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# An innovative framework for sustainable and centralized material procurement management based on a full-domain set theory

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**A B S T R A C T**

The purpose of this study is to propose a theoretical framework to solve the problem of insufficient data integrity, insufficient information circulation, and poor global data integration and linkage in the material procurement management subsystem. Based on the theory of full-domain set, this study proposes the conceptual framework, the full-domain linkage model, and the theoretical framework of centralized material procurement management. With the proposed innovative management framework, current problems such as insufficient data integrity, insufficient information circulation and data linkage in the procurement management system can be solved. This study provides reference significance for the construction of centralized material procurement management in the context of big data and offers theoretical guidance for large group enterprises to carry out centralized procurement management.

**A R T I C L E   I N F O**

*Keywords:*
Centralized procurement;
Full-domain set theory;
Big data;
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## 1. Introduction

With the application of information technology in all walks of life, the traditional data order and management methods can no longer meet the development needs of enterprises, and the management innovation work based on big data is urgent [1]. The centralized procurement management of materials refers to the unified procurement department of the enterprise through access to marketing resources to meet the production process of equipment and materials and other production materials. The information technology process and digital transformation of enterprises have aggregated data from various production factors and nodes in the business management process into a huge material procurement dataset, making it possible to innovate centralized material procurement management with the help of big data technology. However, the diversity of the form of big data itself and the extensiveness of the sources have led to the problem of dispersion and confusion among the subsystems of procurement management, mainly in the following ways: (1) Data are not complete. The heterogeneity of data between different subsystems in the procurement management system makes it difficult to integrate data. Most of the data collected and obtained by the procurement department are fragmented and incomplete. In order to make full use of them, it is necessary to spend a lot of human and material resources to analyze and process the data in the first place, which is costly. (2) Insufficient information flow. The lack of data integrity makes the integration of information between different systems poor, the procurement department and the demand department of material procurement information cannot be quickly synchronized. (3) Data cannot be linked. The limitations of the system and the heterogeneous structure of the data make the inter-departmental data across the system poorly linked, and it is impossible to track the materials from the perspective of their whole life cycle [2].

Current research on procurement, mainly focuses on the procurement research and supplier evaluation and selection under supply chain mode. They emphasized the dual relationship between suppliers and manufacturers [3-5], the ternary relationship between manufacturers and suppliers [6, 7]. It is mainly based on the procurement of manufacturing enterprises or commercial enterprises [8]. The purchased raw materials or components are used for processing and manufacturing (assembly) into new products, or retailers purchase products from suppliers for final sale. There are few literatures on the procurement of non-manufacturing large group enterprises, and there are few literatures on the analysis of procurement management combined with the procurement management practice system. From the overall research results, there are many existing researches have been constructed from the perspective of procurement process [9] and procurement behavior [10], which are mainly conducted through practical operation, organization and relationship management. Counting the number of relevant studies, we can obtain that almost one-third of the studies dealt with partnership issues, but fewer studies applied big data to material procurement management. In the era of big data, the connotation of material procurement management must be combined with big data thinking to enrich research content and expand procurement theory research. Combined with the current problem of the application of big data in the subsystems of procurement management that mentioned in paragraph one, we present the research question for this study: How to build an innovative centralized procurement management method based on big data?

The premise of centralized procurement management is to obtain the demand plans of different units for similar materials through effective communication. The motivation of this study is to innovatively integrate various business contents of procurement management, establish data linkage between the demand side and the procurement side, search for the inner linkage and synergistic mechanism of related material consumption, and realize intelligent centralized procurement management decision support based on big data. The contribution of this study can be summarized as follows: with the help of big data technology and the full-domain set theory, this study achieves management goals such as optimizing material procurement management by analyzing and modelling data that affects the production and operation rules of enterprises, studying the laws of material consumption and demand to forecast material demand, and studying supplier information that affects material acquisition and related factors that affect material procurement performance.

## 2. Conceptual framework of the innovation of centralized material procurement management

### 2.1 Current status of management of centralized material procurement

The centralized procurement mode is mostly applicable to large enterprise groups with large scale and many branches, aiming to improve the efficiency and effectiveness of procurement management. It usually targets procurement items with large volume, large procurement amount, important impact on enterprise production and operation and maintenance or strong commonality, unified technical specifications and easy to collect. Take the centralized procurement of materials of a large enterprise group in the railway industry as an example (as shown in Fig. 1), its management activities involve a large number of cross-departmental and cross-organizational multi-level and multi-threaded complex issues horizontally. The vertical organizational process can be decomposed into a demand plan proposal, demand plan approval, demand plan submission, procurement plan preparation, procurement plan approval, procurement plan commissioning, procurement plan aggregation, procurement sourcing, contract signing, logistics, performance acceptance, etc. It has obvious characteristics of a dynamic and complex system.

With the process of information technology and digital transformation of enterprises, enterprises rely on information technology to record and save production factors and business processes such as people, machines, materials and the environment in the form of data, gradually forming big data for material procurement management. The procurement department uses the information system to manage the demand information of each unit in a unified manner and form a unified organization for procurement after consolidation and integration, which has greatly improved the efficiency of procurement. However, most of the existing participating units in the procurement chain only emphasize the magnitude and acquisition of data when building big data, without giving full consideration to the comprehensive analysis and utilization of data, which creates the problem of difficult coordination between different enterprises and business areas. For example, the information systems of different branches under the same group may be compartmentalized in terms of data storage and processing, making it difficult to directly integrate and summarize information on the procurement needs of different organizations when collecting them, instead requiring a certain amount of human resources to be invested in matching information, such as fields required by different systems, and the extra work defeats the original purpose of centralized procurement to reduce human and material costs and improve procurement efficiency.

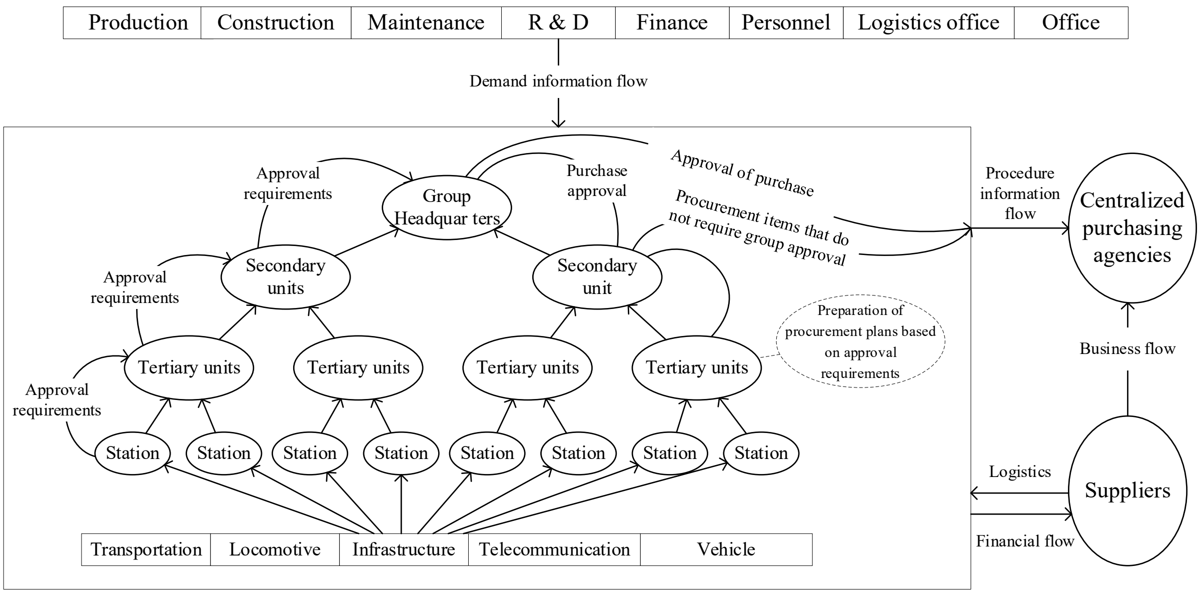


**Fig. 1** Schematic representation of the main centralized procurement process of a large enterprise group in the railway industry

## 2.2 The meaning of innovation in centralized material procurement management

Since Schumpeter introduced the concept of "innovation" in 1912, innovation theory has continued to mature. In this paper, the so-called innovation is all about the "new combination" of products, services, methods, technologies, and resources. In the context of the big data era, centralized material procurement management is not only the centralization of procurement forms, but also the integration of heterogeneous information systems to solve the problem of information silos, and at the same time to explore the intrinsic linkage and synergy mechanism of various business needs, and to realize the new management challenge of data-driven intelligent procurement decisions. Therefore, centralized procurement management innovation in the context of big data should essentially be a process of systematically examining business processes from a data flow mindset, thinking deeply about decision-making behavior from an algorithmic mindset, and making full use of information technology, such as artificial intelligence, to transform the resulting innovative ideas into a new procurement model, which focuses on two points.

