [15]. Meanwhile, present reliability monitoring techniques rely on the availability of data on the condition of the component. Even though component states are always unpredictable and unclear, especially in the early stages of the implementation, it is necessary to consider how the complexity would impact the estimation of device reliability in such situations [37]. System efficiency also depends on age, the underlying factors, such as dimensions, nature of components, raw material, the conditions of usage of the environment, load rate, stress, etc. In this case, RAM considerations represent a systematic approach to the integration of reliability, availability, and maintenance, using processes, instruments, and engineering strategies, such as Mean Time to Failure, Time Setting, and System Availability Value to recognize and measure equipment and system failures that impede the achievement of its objectives [38]. That is why good data collection and analysis, along with the creation of accurate models to help decision-making procedures, are required [39]. This will continue to use studies on the determination of maintenance periods, the coordination and preparation of effective maintenance policies [40].

The concept of RAM analysis is not recent and has been predominantly applied specifically in quality assurance [41]. Much attention is given to engineering design based on technical understanding and practical practices, particularly from the perspective of needs to be achieved if design specifications are to be fulfilled [42]. Unfortunately, not enoughthought is given to what should be ensuredif design requirements are not met. Therefore, it is important to provide an outline of artificial intelligence modeling in the design of reliability, availability, and maintainability to include continual design analysis throughout the process. RAM analyses are common in various manufacturing plants. Many industrial systems have a high degree of complexity, but they can be fixed in certain cases.In those circumstances, it is obvious that the excellent reliability, availability, and maintenance(RAM) analysis will play a vital role in the designstage and in any adaptation necessary to achieve the optimum performance of these systems [41]. However, an attempt is made to test the RAM parameters of such systems to achieve the required degree of accuracy, using accessible information and unreliable data [43]. Analysis of RAM is important to improve the production, performance, and quality of goods. Inaddition, the RAM approach directs us towards continuous improvement based on the principles of Total Quality Management (TQM). Reliability analysis is a critical method to assess how effective the system is and choose a maintenance strategy. It is assumed that RAM is one of the most important areas for improving profitability [43]. Likewise, reliability is the likelihood that the system will operate without a loss for a specified amount of time when it is subject to normal operating conditions. It is the likelihood of non-breakdown for a given duration [44]. Maintainability is the possibility that a broken machine/component or full production system can be returned to working efficiency when the repair is carried out in compliance with the specified procedures and thus the chance of reconstruction within a specified time [41]. In other terms, maintainability is described as a measure of howsimple a product can be sustained or restored [45]. The outstanding maintenance of the product would also increase the durability and repairability of the product, reduce maintenance costs while ensuring that the product complies with the requirements for its intended use [43]. Availability is the likelihood that the device will function satisfactorily at any time, where time involves operational life, active maintenance time, administrative and logistic time [43]. Availabilityis that part of reliability that considers the maintenance of equipment. Designing availability requires evaluating the influence of interconnected systems' inadequate operation or performance and the critical conditions needed to return operation or performance to the design requirements [46]. Historical reliability reports on failure and restoration data are crucial variables to a stable architecture and effective maintenance system [47]. Accumulation of malfunction and repair data is necessary to assess the reliability and availability of the device to produce consistent and reliable performance [43]. RAM can help enhance environmental efficiency, protection while also being a vital element in the management of functions by providing a reliable and available database on the actual state of the facility. The study of RAM of each manufacturing environment is different due to different reasons, such as the working conditions of the system, the level of personnel training for operators, engineers, and supervisors, the current maintenance strategy, etc. [43]. As a consequence, the method is exceptional and has special know-how to solve it [16]. Therefore, this research can serve as a helpful reference for manufacturing companies intending to improve their design and performance of productionfacilities.

However, historical and performance test statistics on failure mechanisms and repair trends are difficult to collect and sufficiently inaccurate due to various practical limitations. Thus, considering the unusual incidence of capital, human control, and economic limitations, it is impossible to collect a significant volume of data from any plant over a long period [1]. In comparison, companies rely on the production process rather than on the compilation of the loss database. It is therefore very difficult to compile accurate and credible evidence for loss. Lack of quantitative evidence is one of the main obstacles for researchers to establish qualitative approaches for reliability study [1]. Conversely, minimal experiments have been carried out to calculate practical efficiency based on historical evidence on the reliability of production lines. As a result, various RAM experiments have been reviewed in the literature for different use fields. In order to determine which reliability engineering should be used to improve pipeline integrity, Omoya et al. [48] researched the adaptation of reliability engineering to oil and gas pipeline systems. Patil [49] established essential human and operational factors and their effect on computer-based numerical management and maintenance performance. Under real operating conditions, Tsarouhas [45] analyzed the execution of six sigma (SS) techniques with RAM analysis on the bag market. In addition, Zhang et al. [50] investigated the time-dependent efficiency of a harmonic drive. In order to perform adequate maintenance control management, Jakkula et al. [51] investigated the reliability analysis of load-bearing dumper. In another research, a system was developed by Zhang et al. [52] to test the effectiveness of interconnected supply chains for building.

RAM studies have been applied in the food industries as well. Tsarouhas [53] also analyzed the RAM study of the food industry, highlighting the key points of the production process that need to be improved by working capacity and maintenance performance. The study was led in numerous food industries, such as bakery and bread products, canning and bottling, and milk products. In order to track and improve the efficiency of the skimmed milk powder production system of a dairy factory according to the actual working environment, Aggarwal et al. [54] suggested a method that would compute RAM indices. Tsarouhas [55] developed analytical probability models for an automated, buffer-free serial production system consisting of n-series machines with a normal transfer mechanism and control system in another study. The study's objective was to develop a comprehensive reliability and maintenance model to support food machine manufacturers, whose objective was to optimize the design and function of their production systems to the highest level of reliability, thereby improving their performance, efficiency, and availability. The reliability of a system is calculated at a given time to produce an outstanding performance under such conditions. The failure database was used to measure the reliability and maintainability of each machinery, workspace, and the entire line centered on empirical models from the actual production environment [55]. Together with maintenance workers, the study can be a valuable mechanism for production supervisors to estimate the present conditions and detect RAM to enhance the management of the system's processes (i.e., total productive maintenance, spare parts, inventory, etc.).

5. Advancements of FlexSim Applications in RAM

5.1. Reported Data on FlexSim in RAM

FlexSim has typically been used for optimization through discrete event simulation. As an industrial purpose simulation software, FlexSim is used in several fields or sectors, including manufacturing (production, assembly line, workshop, etc.), material processing (conveyor systems, automatic guided vehicles, storage, warehousing), logistics and distribution (container terminal operation, supply chain design, distribution center workflow, service and storage layout, etc.), transportation (highway system traffic flow, transit station pedestrian flow, maritime vessel coordination, custom traffic congestion, etc.) and other industries like oil and gas and mining. Fig. 5 summarizes the industries where FlexSim has been used in the literature. In this section, the use of FlexSim for RAM-related studies has been highlighted to provide a clear path on its use or application towards industrial process optimizations.