- The data flow thinking and data-driven role. The core is to use a data perspective to describe the business content of procurement management throughout its lifecycle, dig into the information contained therein, find the inherent synergy mechanism, and build a linkage mechanism, with the ultimate goal of achieving intelligent procurement decisions based on big data. The ultimate goal is to achieve intelligent procurement decision-making based on big data.
- The supporting role of algorithmic thinking and big data technology. The core of this is the use of big data algorithms to build a centralized material procurement model system from a holistic perspective. It mainly includes: constructing a model group of material consumption laws among various processes through quantitative analysis of enterprise production and operation laws; predicting demand information by combining market change trends to construct an optimal procurement model group; Studying supplier information affecting material acquisition and related factors affecting material procurement performance to construct a model group of internal and external dynamic optimization.

### 2.3 Characteristics of innovation in centralized material procurement management

Compared with the traditional centralized procurement management model, the centralized procurement model that integrates data flow thinking and big data technology is mainly based on big data related to the enterprise internal, market environment, macro policy environment and natural environment. It has the characteristics of full-domain (as shown in Fig. 2), which is manifested in three major features such as data integrity, information connectivity and management intelligence.

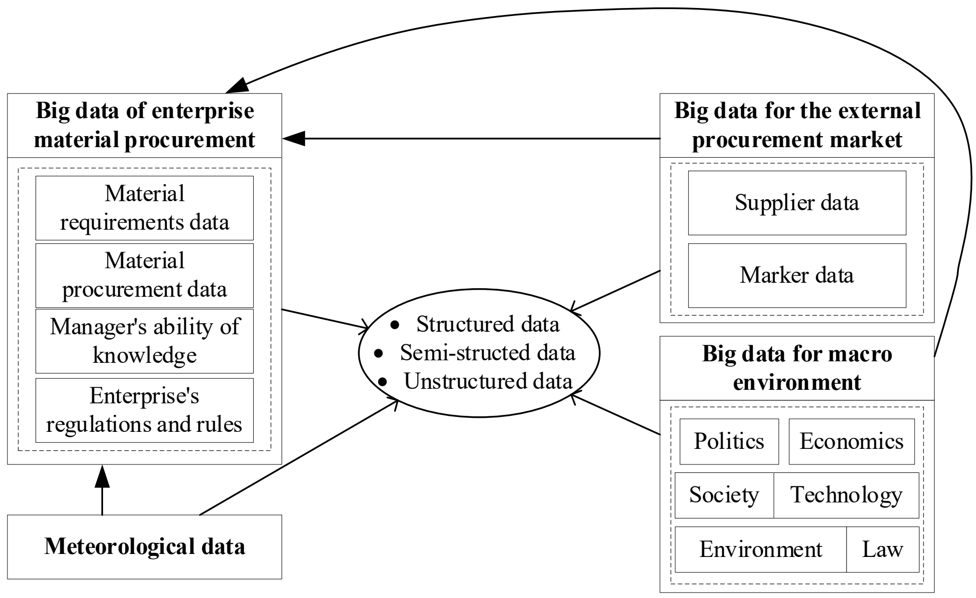


**Fig. 2** Materials procurement management full-domain data

*Data integrity*

From the perspective of the whole life cycle of the materials, its existence form changes from raw materials, finished products, commodities, enterprise production and operation materials to waste materials. Its properties and value of each stage and other information are stored in the form of data. Utilizing big data technology and related theories to organize and collect heterogeneous data from different system's collection, we can build a variety of materials life cycle of various information, which can serve as a basic data support for the enterprise low-cost, high utilization rate of procurement of materials. Accurate prediction of demand and accurate use of materials require comprehensive and common data, and the integrity of data throughout the life cycle of materials is the basic support for intelligent procurement decisions.

*Information connectivity*

The purpose of centralized procurement is to achieve low-cost and high-efficiency communication and sharing, and the process involves the coordination of a large number of resources, so there are more uncertainties. There are many influencing factors in the material procurement process. Obtaining the global data affecting procurement through advanced information technology is the basis for carrying out intelligent procurement innovation In the context of the big data era, ensuring connectivity between the acquired information is the basis for achieving innovation in centralized material procurement management. One of the cores of centralized procurement management innovation is to solve the problem of data heterogeneity and information barriers between different systems. We can obtain external full-domain resources that affect procurement decisions through break down information islands and open up the data connection

*Management intelligence*

In the context of big data, centralized procurement management is no longer just about centralizing the demand information collected, but also about the dynamic management of material changes and the accurate estimation of demand, as well as the correlation and connection of different material demands. The innovation of centralized procurement management of materials can make full use of external market data, supplier data, macro environment data, etc. Through the cloud sharing mechanism, in accordance with the data sharing categories of private cloud, hybrid cloud, public cloud, we can personalized obtain the internal and external global resources that affect procurement decisions. With the help of big data and artificial intelligence and other data processing and modeling technology, we can dynamically and intelligently assist centralized procurement management decisions with instant adjustment and precise matching [11].

The three features of centralized material procurement management innovation complement each other and jointly support the intelligent identification of procurement decisions. Data integrity is a basic requirement for information connectivity, and only by fully grasping the data between various systems can we extract effective demand information. Information connectivity is an important guarantee of management intelligence, and intelligent management requires shared information as support, and unimpeded information exchange and sharing is an important prerequisite for intelligent centralized procurement management.

## 3. Model setting of the whole domain linked procurement system

The innovation of centralized procurement management based on big data emphasizes the integration of technology, internal and external integration, value integration and other comprehensive data integration. The development of information and data processing technology makes the relationship between technology and enterprise operation closer and closer. Incorporating the latest information technology into enterprise centralized procurement management is one of the innovative directions of management concepts in the new era. The effective integration of internal and external data of enterprises can provide powerful data resources support for purchasing decisions. The process of providing products and services by enterprises is closely integrated with that by using and accepting products and services by consumers, so as to create value together. The fusion of social values enhances the benefits of centralized procurement management innovation. To realize the all-round data integration of enterprises, this paper introduces the full-domain set theory to design the research framework of centralized procurement of materials, to realize the data-driven collaboration of multiple subjects and objects of centralized procurement, and to optimize the centralized procurement strategy to achieve intelligent procurement. The overall research logic framework of this paper is shown in Fig. 3.

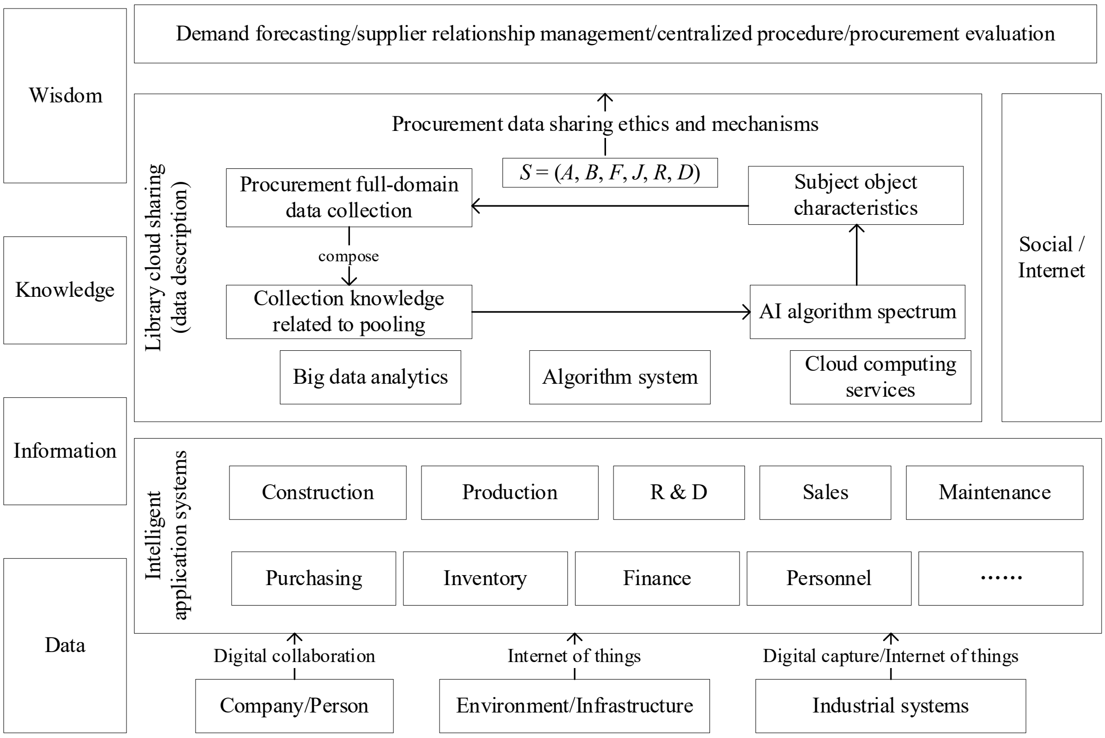


**Fig. 3** The logical framework of centralized procurement of materials based on the theory of the full-domain set with the full-domain linkage