Fig. 5 Industries employing FlexSim

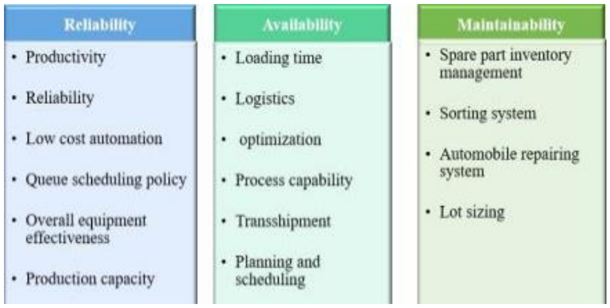

Fig. 6 FlexSim studies for industrial process RAM optimization

The use of FlexSim for the respective industrial process optimization on reliability, availability, and maintainability is presented in Fig. 6. Asseen in the figure, the types of process simulations are dependent on the focus of optimization based on RAM. Reliability-based studies are mostly conducted by authors in the literature. This is probably because the efficiency and profitability of industries highly depend on the process reliability and accurate operation of machines and prosecco flow. In any well-functioning production, reliability and maintenance management, availability play a crucial role. It aims to ensure that the best facilities are correctly maintained at the righttime, encouraging the company to make the most of its capital to ensure optimum productivity.

Machine reliability factors such as First Time Failure, MTBF (Mean Time between Failures), and MTTR (Mean Time to Repair) to determine of enhance are mostly considered. These parameters are calculated by several techniques, although frequently are established on experimental interpretations of the production procedure. The overall reliability of the technological system varies on the reliability of each component and the structure of the links amongst the individual machines. Three separate configurations using the stability analysis, A (serial), B (parallel), and C (mixed), can be used tocheck and validate the effect of the failure rate onthe performance of the technological system [56]. On the other hand, reliability in the queuing optimization using FlexSim simulation is conducted by using algorithms. Usually, these algorithms are based on the respective queue scheduling policy or principles of the process and industries under consideration. This implies that FlexSim can be used to optimize or test different operational policies before implementation. Therefore, the type of queuing algorithm mainly depends on the system or process operation policies or principles. One queuing algorithm reported in the literature with FlexSim simulation is the Pareto algorithm based on optimizing non-dominated genetic sorting algorithm II (NSGA-II). In this scenario, operators' skills and availability are considered to accomplish an interactive decision-making tool for human resources maintenance planning. The advantage of this was to achieve multi-objective maintenance phase optimization, which concerns the maximization of the number of requests for the confirmed interruption, the minimization of device stopping time, and their repair time. This approach is good for companies that produce transmission parts, where the FIFO (First In, First Out) is an inventory valuation approach that claims that inventory items purchased or generated at the earliest are the first to be used. For this approach, the inventory layers are mostly from the most recent sales or manufacturing processes. FIFO is the optimal solution to the historical cost of inventory calculation. It is also an appropriate practice in inflationary economies since it first charges the earliest lowest prices, helping one record higher inventory rates on hand. Therefore, implementing the FIFO policy ultimately generates less waste and incurs less material costs [57].

OEE is another parameter often used by authors for machine reliability optimization in FlexSim. OEE (Overall Equipment Effectiveness) metric is primarily employed to show how availability and reliability parameters infuse. The OEE metric can beanalyzed with simple equations. i.e., multiply thenumber of good parts produced with ideal cycle time and then divide that number with the scheduled production type. An alternative approach is the complex calculations that require availability, performance, and quality of assets. In terms of availability, FlexSim-based optimization is mainly conducted to improve processes, reduce waste, and improve the efficiency of machines' operation time and logistics systems. Based on this, the Petri net method and FlexSim havebeen applied in manufacturing by Wang and Chen [58]. Petri net model and FlexSim simulation is currently an important tool for modeling and simulating manufacturing logistics. Petri net, also known as the Place/Transition (PT) Net, is one of several mathematical modeling languages used to characterize distributed networks [59]. The system provides a graphical notation for stepwise processes that involves preference, iteration, and concurrent execution [60]. Unlike other standards, Petri nets have an exact mathematical definition of their execution semantics, with a well-developed mathematical theory for process analysis [58]. The loading time also plays a substantial role in availability, especially when trucks, conveyors, or other transporters in production have long waiting times. FlexSim is also applied to evaluate and establish different assessment scenarios on the availability of objects transported from one point to the other and optimize the processes. This is to identify bottlenecks and evaluate opportunities for performance improvement to assess several scenarios to enhance decision-making at filling or loading plants.

Concerning RAM, very few studies have been conducted using FlexSim. Most ofsuch studies relating to maintenance deal with spare parts inventory management, queue scheduling policy, task allocation, overall equipment effectiveness (OEE), processcapability (PC), maintenance planning and scheduling using different methods like ABC classification/Pareto analysis, non-dominated sorting genetic algorithm II, Taguchi orthogonal arrays (OA) method, OEE (overall equipment effectiveness), and Pareto approach to achieve that. Some authors have also used FlexSim for process machines maintainability based on spare parts inventory management, automobiles repair management, and sorting. In spare parts inventory management, equipment repairs, most spare parts information, particularly classification information, is usually not complete when it comes to maintainability in the industries. Each type of spare part usually relies on experience or a random basis for classification and storage. Several methods like the hierarchical multi-criteria spare parts classification method, computerized maintenance management system (CMMS), analytic hierarchy process (AHP)methodology, reliability-centered maintenance (RCM) could be used to manage spare parts depending on the area of application. The ABC classification method has been used tooptimize spare parts management using FlexSim simulation software. It is often referred to as the Pareto analysis, which defines events, objects, or actions by their comparative significance. It is commonly applied in inventory management to divide stock items into classes centered on the yearly income price for each item or the overall stock cost for each item. The amount of inventory will be minimized by this type of classification system, which strictly regulates key items [61].

5.2. Elements and Systems Used for FlexSim Simulation

In FlexSim simulation, the elements used in the system are very important. They allow users to translate the real system into the simulation environment. It enables a clearer picture of how the real-time system works, and with that, onewill be able to predict, perform and adjust where necessary for good optimization. The number of the elements used creates a clear understanding for the users in future works, and it makes it easy tofigure out the required amount depending on the type of study and method being applied. Table 1 highlights the different methods for analysis and the number of elements that have been used by different studies in the literature regarding the RAM application study. The typical types of elements used for RAM analysis vary with different study areas. For example, in spare part inventory management in the casting and mechanical operations, flow items represent the spare parts. The source element denotes the supplier, other elements used in different studies are shown in Table 2. Othersgenerally allocate time or flow speed to define the behavior of each element. However, some authors fail to report such details, which could affect the repeatability of the analysis.

6. Discussion

In this section, the results on the use of FlexSim in the industry were discussed. The discussion is categorized based on different areas of applications for various available literature.