Based on big data technology and the full-domain set theory, this study first collects and integrates the business requirements of various aspects of procurement management. This study describes the big data system of material procurement management in the full-domain set, and proposes a centralized procurement management target spectrum and determines the research boundary. This paper constructs a related global information collection for the data of the enterprise's internal material demand system information and the enterprise's external information involved in the target pedigree. Subsequently, based on the rules of centralized procurement management, we can determine the contextual function of the research boundary and the research objectives. Further, the global collection field data pair of the procurement management is trained by the dynamic function, and the spatiotemporal linkage rule set between the centralized procurement management and the global field is established. Finally, to solve the actual problems required by intelligent procurement and establish a decision set of centralized procurement targeting problems, this study the decision set of the centralized procurement targeting problem is established. This study adopts the deep learning technology to continuously mine the inherent laws and representation levels of the data, thereby forming an AI adaptive algorithm based on centralized procurement targeting problems and data pedigrees. In other words, the AI algorithm system can be adaptively adjusted based on the problem structure for different procurement management problems.

### 3.1 Definition of a centralized procurement of materials full-domain set

The concept of a full-domain set comes from the study of Borzooei *et al.* for full-domain control sets [12], as well as the study of several convex domains and their relations in multivariate complex spaces proposed by Cheng *et al.* [13]. Defining the full-domain set $S = (A, B, F, J, D)$, where $A$ and $B$ are non-empty classical sets, $A$ is used to describe the range from which the data arises, and $B$ is a description of all elements in $A$. $F$ denotes the mapping from set $A$ to set $B$, which defines the affiliation function of all elements in $A$, that is, defines a description for all elements in $A$. $J$ denotes the constraint scope of the membership function $F$, and $D$ represents the variable granularity of the data [14].

From the above definition, in terms of big data in a specific domain, and based on the studies of Lenin *et al.* [15] and Li *et al.* [16], this study gives the definition of each element in the centralized procurement of materials full-domain set $S_p = (A, B, F, J, R, D)$ in the business scenario as follows.

*Parameter A*. Parameter $A$ represents the root field element of the material procurement management business system and associated systems, which contains all existing material procurement management systems, industrial systems, monitoring systems, management systems and external information of the enterprise, such as supplier information, market information, environmental factors information and other full-domain information root fields associated with material procurement management. The specific structure and fields of each system are represented by $A_i$, which is a power set of related fields for material procurement management. Therefore, there is a full-domain collection of root fields $A = A_i = \sum_{i=1}^{n} A_i$ $(i = 1,2, \cdots, n)$. The field structure of $A_i$ depends on the specific business system database.

*Parameter B*. Parameter $B$ refers to the set of global root fields in different business scenarios drawn from the global root field set $A$ by the material procurement management business module on the basis of goal management. To obtain this field set, we first need to carry out a scenario transformation based on the target decision conditions and logic change rules of the material procurement management business module, and describe the transformed field power set based on problem characteristics (labels). Then, the corresponding data sub-field meta-system is constructed for the contextual description of different business target scenarios. This is a process of automatic separation of the spectrum, with the aim of enhancing the relevance and accuracy of data analysis for each target business system and increasing the depth of knowledge mining. Through the contextual descriptions, different data genealogies can be formed for different material procurement management objectives, and the intelligent decision-making of each business module of data normalization management and procurement management can be realized.

*Parameter F*. Parameter $F$ is an associative mapping relationship $A \overset{F}{\rightarrow} B$ between the root field set $A$ and the field power set $B$ in the material procurement management universe. $F$ can be obtained by logical operations on a variety of traditional sets or by training with various AI algorithms, econometric models, etc.

*Parameters J* and *R*. Parameters $R$ and $J$ are the associated business scope and the data scope of the study, respectively, which transformed into $F$ by the definition of the knowledge rules. The parameters $R$ and $J$ represent the business scope associated with the material procurement management full-domain data analysis requirements, and the data scope of the study according to the target spectrum extracted from the decision problem. They are used to define the scope of the thesis domain of the decision problem, which can be determined by the application scenario where the target problem is located.

*Parameter D*. Parameter $D$ is the set of decision objectives, which represents the optimization objectives of the fields in the power set $B$ after combining with the relevant scene data constituted by the realm-variant features, and it is the objective function for the operation of the AI algorithm system.

The full-domain set provides clustered and compressed various patterns by establishing the mapping between the target and the object features and constructing the image of the external information and the boundary shell. Moreover, it also transforms management coordination problems into data description problems through the effective management of related concepts, so as to realize the autonomous understanding of data on the objective world [17]. This idea can provide a standardized standard for the unified description of data, provide an effective protocol mechanism for simultaneously meeting the goals of confidentiality, business heterogeneity and barrier-free sharing of big data across specific business sectors. It is also an effective way to break through the information barriers of data resources in different sectors [18]. Zhang proposed collaborative analysis method for the management of data assets across the digital grid enterprise [19], Duan introduced a solution for a group-level full-domain data management and sharing platform based on DCMM [20], and Elouneg *et al*. established an open-source framework based on full-domain data [21]. These researchers all demonstrate the effective role of full-domain set theory in describing big data fields and their target genealogies, exploring the standardized granular representations [22], breaking through data barriers between scenarios and systems, and establishing a standard data cloud repository.

### 3.2 Algorithm selection for material centralized procurement targeting problem scenarios

Along with the increasing digitalization of human society, algorithms have become the basic rules that affect the operation of the world. The rise of the third wave of AI development, represented by machine learning algorithms, has broken through the limitations of human expression as revealed by the "Polanyi paradox" and made algorithms self-producing. Modern AI-based algorithms can form rule sets by learning from large data sets and assist in perception and decision making in different scenarios [23]. In this paper, we believe that selecting suitable AI algorithms and apply them to different scenarios of centralized procurement of materials, mining and analyzing the intrinsic connections and laws of data in different business scenarios, and promoting the system to automatically select the matching algorithms according to the scenario transformation, can effectively assist centralized procurement management.

Artificial intelligence is the science of how to simulate the implementation of human intelligence. Among the many algorithms to achieve artificial intelligence, machine learning algorithms have developed faster and deeper. It is mainly studied how to simulate the implementation of human learning behavior with computers to acquire new knowledge or skills and reorganize the existing knowledge structure to continuously improve its performance. Deep learning is a branch of machine learning, and an algorithm that uses artificial neural networks as an architecture for learning representations of data. It obtains a deeper and more expressive model by superimposing simple models on top of each other. Machine learning can be divided into supervised learning according to whether the input data has labels or not: supervised learning, which models the correlation between several features of data and several labels (types), and unsupervised learning, which models the features of data without any labels, . Compared to supervised learning, unsupervised learning is more like an exploration of the data structure. Supervised learning algorithms can be further classified into subtypes and regression types according to whether the data are discrete or continuous values. Unsupervised learning algorithms can be further classified into aggregation types and dimensionality reduction types according to different operational purposes. In the innovation of centralized material procurement management based on the full-domain set theory, managers can select matching AI algorithms to provide decision support for scenario-specific targeting problems according to management objectives. For example, we can obtain the usage status of various materials in the chain by analyzing and mining the full-domain data of supply chain and production chain, and then combine the supply capacity of suppliers and the current procurement status of enterprises to select suitable algorithms to predict the next optimal procurement time and procurement quantity, thereby reduce the inventory pressure from the whole supply chain level. Currently, the available algorithms are logistic regression, ridge regression, K-means, support vector machine, Bayesian network, neural network, etc., which can be selected according to the actual situation.

### 3.3 Material centralized procurement full-domain linkage algorithm system construction

One of the key points of centralized procurement of materials based on global set theory is the construction of linkage relationship of full-domain data, the algorithm system of centralized procurement of materials involving the algorithm and linkage relationship is defined as follows.