6.1. FlexSim Simulation on Machines Reliability

Machine line reliability is a very important parameter of operating evaluation and technical design. It represents the ability of the machines in a manufacturing line or systems to operate at the maximum capacity to avoid underperformance. The reliability of machines is dependent on the system assembly line arrangement. Kuboń et al. [56] suggested that the reliability of a machine is affected by its configuration in a manufacturing line. Also, the MTBF and MTTR of the machines affect the reliability of a system. However, machines connected in series also have low reliability is the total system reliability is affected by the individual machines [56]. Another study confirmedthese findings by claiming that the system's overall performance, therefore, varies by its structure, i.e., sequent, series-parallel, or series-mixed [62]. This proves the use of FlexSim to optimize machine reliability in manufacturing lines. However, the addition of analysis, such as the time and distance between machines, could provide more realistic and practical results. Also, the effect of additional time intended for planned maintenance and regularinspections could be added to study its effect on the system's overall reliability. In such instances, using stochastic procedures, such as the Markov method, as proposed by Guo et al., [62], changes in the breakdown rate, restoration rate, and handling time of every single stage can be employed to maximize the utilization of the subsystems as well as the overall production system.

On the other hand, breakdowns and human factors, such as tiredness, illness, and mood swings, impact the performed work, undermining the production OEE, which plays an important role in determining the reliability of machines and the overall system. Mugwindiri et al. [63] stated that men and machines' total coordination and utilization play a very important role. This dramaticallyaffects the reliability of production processes,especially job scheduling, which decides when the task is to be carried out or finished. Kampa et al. [64] reported that the OEE measure greatly impacts the availability, reliability, and quality of a machine or system, which influences performance efficiency. In addition, buffers in production flows give lower OEE value, and the quality alsodepends on the stability of the manufacturing process parameters. Moreover, machine reliability metrics have a huge effect on the efficiency of the production system. The OEE score can be altered by enhancing reliability to comprehend the true parameters that control any production process [65]. Interestingly, the productivity measures, such as throughput and utilization rate, have less or no effect on the productivity improvement in a manufacturing system, as reported by Barosz et al. [66]. It can be said that there is a smaller influence when machines are operating in parallel than in normal cases of failure. That ensures that the other machines will continue to operate while one machine is stopped. As a result, Tomas and Pawel propose that the allocation of buffers also increases the overall production line throughput, which would reduce the negative impact of machine failures on the performance of a line, thereby optimizing the productivity of a company. However, in some cases, the impact is dependent on the size [67].

In process management operations, Halim and Pra [68] reported that FlexSim could be used to significantly minimize manufacturing cycles losses involving the use of robots [68]. Based on their findings, manufacturing process operations productivity could be maximized, with reducing labor costs and yielding high outputs. Such operational production performance is best measured via product quality, customer satisfaction, lead time, rejection ratio, and inventory level [69]. However, on the other hand, the operating costs must be closely weighed as well and factored in the analysis. Also, the need to monitor KPIs other than equipment reliability and budget performance is to classify areas responsible for undesirable patterns (leading indicators). Tracking positive leading KPIs (for production planning) also provides valuable, motivating encouragement for the maintenance of staff in the department.

6.2. FlexSim Simulation on Machines Availability

FlexSim simulation has been proven as a good tool to optimize machine availability for efficient manufacturing results. Most FlexSim studies in literature related to system availability are based on machine scheduling optimization, logistics flow, sorting, and queuing optimization. In such simulations, operators can determine their operational or process capacities and understand parameters that affect the system configuration for better improvement. Aside from knowing the challenges facing the process, the appropriate response and possible reconfiguration of the system could be corrected to avoid machine delays and increase the machines' operational availability. Kierzkowski and Kisiel [70] used FlexSim to schedule flights timelines of arrivals and departure to avoid delays. Their results suggested that flight schedules were effectively planned to improve flights' availability by efficiently forecasting flight traffic flows for a short and long-term horizon. However, the effect of flights reliability (MTTF and MTTR) were not considered in the availability. The task duration time and the number of products of passages could also improve the models. Therefore, an effective simulation that relates machine availability and reliability would be more robust and provide practical applications of the model for profitability. In some cases, machines' availability depends on the product demand and the manufacturing plant distribution sources available. For instance, Chan et al. [71] showed that making products more available would decrease truck loading time for lubricating material distribution centers. This means that when products are widely available, it prevents or minimizes restriction on the distribution systems. In mixed flow production systems, the process efficiency is greater when production planning and scheduling are combined. This represents an external order-driven viewpoint and achieves output measurements in terms of reliability, availability, and maintenance. However, preventive repair, MTBF, and MTTR affect the availability of the machine [72].

FlexSim, on the other hand, can be used directly to optimize a queuing method to reduce loading time before shipment from a factory to vehicles. In the ABC classification system, the last-in, first-out LIFO method proves to be a promising method of classifying the size of items according to the number of sales. Chayut and Sudawan [73] indicate that this strategy can minimize loading time and reduce utility costs due to the less distance traveled by a crane and quicker distribution [73]. Queuing mechanisms are mainly influenced by factors, such as inter-arrival time of vehicles, breakdowns of handling equipment, and operator availability. Thus, a more effective way to configure the transportation handling system is to focus on the purchasing costs of vehicles and the running costs, including operators, repairs, and energy [74].

To deal with problems, such as availability of room for material storage, backtracking, and presence of bottleneck in machine shops, FlexSim has proven to be a good software used to model, visualize, simulate and monitor the Machine locations and flow of activities. According to Patil et al. [24], for effective optimization, parameters including manpower, processing time, setup time, the processor used, layout, and production rate, when considered, give a basic idea about the effect of the modification. This can reduce the processing time, material movement, abolish the backtracking issue and increase space [24]. However, in complex systems such as mines, maintaining high conveying reliability and continuous production with maximum transportation process capability requires a good simulation program such as FlexSim that can trace the quantity and quality of the loaded and transported products [75]. During the processing, several irregularities could occur, which should be avoided for smooth processing. The use of the Petri net model can optimize the irregularities of processes and achieve maximum value and efficiency in logistics. For instance, Wang and Cheng [58] reported that longer idle time in production lowers manufacturing processing productivity. Based on such poor productivity, the tact time method could reduce overload time and idle time. To achieve good results, setting a reasonable tact time has a significant effect on improving logistic production systems' operating efficiency. The tact time method is good for optimizing various logistics systems as it is flexible and has low cost, short cycle, and is easy to implement [58]. In some cases, as reported by Riskadayanti et al. [6], a high level of efficiency can be achieved by optimizing aspects of raw materials, machines, and operators by considering the arrival time of raw materials, quality of the products and machine utilization.