*Unary operation*. The unary operation mainly includes the compound of selection operation, projection operation and relational operations.

*Binary operations*. Binary operation mainly includes Cartesian product operations, renaming operations, and linkage operations.

*Linkage relations*. On the basis of unary and binary operations, the linkage relations of data (Definition 1), the full-domain linkage relations of data (Definition 2), the equality relations of data (Definition 3), and the set size relations of data (Definition 4) are given as follows.

Definition 1: Linkage relations. Given the relations $r_1(R_1)$ and $r_2(R_2)$, $R_1, R_1 \in D$ let $X$ denote a relation instance, $X_1$ be a tuple of $r_1$, $A_1$ be the power set of fields in the relation $R_1$, $A_2$ be the power set of fields in the relation $R_2$, where $a_1 \in A_1$ and $a_2 \in A_2$ , then a sample of the generalized Cartesian product between fields satisfying certain conditions from the relation $r_1$ and the relation $r_2$ can form a linkage operation

$$r_1 \rhd\lhd r_2 = \{X_1 \in R_1 \wedge X_2 \in R_2 \vee [X_1(a_1)] \leftrightarrow V[X_2(a_2)]\} \neq \emptyset \tag{1}$$

where $\leftrightarrow$ is the relationship comparator, $V(\cdot)$ is the field value. It can be seen that when $\leftrightarrow$ is the "equal sign",$r_1 \rhd\lhd r_2$ is the equal value link, and if $\{X_1 \in R_1 \wedge X_2 \in R_2 \wedge [X_1(a_1)] \leftrightarrow V[X_2(a_2)]\} \neq \emptyset$ exists, then the relationship $r_1$ is linked to the relationship $r_2$.

Definition 2: Full-domain linkage of data. Given a relation $R_i$ and its corresponding sample $X_i$ , for a target system $D = \{R_1, R_2, \cdots, R_n\}$ containing multiple relations in the bounding shell, all relations $U_{j\in[1,n]} R_j$ satisfying the condition$\{X_i \in R_i \wedge X_j \in R_j \wedge V[X_i(a_i)] = V[X_j(a_j)]\} \neq \emptyset$ are full-domain linkage off the sample $X_i$ and $U_{j\in[1,n]} A_j$ is the full-domain field of the sample $X_i$.

Definition 3: Equivalence relationship. For two data samples $X_1$ and $X_2$ located in a common bounding shell $J_1 = J_2$ and business system $D_1 = D_2 = \{R_1, R_2, \cdots, R_n\}$ , there is $S(X_1|J_1) = S(X_2|J_2)$ if $X_1$ and $X_2$ have the same full-domain linkage field $B_1^{'} = B_2^{'} = \cup_{i\in[1,n]} A_i$ .

Definition 4: Set size relationship. The size of a full set represents the coverage of all data associated with sample $X$ within the bounding shell. Given a full set $S(X_1|J)$ and $S(X_2|J)$ under the condition of bounding shell $J$, the comparison of the set size relationship reflects the probability that the range of values of one full field $B(X_1)$ is greater than the range of values of another full field $B(X_2)$ , let $B(X_1) = \{b_{11}, b_{12}, \cdots, b_{1i}, \cdots, b_{1m}\}$ , $B(X_2) = \{b_{21}, b_{22}, \cdots, b_{2i}, \cdots, b_{2n}\}$ , based on the full probability formula

$$P\{S(X_1|J) \geq S(X_2|J)\} = \sum_{i=1}^{s} P(N_i) P\left\{\frac{V[B(X_1)] \geq V[B(X_2)]}{N_i}\right\} \tag{2}$$

Where $N_i$ denotes the number of possible field range distributions for the $i$-th possible field. $V(\cdot)$ and, obviously, $\sum N_i = max\{m, n\}$. Let the full range of field values be denoted as: $V[B(X_1)] = [X^-, X^+]$ , $V[B(X_2)] = [Y^-, Y^+]$ , $x^- \in X^-$ , $x^+ \in X^+$ , $y^- \in Y^-$ , $y^+ \in Y^+$.

In particular, when the range of values of the full field obeys the same distribution, the set size relationship can be expressed as

$$P\left\{\frac{V[B(X_1)] \geq V[B(X_2)]}{N_i}\right\} = \min\left\{\max\left\{\frac{x^+ - x^-}{x^+ - x^- + y^+ - y^-}, 0\right\}, 1\right\} \tag{3}$$

However, in many cases, the values of the full field do not necessarily obey the same distribution. For the case where the range of values of the fields do not overlap, the result of Eq. 3 can be followed. For the case where the range of values of the full field overlaps, let the interval between $[x^-, x^+]$ and $[y^-, y^+]$ be $[z^-, z^+]$ , where the probability density of $[x^-, x^+]$ is denoted as $\psi_1(x)$ and the probability density of $[y^-, y^+]$ is denoted as $\psi_2(x)$ . Dividing $[z^-, z^+]$ into $s$ equal parts and taking the limit, the set size relationship can be expressed as

$$P\left\{V[B(X_1)] \geq \frac{V[B(X_2)]}{N_i}\right\} = \begin{cases} 1, x^- \geq y^+ \\ \int_{y^-}^{z^+} \psi_2 dx - \lim_{s\to\infty} \frac{1}{s^2} \sum_{p=1}^{s} \left\{\psi_2\left[z^- + \frac{p(z^+ - z^-)}{s}\right] \sum_{q=1}^{p} \psi_1\left[z^- + \frac{p(z^+ - z^-)}{s}\right]\right\} \\ 0, y^- \geq x^+ \end{cases} \tag{4}$$

# 4. Theoretical framework of the innovation of centralized material procurement management

## 4.1 Innovation of centralized material procurement target system

The material procurement management of large enterprise groups focuses on supplying materials required for production operations in a timely manner, with the main goal of not affecting the operational production of the enterprise, while ensuring safe production and implementing policy requirements such as low carbon emissions and green environment protection [24]. In this paper, the five comprehensive management objectives of Right quality, Right time, Right cost, Right quantity, and Right place, and the two emerging objectives of Safety and Sustainability are introduced. The "5R+2S" target model of material procurement management is constructed, and a multi-level target spectrum analysis is conducted around the target model, including four levels of target management indicators, business module description, information system, and data sources. The procurement management spectrum framework is shown in Fig. 4.

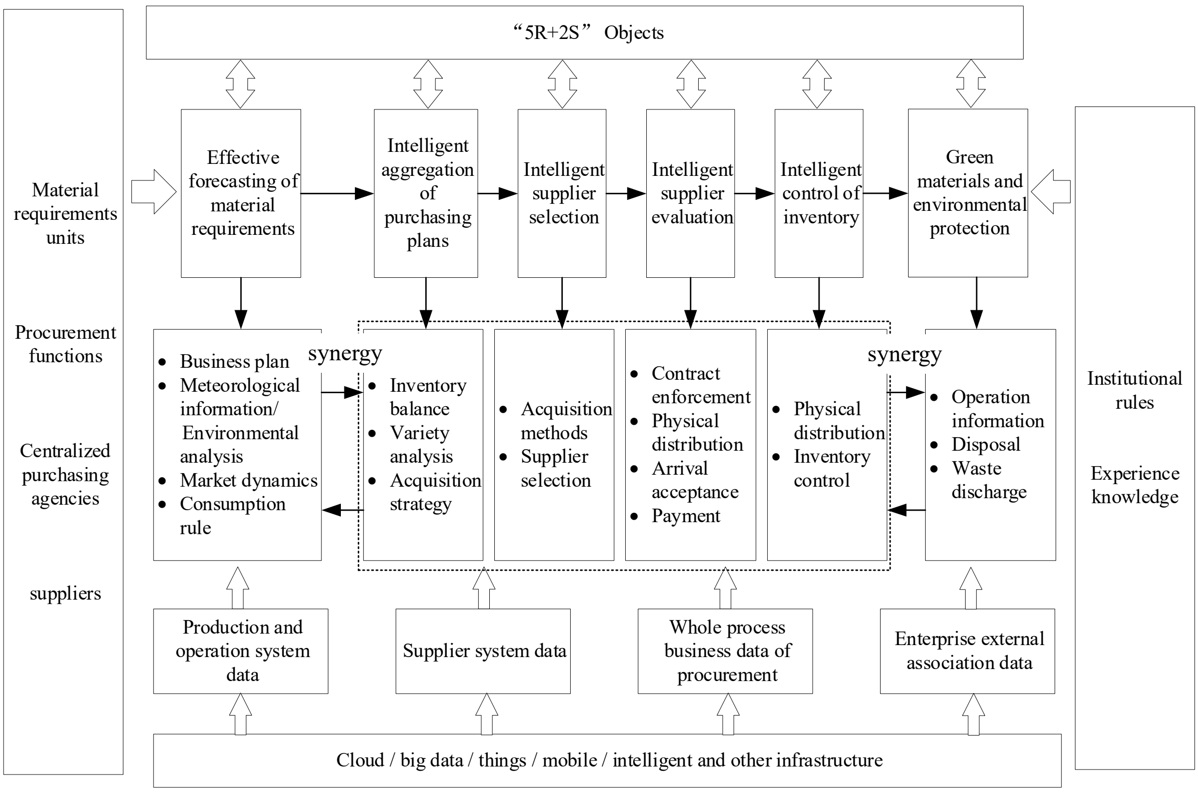


**Fig. 4** Material centralized procurement target system

- Quality (Right quality). Quality management is the life of the enterprise. The purchasing department should establish a strict quality management system, set standards for measuring quality, find out the possible quality problems of the products in the whole area through the analysis of data mining, identify poor quality products at the earliest, and give quality control and quality improvement and other aspects of quality management advice.

- Right time. Procurement managers not only need to achieve on-time and on-demand procurement goals and avoid unnecessary storage and warehousing costs, but also need to ensure supply and minimizing procurement costs in the face of market fluctuations, and maximize the organization's capital utilization and procurement management efficiency. Managers can apply new technologies such as mobile internet, big data, cloud computing, internet of things and artificial intelligence to achieve online, data-based and intelligent material management, and make reasonable forecasts of material consumption and supply time points to ensure supply and cost reduction.

- Right cost. The main indicator to measure the effectiveness of procurement management is the total cost of procurement. The centralized procurement management based on the full-domain set theory can break the information barrier of each link, make the procurement of materials more transparent, and grasp the usage status and inventory situation of the whole life cycle of materials to the greatest extent. Therefore the whole procurement demand chain can be managed prospectively and the procurement cost can be effectively reduced.
- Right quantity. Centralized procurement management based on the full-domain set theory can obtain clear production and demand information for each link in a timely manner. According to the accurate target information, we can use artificial intelligence-related algorithms to forecast the quantity of materials required for the production link and provide decision support for the procurement department.
- Right place. Enterprises are often prone to take the initiative in cooperation with suppliers that are close to them, and it is best for enterprises to choose close suppliers to implement when choosing pilot suppliers. Proximity not only makes it easier for buyers and sellers to communicate and deal with matters more quickly, but also reduces procurement logistics costs.
- Safety. The centralized procurement management of materials based on the full-domain set theory can accurately provide detailed labels for each material, each link in the production process, and even all kinds of data on the environmental conditions required for accidents to occur in the warehouse. Based on the system's analysis and prediction of potential dangers in advance warning, we can maximize the elimination of products and warehouse security risks.
- Sustainability. The centralized procurement of materials based on the full-domain set theory has a strong scale and accuracy, symbolizing not only the comprehensive development of procurement management from paper to electronic, but also the change of management from decentralization to centralization. The accumulation of data gradually improves the accuracy of the algorithm, resulting in more accurate forecasting of demand budgets and a virtuous and sustainable cycle.

### 4.2 Innovation in the management concept of centralized material procurement

In accordance with the concept of supply chain management, we innovate the procurement model and establish a supplier integrity system to reduce procurement costs. Exploring the multi-life cycle management of materials and equipment based on the whole life cycle management of materials and equipment. Specific measures are shown as follows:

- By continuously optimizing and improving the information system, the scientific level of management of the entire supply chain is improved, and upstream and downstream visibility of the supply chain is achieved. The supplier collaboration function deployed in the system realizes horizontal collaboration with suppliers in terms of inventory resources, delivery and receipt, logistics progress and invoice settlement; the big data analysis system provides reliable data and analysis tools for the entire supply chain to carry out decision-making analysis; Through the electronic material issuance intelligence system and the joint management of inventory by suppliers and other aspects of information technology, the collaboration level of the overall supply chain is improved to achieve management low-cost and efficient operation.
- The intensive procurement model was further applied. Carried out framework agreement procurement business for collectively procured materials. We establish a strategic cooperation model with suppliers, set up an integrated information sharing platform for procurement and supply, and establish procurement and supply-wide data. On the other hand, through framework agreements for the procurement of bulk goods, the supply chain cooperation model is continuously innovated.

- Promote localization substitution and new product trials. Study the main content of localization work, the way to carry out it, and how to support and encourage localization work from the material procurement management system and bidding and procurement strategy. For example, set up an assessment index of "completion rate of high-end parts development" to ensure the process and quality of high-end parts development.
- Establish a supplier integrity management system. Use big data technology to establish a secure information channel. We can establish a set of honest supplier management system by continuously optimize business processes, create a clean procurement environment, cultivate a group of honest and excellent suppliers, and provide a guarantee for intensive procurement, sunshine procurement and green procurement.

### 4.3 Innovation of centralized material procurement management mechanism and system

The centralized procurement management of materials based on the full-domain set theory can link information from various departments, so that operations such as demand information reporting no longer have to be done centrally in a limited time, but can be managed as part of daily work and reported in real time. With the help of a global platform, the procurement management department can change the procurement model from the original multi-layer structure to a flatter system, improving the flexibility of the organization and the efficiency of procurement management [25].

Large groups of companies often set up supply chain management committees or similar bodies to lead the group-wide procurement management, with systems and regulations to clarify and ensure that data owners can share the required data with purchasers. In addition, the group needs to work with suppliers to build an appropriate big data sharing system based on the actual situation of each department [26]. At the group level, develop group company procurement strategies, models, basic management systems for procurement management and consider major procurement matters. A full-time procurement management department is set up to independently categorize procurement as responsible for procurement management system construction, centralized procurement plan management, tender and procurement management, information system construction, supplier management, material reserve management and procurement supervision and management, laying the institutional foundation for the realization of a region-wide data platform.

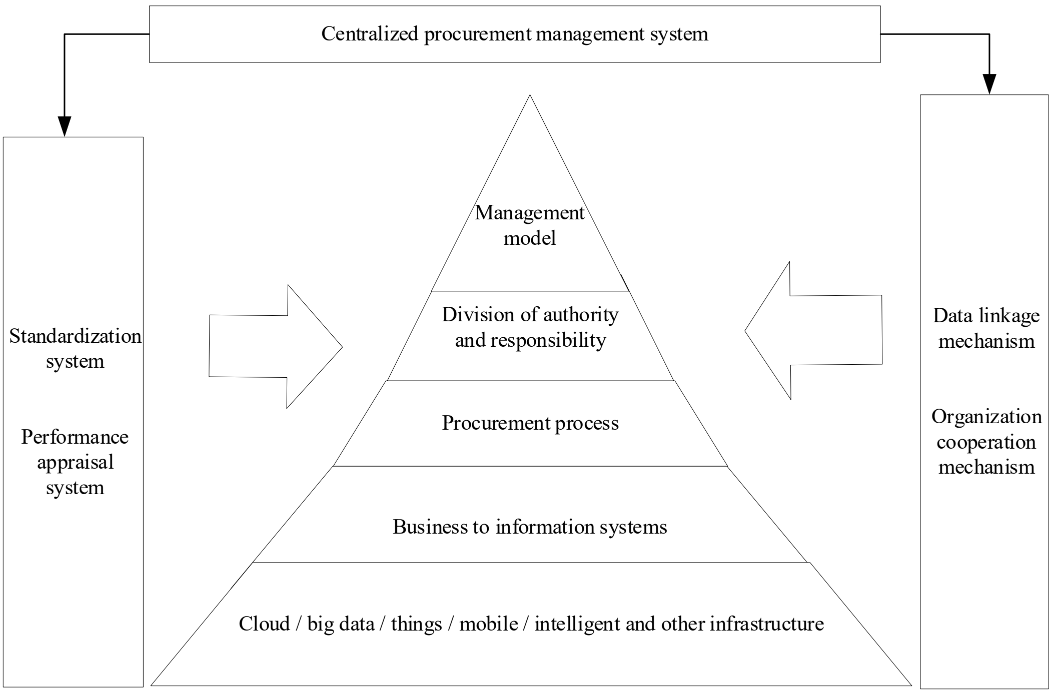


**Fig. 5** Centralized procurement management system

Horizontally, it coordinates various functional departments at the group level to carry out procurement-related business audits, and vertically coordinates enterprises at all levels to ensure smooth information communication. At the same time, a specialized procurement execution unit is set up to execute group-wide procurement operations, forming a management model with "separation of management and administration" and "clear authority and responsibility" with the group's procurement management department to ensure sunshine procurement. Secondary enterprises have a clear department responsible for the implementation of procurement management. The centralized procurement management system is shown in Fig. 5.