Maintenance policies are also incorporated into production planning, which determines the availability of the subsystems and the overall production system. Therefore, the system configuration and maintenance policy decisions influence the state changes of the production system in a complex production phase [62]. Normally, the greater the usage of the facilities in transportation, the longer the waiting time is. However, it is not economical when the efficiency of machinery is poor. As suggested by Weiyu and Zhiqiang [76], the solution to this problem is continuously comparing the various equipment usage and changing the volume of the equipment and the specifications of the operating distribution center. However, avoiding over-staffing is also a great way to boost efficiency [76].

6.3. FlexSim Simulation on Machine Maintenance

FlexSim simulation has been shown to be a good tool for optimizing machine maintenance, thereby preventing breakdowns or stoppages during production. In order to achieve effective maintenance, optimizing the layout of a facility plays a crucial role. Moreover, material handling cost based on distance and efficiency have a great effect on maintenance unit design in facilities. Sugandhi et al. [77] suggested that the time it takes to perform repairs affects the overall efficiency of the system. However, taking sufficient time for automation and layout design will yield a better optimization result. With respect to maintenance, the facility layout design involves the organization and management of numerous departments, such as logistics, inventory workstations, machinery, storage facilities, raw materials, and spare parts, which could improve maintenance efficiency in manufacturing systems. The maintenance of a machine or unit or the entire system can be optimized depending on the type of maintenance program, machine line configurations, and system design layout [61]. This method is called the ABC classification or Pareto analysis. Hence, implementation of this methodology makes it easier for managers to realize which objects to concentrate on or specifically regulate to achieve effective maintenance.

Maintenance material handling involving the transfer and storing of items inside a facility typically follows the FIFO process. Here, the distance between travels is inspected. According to Greenwood [78], longer intervals between the inspections result in less distance traveled, leading to more downtime in production. Maintenance process optimization typically involves reorganizing the maintenance processes of certain industries in order to achieve optimal efficiency. The study by Nouha et al. [66] has shown that optimization by incorporating FlexSim and Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) can solve a maintenance problem by selecting the scheduling strategy for the right maintenance queues of machines. This provides the best options to maximize the number of intervention checks effectively, minimize stopping time and system repair time, resulting in major improvements to the maintenance system. Other ways to minimize non-value-added tasks for maintainability can be achieved by implementing lean tools [79]. By performing motion and time analysis, minimizing non-value-added movement is commonly used, contributing to efficient changes in the production layout structure. The combination of motion and time research with FlexSim simulation has been found to allow the efficacy of the sorting machine maintenance or repair [80]. Consequently, the Karakuri method in material handling is another lean technique used to optimize an assembly line, a major component in all manufacturing industries, particularly for delicate and huge parts. Fuel or energy is normally consumed by typical material handling systems. As the demand and expense of energy supplies rise day by day, this brings added costs to the output of goods. Karakuri is often used to replace material handling devices that consume energy. Kit et al. [81] proposed that this approach be followed in the assembly line to reduce motion, transport, and waiting in the assembly line. Service facilities, the safety of workers, the type of goods, the type of process, and the management policies influence the facility's configuration.

7. Other FlexSim RAM-Related Application

Maintenance costs are very important to the overall operation cost of any manufacturing system. Therefore any optimized machine spare parts and repair sorting system must be carefully planned to beat down the maintenance expenditures and avoid wasteful spending substantially. The analog simulation approach significantly prevents wasteful maintenance expenditure by ensuring regular express processing capability achievements through the quality sorting method [82]. Through this method, the complete maintenance of any production line station can be optimized to help achieve the optimum production results. Machine operation conditions, such as resources available, process times, and machine location, should be considered to achieve good machine output performances [14]. Also, an effective way to achieve successful structural optimization of logistics in manufacturing is to consider the influence of time variables under various production conditions. Wu et al. [83] indicated that the model's material flow under various production conditions significantly impacts the process, especially considering the effect of the time factor. However, actual production fluctuations, device processing time fluctuations, and sudden failure frequency can influence the capacity to maximize process flexibility. Reducing maintenance lead time and WIP increases the operating rate so that the system productivity is at its best. Sugandhi et al. [77] confirmed that the time margin for internal and external work increases with a reduction in operating maintenance time. Therefore, the industries require a reorganization of the configuration to improve the overall efficiency of the unit.

In order to enhance the industrial layout, the FlexSim application can be used to describe the variation in layout between the present and the proposed future. Other relevant considerations are the quality of the product, the level of demand, the factory's location, the type of machine, the environment. In addition to the RAM application, FlexSim has been used in other tests. For example, the use of FlexSim to build a cyberlearning factory for smart factory education and training [84]. The cyberlearning factory can have hands-on training in understanding, developing, and maximizing the smart factory. As a result, the cyber technology factory will train the production managers of manufacturing firms and the information systems developers of IT companies. However, it is not easy to turn complex industrial processes into virtual production facilities. Kim et al. [12] considered just production processes, which means that the methodology used in the analysis cannot be extended to assembly processes. The expansion of the system would also provide support for a broader variety of industrial processes. Users can access personalized data output reports flexibly by refining the reporting capabilities of the web-based information system.

FlexSim may also be used to assess the effect of technological and organizational limitations on longwall efficiency in order to evaluate and set the optimal operating parameters for the longwall system. According to Cai and Porter [85], the machinery used in longwall mining is distinct from that used in the automotive industry. Thus, FlexSim, which is an object-oriented simulation program, has no fully prepared agency to construct any aspect of underground coal mining. In addition, operational delays significantly reduce the outputrate. On the other hand, the software facilitates the precise identification of the right parameters and calculates the key measures characterizing the development phase of the longwall complex. This calculation depends on various dimensions of the wall, such as thickness, height, long wall shear, working speed, speed of maneuvering, haulage, and backhoe depression. Kęsek et al. [52] stated that in view of these factors, it would be possible to reduce operating time and ensure economic efficiency without making expensive and risky changes in the actual process. Dev [86] has also implemented a flexible automation software as a form of lean manufacturing technology, which is recognized as a solution to the demand for a variety of goods. However, the variance in product styles and the possible advantages of increasing efficiency and consistency while reducing running costs have a substantial influence on the flexibility of automation. FlexSim can also be used to resolve line-balancing problems based on inconsistent production, using the Minitab statistical method in the software. FlexSim aims to increase efficiency by improving line balancing within a shorter timeframe [87]. In addition, Ge and Zhang [88] proposed that a comparative study of the essential indicator and station use before and after balance can be carried out using the balance simulation approach. This will help achieve balanced loading of systems and boost the balancing of assembly lines. It will also minimize waste and cost of production. Moreover, Ciszak [89] studied investigations, which primarily involved human labor and marginally used manufacturing machinery in order to improve the efficacy of the assembly technical processes by applying the current hidden labor resources. Nevertheless, proper load balancing of the production line and minimizing the inter-stand flow are the key factors determining the consistency and performance of the assembly process. Alternatively, Krenczyk et al. [90] suggested an approach for the balancing of integrated and multi-model assembly lines by introducing an IT solution, a machine-fusion application of joint data-driven generation of automated simulation models, and a heuristic solution for line-balancing approaches. Using this approach, the management can benefit from increased stability, better preparation, and enhanced regulation of the process flow. This approach also allows for the removal of wasteful and time-consuming procedures and offers the opportunity to adapt flexibly to evolving consumer needs. According to Jiuran and Xiaoxia [91], taking the minimum production-line overload time, the idle time and the PATS utilization equilibrium as optimization objectives, helps optimally collect a variety of products in the mixed-model series.