## 5. Concluding remarks

In this paper, in view of the problems existing in material procurement management based on big data, the full-domain set theory is introduced, the theoretical basis of material centralized management innovation is discussed, and the corresponding theoretical framework of material centralized management innovation is constructed. The analysis in this paper shows that: Firstly, there are problems of incomplete data, insufficient information circulation and inability to link data in material centralized management in the context of big data. Secondly, the connotation of innovation in material centralized management in the context of big data and its three distinctive features of data integrity, information connectivity and management intelligence are proposed to provide strong support for the in-depth exploration of material centralized management innovation in the perspective of the full-domain. Furthermore, the theory of full-domain set is introduced into centralized material procurement management, proposing a logical framework for centralized procurement of full-domain linkage, and illustrating that existing artificial intelligence algorithms provide a technical basis for the solution of material centralized targeting problem scenarios. Finally, through the innovative definition of the target system, management system, management concept and management mechanism of centralized material procurement, a theoretical framework for centralized material procurement management innovation based on the theory of full-domain set is built. This paper provides innovative ideas for large group enterprises to carry out centralized procurement management in the era of big data.

#### Data availability statement

All data could be accessed upon request to the corresponding author.

#### Conflicts of interest

The authors declare no conflict of interest.

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# A matheuristic approach combining genetic algorithm and mixed integer linear programming model for production and distribution planning in the supply chain

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**A B S T R A C T**

A number of research studies has addressed supply chain planning from various perspectives (strategical, tactical, operational) and demonstrated the advantages of integrating both production and distribution planning (PDP). The globalisation of supply chains and the fourth industrial revolution (Industry 4.0) mean that companies must be more agile and resilient to adapt to volatile demand, and to improve their relation with customers and suppliers. Hence the growing interest in coordinating production-distribution processes in supply chains. To deal with the new market's requirements and to adapt business processes to industry's regulations and changing conditions, more efforts should be made towards new methods that optimise PDP processes. This paper proposes a matheuristic approach for solving the PDP problem. Given the complexity of this problem, combining a genetic algorithm and a mixed integer linear programming model is proposed. The matheuristic algorithm was tested using the Coin-OR Branch & Cut open-source solver. The computational outcomes revealed that the presented matheuristic algorithm may be used to solve real sized problems.

**A R T I C L E   I N F O**

*Keywords:*
Production and distribution planning;
Supply chain;
Matheuristic;
Genetic algorithm;
Mixed integer linear programming model

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## 1. Introduction

The globalisation of markets has lee to companies to optimise their processes and resources to remain competitive. Nowadays, optimisation is a relevant factor for improving firms' performance, and for turning the challenges that they face into competitive advantages [1]. One optimal strategy for profits that can minimise a company's total costs is to integrate different business functions, such as purchasing, inventory management, production and distribution [2]. Therefore, it is an important factor for optimizing supply chain enterprises to establish greater integration production and distribution planning (PDP) [3]. The PDP problem is defined by Safaei *et al.* [4] as a firm's scheduling process to manufacture the right products and to ship the quantities of the right products to the right place at the right time.

Increasing pressure to minimise total production and logistic costs means that supply chain agents are having to re-examine production-distribution policies, and to maximise the use of physico-technological assets [5]. Properly coordinating PDP in supply chains is a challenging problem because companies expand internationally and move to a competitive environment that requires greater collaboration. Efficient supply chain cooperation involves many coordinated decisions being made at several decision levels (e.g., strategical, tactical, operational) about products, financial resources and information.

In this context, the present research work develops an efficient matheuristic approach to solve the integrated PDP problem. A matheuristic algorithm is defined by Boschetti *et al*. [6] as “the interoperation of metaheuristics and mathematical programming techniques". There are different approaches for combining metaheuristics with exact methods, and each technique has its individual advantages and disadvantages. However, the aim is to benefit from synergy. Several researchers present a taxonomy that classifies this type of cooperation. Table 1 shows several approaches by different authors, although some have similar characteristics.

When designing a matheuristic, the question is, which components can work together to generate an efficient algorithm? Although supplying a collaboration rule does not seem a feasible approach, the matheuristic design involves functionality and architecture. Thus, the cooperation level can be ranked according to its hierarchy, as in Table 2.

**Table 1** Classification of matheuristic approaches

<table>
<tr><th>Approach</th><th colspan="2">Classes</th></tr>
<tr><td>Cooperation between exact and local search methods [7] based on Dumitrescu & Stützle [8]</td><td colspan="2">• Exact algorithms to browsing through neighbourhoods in local search algorithms.<br>• Exact algorithms intended for specific hybrid metaheuristics procedures.<br>• Explore boundaries in constructive heuristics.<br>• Local searches or constructive algorithms guided by data from integer programming model relaxations.<br>• Exact algorithms for smaller problems using solutions from local searches</td></tr>
<tr><td rowspan="2">Combination between exact techniques and metaheuristic algorithms [9], [10]</td><td>Collaborative combinations<br>Algorithms exchange information. None is contained in any other. Both procedures can be executed sequentially, interlaced or in parallel.</td><td>Subclasses<br>• Sequential execution<br>• Parallel and intertwined execution</td></tr>
<tr><td>Integrative combinations<br>One technique is component-integrated into another technique with a master-slave structure. An exact or metaheuristic algorithm can be presented with a master-type structure and at least one integrated slave.</td><td>• Incorporating exact algorithms into metaheuristics<br>• Incorporating metaheuristics into exact algorithms</td></tr>
<tr><td>“MASTER-SLAVE” structure with a guiding process and application process [11]</td><td colspan="2">• Metaheuristics operate at the master level and, thereby, control and guide actions to the exact technique.<br>• The exact method operates as a master to call/control by the metaheuristic approach.</td></tr>
</table>

**Table 2** Hierarchical matheuristic classification [12]

| Hierarchy | Description |
|---|---|
| LRH (low-level relay hybrid) | It depicts hybrid schemes in which a metaheuristic approach is included in an exact approach to improve the search strategy |
| LTH (low-level teamwork hybrid) | It describes one search element of a metaheuristic to be replaced with another exact algorithm |
| HRH (high-level relay hybrid) | Autonomous algorithms are executed in a sequence. The stage can be either pre-processing or post-processing, i.e., two groups of algorithms (metaheuristics + exact algorithms) are provided with some data in sequence |
| HTH (High-level Teamwork Hybrid) | A combination of metaheuristics and exact algorithms that performs a parallel search and cooperate to find relaxed optimal solutions, better lower or upper bounds, optimum subproblem solutions, partial solutions, etc. Metaheuristics and exact algorithms solve partial, specialised or global optimisation problems and exchange helpful information. |

Recent studies, such as that presented by Kumar *et al.* [13] , provide a literature review of the quantitative approaches applied to combined PDP. These authors concluded that the main modelling approaches for this problem type are MILP (mixed integer linear programming), while the main applied solution approaches are those that resort to optimisation software, followed by genetic algorithms (GAs). Computational experiments in small instances use mainly LINGO and CPLEX to solve MILP and Matlab and C++ in large instances to solve heuristic and metaheuristic methods. In this review, we observe that matheuristic methods have not yet been discussed in-depth. As far as the authors know, to date no research has addressed the PDP problem using this type of matheuristic.

In this context, we propose developing a solution strategy for the PDP problem with a mathematical algorithm that is positioned in the hierarchical classification described in Table 2 as a High-level Teamwork Hybrid. This strategy is useful because the search space of the MILP model is considered to be too big for a solver to solve it. Therefore, we employ a GA that exchanges information in parallel to the MILP model to diminish the search space.

Given the complexity of PDP problems, they prove difficult when implementing large datasets or solving real SME problems with a MILP model. For this reason, some companies choose to use commercial solvers for this type of problem. However, some SMEs cannot afford to buy a commercial solver because of its high cost but, as digitisation needs are accelerating, many companies are considering how to be equipped with a digital infrastructure insofar as it does not constrain them and does not cost too much. So those SMEs that have implemented open-source software have made significant savings in technology spending because they do not have to pay annual software licences and have not run the risk of software becoming obsolete when licences expire [14].

Accordingly, this article contributes: (i) a new matheuristic approach to solve the PDP problem; (ii) the matheuristic algorithm was tested and compared to a non-commercial Coin-Branch & Cut (CBC) solver and employs a free open-source operating system (Linux). The proposed approach's effectiveness is proven by solving randomly generated test datasets with real data sizes.