8. Recommendation and Prospects

Based on the findings of this study, the following recommendations and prospects for future works must be considered:

- The reliability of machines depends on the arrangement of the system assembly-line and must be optimized well for high productivity. In addition, the most important indicators for measuring performance are product quality, customer satisfaction, lead time, rejection ratio, operating costs, and inventory level.
- There is a need to monitor KPIs, other than equipment reliability and budget performance, to be able to classify areas responsible for tracking positive-leading KPIs, especially in production planning. However, the takt time must be closely studied as it is a good method for optimizing availability in various logistics systems due to its flexibility, low cost, short cycle, and ease of implementation.
- A more effective way to configure the transportation handling system is to consider factors such as the inter-arrival time of vehicles, breakdowns of handling equipment, operator availability, and the purchasing and running costs of vehicles, including operators, repairs, and diesel/fuel.
- For effective maintainability, optimizing the layout of a facility is critical and must be carefully considered. Another factor to consider is material handling, based on both cost and distance. Most importantly, a time and motion study of all production operations is recommended.
- Stochastic techniques, such as the Markov process, can optimize the utilization of subsystems as well as the overall production process. In addition, the pull-from-the-bottleneck (PFB) technique is suitable for waste management and lean production, while the Petri net model best addresses process errors to achieve optimum value and reliability in the logistics approach. The ABC/Pareto approach can also increase station utilization and reduce overload and idle times in queuing and sorting in the logistics field. The Karakuri method of material handling is another lean technique used to refine the assembly line. A Non-dominated Sorting Genetic Algorithm-II (NSGA-II) cansolve a maintenance process problem by indicating the correct queue-scheduling process strategy.
- Further studies are needed to establish the relationship between KPIs and how they affect the efficiency of the maintenance unit and the system as a whole. In comparison, there is less emphasis on the oil and gas processing flow by using FlexSim. Future research should apply simulation techniques used in the oil and gas industry, especially in maintenance-related areas. Such studies will serve as an alternative method to improve the sustainability and overall process efficiency.

9. Conclusion

The research presented in this study contributes to the emergence of knowledge, in academia, regarding FlexSim applications that use DES to tackle complicated industrial challenges from a RAM perspective. It also provides researchers with a better grasp of what is happening in the development or advancement of FlexSim and applied scientific fields. However, based on the results, it can be concluded that the RAM review is especially useful for determining maintenance cycles and for coordinating and managing an effective maintenance policy. It is also observed that FlexSim is a highly effective method for addressing industrial productivity as it can optimize system or machine processing reliability, availability, and maintainability, contributing to major cost reductions.

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Table 1 Summary of FlexSim simulations involving RAM

Authors	Area of study	Type of study	No. of elements	No. of systems	Analysis method	Duration of simulation (min)	Remarks
Sun [61]	Casting and mechanical operations	Spare part Inventory management	113	13	ABC classification/Pareto analysis	10080	The efficiency of spare parts inventory management can be effectively optimized for efficient maintenance using FlexSim simulations.
Nouha et al.[92]	Tractor transmission parts	Queues' scheduling policy	10	6	Non-dominatedsorting genetic algorithmII	525600	Improved and efficient maintenance queuing scheduling policy was optimized in FlexSim to reorganize the maintenance process for emergency intervention in manufacturing companies.
Zhang et al [93]	AutomobileRepairing System	Production scheduling, taskallocation, production planning	11	11	Genetic algorithm	Not specified	The use FlexSim software can be used to optimize the maintenance process of line balancing for car repairs.
Jose et al. [94]	Automated bottling line	Overall equipment effectiveness (OEE) and process capability (PC)	14	9	Taguchi orthogonal arrays(OA) method	Not specified	PC affects OEE linearly until a critical point where is the effect is negligible andnot insignificant. A critical Cp/Cpk valueof 0.8 best defines the linear effect of Cpon OEE.
Piotr et al[66]	Automotiveindustry (industrial robots)	Productivity and reliability	10	10	OEE (overall equipment effectiveness)	345600	An increase of about 30% productivity inmanufacturing lines can be achieved using FlexSim. However, the reliability of operators highly affects productivity.
Suyash et al. [77]	Diesel-electric locomotive maintenance unit	Maintenance schedule	8	10	Access and process timemaintenance	280 (present layout) 265 (modified layout)	FlexSim could be used to increase the overall efficiency of a production unit byoptimizing the process of the machine layout.

Maciej et al. [56]	Robotic manufacturing line	OEE indicator	23	10	Impact of failureparameters on the system	57600	The reliability of machines can be achieved in FlexSim using MTTR andMTBF analysis for maximum performance and productivity.
Yanting et al. [72]	Mixed flow manufacturing	Integration of production planning and Scheduling	188		Double decoupling postponement (DDP) approach	131040	The incorporation of shop floor production preparation and planning formixed flow production systems can be accomplished and streamlined using FlexSim.
Artur et al. [70]	Aircrafts	Logistics	22	11	FIFO strategy.		FlexSim can estimate the availability of aircraft handling agent equipment by evaluating the execution time for a given operating schedule.
Grzegorz et al. [65]	Automotive industry car body parts	Production efficiency	22	9	OEE indicator	360000	Availability, reliability, and quality parameters have a significant impact on the efficiency and performance of machines, particularly in short and long-term production processes.
Prasad et al. [14]	Automotive transmission system	Strategy to increase the throughput	58	9	Alternate possibleScenarios comparison		The throughput of a manufacturing facility can be improved to the desired value, and bottlenecks can also be avoided using discrete-event simulation in FlexSim
Weiyu et al. [76]	Meat food distribution	Logistics	19	8	System performance	1066.6667	Logistics performance, utilization of testing, packaging, and other equipment

					(equipment utilization)		in meat food distribution can be optimized using FlexSim.
Ben Cohen and Bart Mateman [71]	Fuel filling plants	Logistics	22	7	Priority rules	142560	FlexSim can maximize the efficiency ofcomplex logistic processes at large plants, particularly for trucks with multiple compartments for various fuel items, and the throughput time can be greatly improved.
Allen G. Greenwood [78]	Human-operated industrial trucks	Materialhandling	18		FIFO strategy anddistributed network approach	Not stated	A distributed network approach can beused to assign agent functionality to various objects and provides the meansfor such agents to operate together as required in the DES model.
Jun et al. [12]	Smart factory	Smart factoryeducation and training.	23	7	Cyberlearning	Not specified	FlexSim 3D Factory Simulation gives detailed insight into the function of the entire smart factory environment that canbe applied by integrating an information system, a database, and a simulated production plant.
Chayut et al. [73]	Steel coils manufacturing	Loading Time	6	4	ABC analysis, Last in, First out(LIFO) method	44640	A significant reduction in loading timeand the utility cost with less distance travel with the application of the ABC method is achieved in the manufacturing

Mosca et al. [74]	Inland freight-terminal	Optimization ofcontainer operations	6	4	Concept of MSpe(robustnessanalysis)	Not stated	Efficient optimization of container queuing processes by optimizing (inter-arrival time of vehicles, breakdown of handling facilities, availability of operators in various scenario setups in FlexSim).
Zhou et al. [95]	Ship-pipe parts production	Lot-sizing optimization		8	Strategic CONWIP (constant work-in-process) control		In FlexSim, a non-linear programming model can be devised to minimize the overall cost of ship-to-pipe component output and particle swarm optimization(PSO) using pull-from-the-bottle (PFB) and strategic CONWIP (constant work-in-process) control.
Rajtilak et al. [24]	Machine shop	Optimization oflayout	27	27		36000	Optimizing system configuration with FlexSim provides a simple insight into theimpact of adjustment that decreases processing time, increases space, reducesmaterial movement, and avoids tracking problems.
Nuntiya et al. [68]	Ceramic plate production	Efficiency improvement of robots	22	22	Probability plot(Minitab Software)	131400	FlexSim can be used to increase efficiency, minimize labor and processing time for robot-operated ceramic plate production.

Rao et al. [79]	Spool casing assembly, vehicle horn industry	Productivity enhancement	15	11	Method study,time study, and value stream mapping VSM	Not stated	In FlexSim, VSM can be built to minimize excessive waste, such as transport, total product cycle inventory, overall lead time, and increased efficiency in the industry.
Marek et al. [36]	Longwall Complex	Process flow		6	Process flow		The process flow model enables the precise selection of the right parameters,and the calculation of the key indicatorscharacterizing the development processof the longwall complex maximizes its performance.
Arun Kr Dev [86]	Small to medium scale shipyards	Automation	9	6	Low cost, flexibleautomation system	6000000	Implementation of flexible automation increases productivity, quality and reduces operational costs. Small to medium shipyards
Arun Dev [96]	Hull panel, shipyard	Logistics improvement	9	7	Toyota Production System TPS approach	23580	Logistical flow can be optimized by adopting the TPS in shipbuilding.

Bung et al. [81]	Lamp Production	Assembly line optimization	28	15	Root causeanalysis	480	The efficiency of an assembly line directly affects productivity, and an improved version can be developed based on Root cause analysis which identifies the causeof the problem in the assembly lines.
Zhou et al. [97]	Multi-stage manufacturing system	Production lot-sizing	16	16	Queuing networkanalyzer (QNA) method		The Queuing Network Analyzer (QNA)approach can be used to minimize the overall system flow time.
Chandra Kumar et al. [98]	Transshipment Terminal Operations	Enhance Productivity	14		LEAN and Greenconcepts towards overalloperations		The integration of LEAN and green principles along with multi-model transport strategies between major ports would improve the overall Productivity of the transshipment operation.
Leszek et al. [75]	Mining industry	Material flow	39	10	Geometallurgy		FlexSim combines the possibility of continuous and discrete event simulationsof material flow in the mining industries.
Wang et al. [58]	Automobile manufacturing	Production logistics optimization	18	8	Time Petri netmodel	3.5	Petri net can be comprehensively used in FlexSim to optimize production
	assembly workshop						efficiency of logistics system by setting reasonable tact time.
Fubin et al. [82]	Express sorting distribution centers	Sorting	23	12		14400	The efficiency of the sorting system can begreatly improved using FlexSim.

Tomasz Bartkowiak & Pawel Pawlewski [67]	Filling and packaging production line		17	7	Buffer allocation	Machine failures can be documented in FlexSim by maintenance Data Acquisition method to extract statistical distributions for Time to Fix and Time Between Failures, taking into account various allocation scenarios, and Implementation of buffers results in improved line throughput.
Damian et al. [90]	Gear motor production	Assembly line balancing	13	12	RapidSim software solution	FlexSim allows greater consistency in the management, preparation, and monitoring of process flow, eliminating the high cost and time-consuming process of verification of modifications in development schedules and the opportunity to react flexibly to changing consumer requirements.
Ignatio et al. [69]	Margarine production planning and control strategy	Overall equipment effectiveness	15	16		Maximum output with minimum input can be achieved with overall equipment effectiveness analysis and tracking of manufacturing processes to improve production planning and control strategy for manufacturing companies.
Nuntiya et al. [68]	Ceramic plant	Improvement of sorting process	30	9	Motion and time study	FlexSim can be used to maximize the performance of the sorting process in a ceramic plant by evaluating the manufacturing process in terms of throughput, productivity, number of employees and work efficiency.

O. Riskadayanti et al. [6]	Newspaper production	Increasing efficiency	24	6	Discrete Event Simulation (DES).		A high degree of performance can be accomplished by optimizing aspects of raw materials, equipment, and operators using DES in FlexSim to reflect the interaction of all components of the device as a case.
Jian Guo et al. [62]	Multi-stage Production Systems	Reliability and Availability Measure	23	14	Markov process	1560	Markov process can optimize the maintenance efficiency by assessing the reliability and availability of multi-stage production in different configurations.
Shuangping et al. [83]	Steel Plants	Structural Optimization	17	13	Process structure optimization.		Process structure optimization methods for logistics operation especially considering the influence of time factors is very effective in steel manufacturing.

Table 2 Model elements and system elements used in studies

Author	**Duration ofsimulation (min)**	**Model element**	**Systems element**	**Time assigned (min)**	**Parameters of analysis**	**Factors considered**
Sun [61]	10080	Flow item	Spare parts	Not specified	Quantity of spare parts, percentage of quantity, Quantity of consumption, Proportion of those types of spare parts funds.	
		Source	Supplier	0.5		
		Queue	Check-waiting area	Default		
			Waste products area			
			Qualified productsarea		funds of spare part, percentage offunds	

		Processor	Spare parts inspection	Processing speed (1)		
			Spare parts sorting			
			Outbound processor			
		Conveyor	Spare parts conveyor	0.5[a]		
		Operator	Quality inspector	Not specified		
			Storekeeper			
		Sink	Workshop			
		Rack	Storage rack			
Nouha et al. [92]	525600	Shuttle	Not specified	Not specified	Intervention Requests' Type, stopping time,	Maintenance human resources assignment, qualifications of operators and availability.
		Source				
		Operators				
		Dispatcher				
		Sink				
		Queue				
		Machines				
Zhang et al. [93]	183	Workstations	Vehicle maintenance	9	Processing time	Task allocation, idle time, buffer.
			Engine maintenance	40		
			Electronic control Electrical system maintenance	16		
			Clutch maintenance	2		
			Transmission maintenance	3		
			Steering maintenance	10		
			Brake system maintenance	67		
			Driving system maintenance	13		
			Taxi inspection	5		
			Emissions inspection	3		
			The entire vehicle lubrication	15		