The rest of this article is arranged as follows. Section 2 briefly presents a literature review about the integrated approach to supply chain PDP. Section 3 offers a mathematical model. Section 4 details the matheuristic algorithm for solving the planning-distribution problem. Section 5 presents the evaluation of the matheuristic algorithm using large instances to simulate real-life companies. Finally, Section 6 defines some conclusions and future research directions.

## 2. Related works

This section reviews the literature about integrating decisions from PDP functions, along with the solution approaches suggested for these problems. This problem has been paid plenty of attention in recent years. Literature reviews like that by Chen [15] indicate several future research lines. One of them states that more effort should be made to create heuristic or metaheuristic methods for this type of problems, which are NP-hard, as there are very few solution algorithms for this type of problems. Years later Fahimnia *et al*. [16] describe that the use of heuristic, metaheuristic and simulation techniques predominate in the literature, but propose employing new techniques, and suggest having to extend the effectiveness of solution techniques to deal with realistic PDP problems as most techniques have been applied to deal with small- and medium-sized problems. Lastly, the work by Kumar *et al*. [13] indicates the extensive use of metaheuristic algorithms like heuristic algorithms, GAs and exact methods, but does not reveal the use of matheuristic algorithms.

Accordingly, related work like that of Raa *et al.* [5] proposes an aggregate PDP model for injection moulding production in the many facilities of a plastics manufacturer. This MILP is solved by the Gurobi solver for small instances. For large instances, these authors employ an iterative matheuristic that utilises a decomposition heuristic. Bilgen and Çelebi [1] offer a combined simulation and MILP approach for integrated production and distribution problems in the dairy industry. The MILP model is solved with CPLEX and the hybrid approach employs ARENA.

Su *et al.* [17] propose combining distinct algorithms like the GA and particle swarm optimisation (PSO). The GA comes with a learning scheme, and a hybrid algorithm that combines PSO techniques with the GA and a learning scheme to solve both partner selection and the PDP problem in a manufacturing chain design. Moattar Husseini *et al.* [18] put forward bi-objective MILP for integrated PDP with manufacturing partners. One of the objectives of this model is to minimise the total cost by covering production, inventory holding purchases from partners and transport-distribution costs. Another objective aims to maximise the quality level of the products that partners supply on the planning horizon. For this problem, they employ LINGO to solve the model in small instances. However, as the problem in large instances is classified as NP-hard, the authors solve it by a Non-Dominant GA II (NSGA-II) and a Multi-Objective PSO (MOPSO) algorithm. The computational results confirm the suitability and practicality of these two algorithms, but the MOPSO algorithm obtains better results in most instances. Devapriya *et al.* [19] report a PDP problem with a perishable product. The problem is modelled by MILP, is solved with CPLEX, employs a memetic algorithm to solve the problem in large instances, and obtains good solutions in a relatively shorter computational time.

Kazemi *et al.* [3] put forward a hybrid algorithm that combines a multi-agent system and three metaheuristic algorithms, including a GA, a tabu search and simulated annealing. They propose a MILP model that is solved with LINGO. They employ Matlab to evaluate the hybrid approach. Their results reveal that LINGO better works in small instances, while the hybrid approach delivers better solutions in large instances. In a multifactory supply chain, Gharaei and Jolai [20] study a multi-agent scheduling problem with distribution decisions. To do so, they propose using a MILP formulation to solve the problem with CPLEX by employing small and medium instances. They also develop a multi-objective evolutionary algorithm based on decomposition by combining the Bees algorithm and using Matlab, which well performs in long instances. Marandi and Fatemi Ghomi [21] put forward an integrated production-distribution scheduling problem. They aim to simultaneously find a production schedule and a vehicle routing solution to minimise the sum of delay and transportation costs. They apply CPLEX for small problems and propose a new algorithm for medium and large problems, namely the Improved Imperialist Competitive Algorithm, which applies a local search algorithm based on a simulated annealing algorithm.

The literature review highlights a growing research tendency to integrate PDP functions. It reveals that companies tend to collaborate with manufacturing partners to better respond to demanding market conditions, and they focus more on their core activities. Interest is shown in heuristic and metaheuristic methods, which are frequently employed to solve these problems with large instances. These instances normally represent the size of the data actually employed by real companies, although different variants of the PDP problem exist. Models tend to be solved mostly with a commercial solver, of which CPLEX is the most widespread. Despite previous works having discussed some combinations of the above algorithms, other combinations have not yet been addressed by the literature, such as those using matheuristic algorithms in practice.

Based on these results, this study considers an integrated PDP problem formulated as a MILP model. As the literature reports the potential effectiveness of GA-based algorithms [18], a combined solution approach with a GA and a mathematical model is herein considered. A non-commercial solver and an open-source operating system are also implemented. The next sections discuss the particulars of the posed problem, its formulation and the solution approach.

## 3. Problem definition

This section offers details of the studied problem and formulates the proposed model. The PDP problem herein contemplated is based on Park [22].

The MILP model takes these assumptions:

- For the production stage: many production plants produce multiple items with a limited capacity per time period. Each product type has a setup cost, while production plants have a limited storage capacity, and produced items are shipped directly to points of sale.
- For the distribution stage: distribution is performed with a fleet of homogeneous vehicles, which are parked in production plants.
- The vehicle movement incurs on: (i) a fixed cost in relation to the depreciation of vehicles, insurance, etc.; (ii) a variable cost according to the transported item, quantity and route.

For points of sale: an item's demand during a period at a point of sale consists of two components: (i) "core demand": the amount of main demand that the point of sale must meet by loyal customers in the long term; (ii) "forecasted demand": the total amount, including core demand. Unmet demand at a point of sale is considered a stockout (rejected demand) and does not allow deferred demand. Each point of sale can maintain a limited amount of inventory at a very high cost. An overview of the considered problem is demonstrated in Fig. 1.

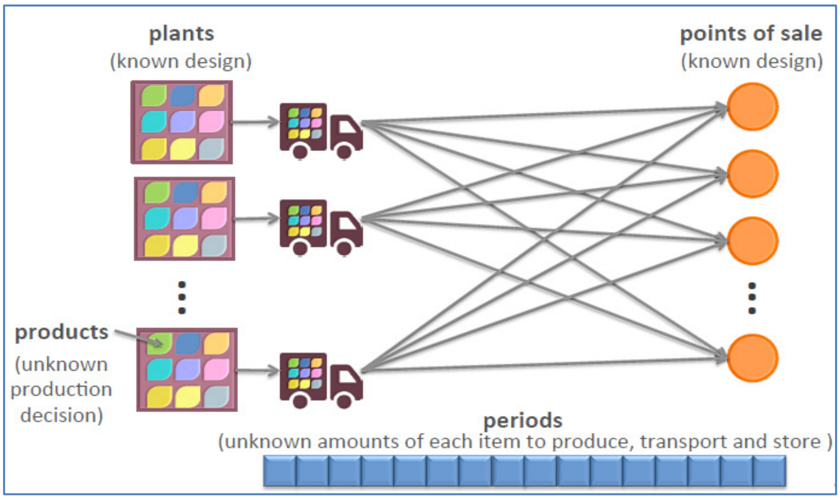


**Fig 1** Illustration of the integrated production and distribution planning problem

### 3.1 Notation

The PDP problem nomenclature is shown below.