		Buffer	Not specified	5		
		Sink		Not specified		
		Queue	Waiting area			
		Processor	Handle the current flow of vehicles			
		Source	Car to be sized			
		Conveyor	Transport vehicles to be seized			
		Operator	Station operator			
		Dispatcher	Operators according to certain strategies work arrangements			
Jose et al. [94]	Not specified	Workstation	Filling	375[b]	Capability indices (CI, CP CPK)	Availability, performance, and quality.
			Loading	472.6		
			USL	376[b]		
			LSL	374[b]		
		Conveyor	Not specified	Not specified		
		Buffer				
Piotr et al. [66]	345600	Entities	Bottles	Not specified	MTBF, overall factory effectiveness, approximate efficiency, availability, OEE,	Reliability, performance.
		Machine	Milling	0.5		
			Drilling	0.5		
			automatic deburring	0.5		
			hand deburring	0.666667, 0.833333		
			Washing (with capacity 10 part)	180		

Station	Flow test	1
	Leak test	1
	Inspection	0.833333
Operator	Human (load/unload time)	0.333333- 0.5
Conveyor	Robot (load/unload time)	0.0833333
		1[a]
Queue	Not specified	Not specified
Source		
Buffer		

Chen and He [76]

1066.6667	Object	cooked food	2.4	N	Equipment utilization
		frozen foods	4.8		
	Queue	dairy products	0.6		
	Source	Not specified	Not specified		
	Processor	Packaging equipment	1		

			Inspection equipment	95%		
		Operator	Not specified	Not specified		
		Sink	Not specified	Not specified		
		Dispatcher	Forklift	2		
		Conveyor	Not specified	1[a]		
Yanting et al. [72]	131040	Machines	Not specified	Not specified	MTBF, MTTR	Preventive Maintenance and breakdown
		Stations		Lot size: 2,625 units		
		Product	CPT – DT and MB	Not specified		
Adrian et al. [64]	360000	Human operators	Machine cycle time	0.0833333	Rest break 15	MTBF, MTTR, OEE
			Operator time	0.166667	OEE 78.2%	
		Buffer	Loading and unloading time	0.0166667	MTBF (m 60000) (r120000) MTTR (both m & r) 240	
		Output	Planned setup time	15		
Suyash et al. [77]	Not stated	Source 1	Location x	Not stated	Troubleshooting, Minor repair, major repair	Running repairs operations.
			Location y			
			Location z			
		Processor	Entry point	0		
			Fueling point	15		
			Washing area	30		
			Lobby	10		
			Repair section	30		
			Driver booking	30		
			Working on locomotive	105		
			Final inspection	30		
			Exits	30		
			Service cabin			
			Service baggage			
Artur et al. [70]	Not specified	Processor	Fuel airplane Tasks (AFT stairs	Not stated	Availability, arrival time, arrival delay time	First in, first out (FIFO) strategy
			Service galleys			

			Service vacuum toilets			
			Service portable water			
		Operations	Flight no. LO01	0		
			LO02	18		
			LO03	28		
			LO04	60		
			LO05	85		
			LO06	95		
			LO07	130		
			LO08	140		
			LO09	165		
			LO10	170		
			LO11	175		
			LO12	200		
			LO13	230		
			LO14	250		
			LO15	255		
Grzegorz et al. [65]	Not specified	Not specified	Constant machine cycle time	0.0833333	OEE, availability (MTBF, MTTR, MTTF), human factors,	Failure parameters, short time human errors rate, long time machine, and robot MTBF.
			Constant robot speed	180°/s		
			Operator time	0.166667		
			Setup time	15		
			Break for rest for workers	15		
		Machine	Constant robot speed	180°/s		
		Input station	MTBFm	30000		
		Output station	MTTRm	240		
		Operators	MTBFr	60000		
		Buffers	MTTRr	240		

Prasad et al. [14]	Not stated	Source	Raw material	Not stated	Type of machines and number of machines, throughput Not stated	Not stated.
		Processors	Lathe			
			Facing center			
			Turning			
			CNC			
			Hobbing			
		Transporter	Forklift			
		Sink	Output			
		Queue	Waiting lines			
Weiyu et al. [76]	1066.6667	Source	Not specified	Not specified	Not specified	Not specified.
		Object	Not specified			
		Processor	Not specified			
		Queue	Not specified			
		Transporter	Not specified			
		Operator	Not specified			
		Conveyor	Not specified			
		Sink	Not specified			
Ben Cohen and Bart Mateman [71]	142560	Not stated	Truck arrival	Not stated	Order and arrival of all trucks, assignment method, time delay processes trucks go through	Logistical scenarios (trucks are classified in three different categories (Priority 1, 2, and 3). low investment solutions.
			Access control			
			Inspection			
			Bay assignment			
			Loading			
			Collecting bill of loading			
			Loading bays			
			Lubricant arms			
			Trucks			
Allen [78] Greenwood,	Not stated	Source	Not stated	Not stated	Web-based information system	Virtual manufacturing facility.
		Queue	Not stated			
		Processors	Not stated			

		Transporters	Material handler	10		
Jun et al. [12]	Not stated	Sources	In	Not stated		
		Queue	Not stated			
		Processors	Drilling			
			Milling			
			Testing			
			warehousing			
		Sink	Out 1			
			Out 2			
		Operators	Human			
		Task executers	AGV (automatic guided vehicles)			
Chayut et al. [73]	44640	Source	Not specified	Average loading time (from the queue to sink) is 17.82 minutes per coil.	Statistical distribution of inter-arrival time.	Not specified.
		Queue				
		Crane				
		Sink				
Mosca et al. [74]	Not stated	Source	Not specified	Not specified	Purchase costs of vehicles and the operating costs (operators, maintenance, fuel)	Impact on waiting times and demand increase.
		Objects	Containers			
		Queues	Not specified			
		Processors	Berth			

			Yard			
			Rail			
			Gate			
		Transporters	Crane			
			Top loader			
			Trucks			
Zhou et al. [95]	1.44e+7	Not specified	Not specified	Not specified	Productivity, Utilization rate of the equipment, cost, leadtime, waiting time, product, lot size product	Not specified.
Rajtilak et al. [24]	36000	Processors	Horizontal milling Machine 1	22	Effect of modification, Performance of five iteration	Manpower, processing time, setup time, The processor used, layout, production rate.
			Horizontal milling machine 2	22		
			Horizontal milling machine 3	22		
			Horizontal milling machine 5	22		
			Vertical milling machine	22		
			Special purpose machine 1	22		
			Special purpose machine 2	22		
			Special purpose machine 3	22		
			Radial drilling machine	22		
			Washing	7		

				Setup time for each machine: 1.10		
		Operator	Not specified	Not specified		
		Crane	Not specified	Not specified		
		Sink	Not specified	Not specified		
		Source	Not specified	Not specified		
Nuntiya et al. [68]	131400	Machines	Inspection	0.0833333	Not stated	Not stated.
			Cleaning	0.0833333		
			Load	0.1		
			Outside painting by robot 1	0.333333		
			Unload	0.1		
			Finishing 1	0.333333		
			Load	0.1		
			Outside painting by robot 2	0.583333		
			Unload	0.1		
			Finishing 2	0.583333		
			Load	0.1		
			Outside painting by robot 3	0.283333		
			Unload	0.1		
			Finishing 3	0.25		
Rao et al. [79]		Source	Not stated	Not stated	Not stated	Not stated.
		Sink	Not stated			
		Processor	Wire Cutting			
			Enamel Cleaning			
			End Cable Crimping			

			End Terminal Crimping			
			Case Moulding			
			Ohm Checking			
			Point Set with Condenser Assembly			
Marek et al. [36]	Not stated	Not stated	Not stated	Not stated	Thickness and height, working speed, maneuvering speed, haulage and backhoe depression, the average time between failures, and average time for repair	Not stated.
Arun Kr Dev [86]	6000000	Source	Not stated	Not stated	Not stated	The simulation is running in an idealistic condition based on realistic assumptions.
		Queue				
		Multiprocessor				
		Combiner				
		Transporter				
		Operator				
		Sink				
		Visual tools				
		Processor	Fabrication area (workshop 1)			
			Assembly area (workshop 1)			
			Painting and architectural outfit area (workshop 2)			

			Launching platform			
			Commissioning Quay			
			Material Store			
Bung et al. [81]	480	Workstation	Not stated	Not stated	Not stated	Not stated
		Queue				
		Operators				
		Processors				
		Sink				
Leszek et al. [75]	Not stated	Workstations	excavation	Not stated	Intensity of loaders and trucks operation	Not stated
			cutting			
			extracting of the ore			
			hauling			
			hauling			
		Conveyor	LHD			
		Transporters	Trucks			
Wang et al. [58]	Not stated	Source	Not stated	3.5	Not stated	Production efficiency, vacancy rate, degree of obstruction of each station
		Processor	Not stated	Not stated		
		Conveyor	Not stated	3m, speed is 0.85m/min		
		Queue	Not stated	Not stated		
		Separator	Not stated	Not stated		
		Object	Processing trucks	Not stated		
		Sink	Not stated	Not stated		
Fubin et al. [82]	14400	Generator	Not stated	Not stated	Not stated	Not stated
		Staging area				
		Processor				
		Resolver				
		Conveyor belt				

		Operator			
		Conveyor			
		Separator			
		Processor			
		Queue			
		Sink			
Tomasz & Pawel [67]					
Not stated	Filling machine	Not stated	Not stated	Not stated	Different allocation scenarios

	Not specified	Labeler	Not specified	Not specified	Not specified	Not specified
		Folding box machine				
		Single cello machine				
		Foil shrinking machine				
		Shipping box machine				
		Shipping box labeler and printer				
Damian et al. [90]	Not specified	Object Station	Not specified	Not specified	Not specified	Not specified
		Operator				
Ignatio et al. [69]	Not specified	Source	Not specified	Not specified	Production profile, key performance indicators, production cost, demand trending	Quality of the product, customer satisfaction is very important, lead time, rejection ratio and the level of the inventory
		Conveyor				
		Sink				
		Operator				
		Object				
Nuntiya et al. [68]	Not specified	Not specified	Unload products from a kiln to conveyor	0.0833333	Throughput, number of workers, productivity	Not specified
			Unload products from trolley to pallets	0.0666667		
			Load products from pallets to conveyor	0.0666667		
			Pack products up from conveyor	0.0333333		
			Inspection	0.15		
			Scrub the products	0.833333		

			Place products to conveyor	0.0333333		
			Food finishing	0.333333		
			Load on the shelf	0.1		
O. Riskadayanti et al. [6]	Not speified	Objects	Plates	Not speified	Not speified	Not speified
			Ink	Not specified		
			Paper	Not specified		
		Combiner	Not specified	0.01		
		Processor	Not specified	0.01		
		Separator	Not speified	0.01		
		Machines	Counter	Not specified		
			Printing	Not specified		
Jian Guo et al . [62]	1560	Processors	Machine 1	120	Reliability of components, stages, and processing time of each stage	Three basic configurations (two-component series system, two-component parallel system, two-component series system with a buffer)
			Machine 2	300		
			Machine 3	180		
			Machine 4	240		
			Machine 5	180		
			Machine 6	240		
	Not specified	Source	Not specified	Not specified	Not specified	
Shuangping etal. [83]		Processor	Kambara Reactor KR processing time	40		Ignore external environmental factors and sudden changes in the production plan, simplify the general layout of production; the transportation between procedure devices brings control through the Conveyor object; omit transport devices and workers, including cranes, trolleys, and personnel; simplify the rotary table of the continuous caster, expressed
			The transportation time From KR to dephosphorization converter DeP	6		
			DeP processing time	20		

		The transportation time from DeP to decarbonization converter DeC	6	by buffer time.
		DeC processing time	30	
		The transportation time from DeC to refining furnace RF	6	
		refining furnace RF processing time	CAS: 25.0 ladle furnace LF: 25.0 RH: 32.0	
		From RF to continuous caster CC ladle turret, to the end of the turn	10	
		The waiting time on ladle turret	Match according to	

			production rhythm
		continuous caster CCR processing time	CCR1: 29 CCR2: 33 CCR3: 38

[a]conveyor speed (m/s), [b]filling capacity (ml)

List of abbreviations

DES	Discrete-event simulation
OEE	Overall equipment effectiveness
PC	Process capability
KPI	Key Performance Indicator
RAM	Reliability Availabilit yMaintainability
TQM	Total Quality Management
FMS	Flexible production systems
LU	Loading unloading
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NSGA-II	Non-dominated genetic sorting algorithm II
FIFO	First In, First Out
PT	Place/transition
OA	Orthogonal Array
CMMS	Computerized Maintenanc eManagement System
AHP	Analytic Hierarchy Process
RCM	Reliability Centered Maintenance
LIFO	Last in, First out
CONWIP	Constant Work-In-Process
VSM	Value Stream Mapping
TPS	Toyota Production System
QNA	Queuing network analyzer
CI, CP CPK	Capability indices
QCs	Quay Cranes
PMs	Prime Movers
PFB	Pull-From-the-Bottleneck
OFD	Object Fact Diagram
MLT	manufacturing lead-time
WIP	Work in Progress
DDP	Dual Decoupling Delay
SLP	Systematic Layout Planning
BSP	Bulk Synchronous Parallel-Based
CNC	Computer Numerical Control
CT	Container Terminals
SS	Six Sigma
WIP	Work in Progress
IT	Information Technology

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