**Table 3** The MILP model nomenclature

| Notation | Description |
|---|---|
| Sets | |
| $i$ | Index of plants $i \in \{1,\ldots, I\}$ |
| $j$ | Index of points of sale, $j \in \{1,\ldots, J\}$ |
| $k$ | Index of products (parts) $k \in \{1,\ldots, K\}$ |
| $t$ | Index of time periods $t \in \{1,\ldots, T\}$ |
| Parameters | |
| $C_{ik}$ | cost of producing 1 unit of product $k$ in plant $i$ |
| $s_{ik}$ | cost of setup for product $k$ in plant $i$ |
| $o_{ik}$ | time of producing 1 unit of product $k$ in plant $i$ |
| $u_{ik}$ | time of setup for product $k$ in plant $i$ |
| $hp_{ik}$ | unit holding cost per period for product k in plant $i$ |
| $L_i$ | production capacity per period of plant $i$ |
| $dijk$ | cost of transporting 1 unit of product $k$ from plant $i$ to point of sale $j$ |
| $g$ | fixed cost per vehicle |
| $B$ | capacity per vehicle |
| $E_{jkt}$ | core demand of product $k$ at point of sale $j$ during period $t$ |
| $F_{jkt}$ | forecasted demand of product $k$ at point of sale $j$ during period $t$ |
| $p_{jk}$ | price of sale of 1 unit of product $k$ at point of sale $j$ |
| $hr_{jk}$ | unit holding cost per period for product $k$ at point of sale $j$ |
| $Wr_j$ | inventory capacity of point of sale $j$ |
| $v_{jk}$ | unit stockout cost of item $k$ at point of sale $j$ |
| Variables | |
| $x_{ikt}$ | amount of product $k$ produced at plant $i$ during period $t$ |
| $q_{ijkt}$ | amount of product $k$ transported from plant $i$ to point of sale $j$ during period $t$ |
| $Y_{ikt}$ | 1 if product $k$ is produced a plant $i$ during period $t$; 0 otherwise |
| $ap_{ikt}$ | inventory level of product $k$ at plant $i$ during period $t$ |
| $ar_{jkt}$ | inventory level of product $k$ at point of sale $j$ during period $t$ |
| $z_{ijt}$ | number of vehicles needed for distribution from plant $i$ to point of sale $j$ during period $t$ |

The objective function maximises sales revenues at points of sale, minus the costs of setup, production and inventory at plants, the costs of inventory and stockout at points of sale, and the costs of vehicles and transport.

$$
\begin{aligned}
MaxZ = & \sum_j \sum_k p_{jk} \cdot \sum_t \left( ar_{jkt-1} + \sum_i q_{ijkt} - ar_{jkt} \right) \\
& - \left( \sum_i \sum_k c_{ik} \cdot \sum_t x_{ikj} + \sum_i \sum_k S_{ik} \cdot \sum_t Y_{ikt} + \sum_i \sum_k hp_{ik} \cdot \sum_t ap_{ikt} + \right) \\
& - \left( \sum_j \sum_k hr_{jk} \cdot \sum_t ar_{jkt} + \sum_j \sum_k v_{jk} \cdot \sum_t \left( F_{jkt} - ar_{jkt-1} \right.\right. \\
& \left.\left. + \sum_t q_{ijkt} + ar_{ijkt} \right) \right) - \left( g \cdot \sum_i \sum_j \sum_t z_{ijt} + \sum_i \sum_j \sum_k d_{ijk} \cdot \sum_i q_{ijkt} \right)
\end{aligned} \tag{1}
$$

Subject to:

*Material flow constraints*

$$ap_{ikt} = ap_{ikt-1} + x_{ikt} - \sum_j q_{ikt} \qquad \forall i,k,t \tag{2}$$

$$ar_{jkt-1} + \sum_i q_{ijkt} - ar_{jkt} \geq E_{jkt} \qquad \forall j,k,t \tag{3}$$

$$ar_{jkt-1} + \sum_i q_{ijkt} - ar_{jkt} \leq F_{jkt} \qquad \forall j,k,t \tag{4}$$

Constraint Eq. 2 guarantees the inventory of all products in each plant at the end of every period. Constraint Eq. 3 ensures meeting "core demand" at each point of sale per product during each time period. Constraint Eq. 4 ensures that the demand served for any product at any point in time at any point of sale never exceeds the expected demand ("forecast demand").

*Physical resource limitations*

$$\sum_k o_{ik} \cdot x_{ikt} + \sum_k u_{ik} \cdot Y_{ikt} \leq L_i \qquad \forall i,t \tag{5}$$

$$x_{ikt} <= M \cdot Y_{ikt} \qquad \forall i,k,t \tag{6}$$

$$\sum_k ar_{jkt} \cdot \leq Wr_j \qquad \forall j,t \tag{7}$$

$$z_{ijt} \sum_k \frac{q_{ijkt}}{B} \qquad \forall i,j,t \tag{8}$$

$$ap_{ik0} = 0, ar_{ik0} = 0 \qquad \forall i,j,k \tag{9}$$

Constraint Eq. 5 guarantees that, per plant during each period, the capacity consumption due to the processing and preparation times of processed items never exceeds the plant's available production capacity. Constraint Eq. 6 ensures that if a quantity of a certain product is produced in a plant during a period, a setup of this product is necessary. Constraint Eq. 7 ensures that the amount of products stored at a point of sale during every period must never exceed the point of sale's storage capacity. Constraint Eq. 8 computes the number of vehicles required to transport products from every plant to each point of sale during all periods. Constraint Eq. 9 represents the initial inventory levels in plants and at points of sale.

$$Y_{ikt} \in \{0,1\} \qquad \forall i,k,t \tag{10}$$

$$x_{ikt}, q_{ijkt}, ap_{ikt}, ar_{ikt}, z_{ijt} \in \mathbb{Z} \qquad \forall i,j,k,t \tag{11}$$

Constraints Eq. 10 and Eq. 11 indicate the binary nature of $Y_{ikt}$ and the integer nature of some variables.

## 4. Proposed matheuristic solution method

The PDP problem is a complex one to solve given the number of integer variables that corresponds to produced and transported products, the inventory level in the plant and at points of sale, and the vehicles needed for distribution, plus the binary variable that indicates in which plants products are produced. Given the difficulty of this problem, a solution methodology is offered and describes how the GA is combined with the MILP model to evaluate the solutions for the PDP problem.

### 4.1 Initial population

Each individual in the population corresponds to binary decision variable $Y_{ikt}$, which takes 1 if product $k$ is produced in plant $i$ during period $t$, and 0 otherwise. An individual's length is a one-dimensional matrix of size $I \times K \times T$ (multiplication of the quantities of every index). The population takes a binary structure and is generated randomly from a uniform distribution with a 50 % probability of 1 appearing on an individual's chromosome. The computational results indicate that fewer infeasible individuals are generated if this probability is applied. Population size $N_{pop}$ equals 10, so we employ this small size to increase the GA's speed. Koljonen and Alander [23] confirm that a small population size increases the optimisation speed to a certain extent. We prove that using this population size suffices to obtain good solutions.

### 4.2 Evaluation function

The fitness function measures the quality of an individual in the population. The problem looks for solutions that maximise the benefits that the objective function represents. The PDP problem's computational difficulty focuses mostly on binary variable $Y_{ikt}$, which refers to the decisions made about which product to produce in which plant. This means that the GA is in charge of producing a suitable binary chromosome with equal dimensions to the binary variable.

As this binary chromosome corresponds to each individual in the population, the evaluation of each individual is made by formulating the mathematical model. The computational and execution times of a MILP versus a linear programming (LP) model are longer given the SIMPLEX algorithm's computational efficiency versus the algorithms dedicated to solve problems with integer or binary variables, along with the problem's difficulty, which is considered NP-hard. The proposed MILP model comprises one binary variable and five integer variables. Thus, to improve matheuristic performance, we apply MILP model relaxation. The MILP relaxation to obtain LP is given by transforming integer variables into continuous variables, and by transforming the binary variable into data.

At this time the solver is in charge of solving LP and the GA is responsible for supplying the binary variable. The binary variable of the GA is fixed to LP. Thus, when executing the matheuristic, it can be quickly solved even for very large problems. In our experiments, on average LP obtains better results than MILP by 3.84 %. Thus, to obtain a final result, we employ the best binary chromosome obtained during the evaluation process and launch MILP to gain a final result. This is explained in Section 4.6.

### 4.3 Selection

In the selection stage, a set of individuals from the current population is chosen to be used as the parents for the crossing stage. The roulette wheel approach [24] is taken to select the individuals with the best fitness values in accordance with the uniform probability of selection distributed over the range [0...1], and the worst individuals are eliminated from one generation to another so that the best individuals are more probably selected.

### 4.4 Crossover

The single point crossover technique [25] is applied. Two parents (P1 and P2) are selected by the fortune roulette wheel selection technique. Then the P1 and P2 chromosomes are cut at a point that is randomly generated and a new offspring (OF) is generated with the genetic information of its parents, as illustrated in Fig. 2.

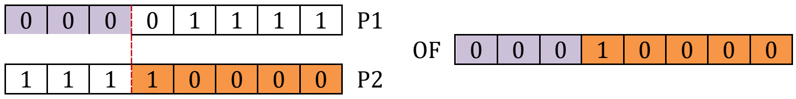


**Fig 2** Single-Point Crossover

### 4.5 Mutation

Mutation allows the GA to explore a bigger region of the ranges of potential solutions by including random genetic changes, which are produced by introducing variations into individuals, and thus allowing the GA to not fall into local optima [26]. The swap mutation operator is implemented here. This mutation method randomly selects two genes from offspring and then exchanges the gene content in its offspring, as shown in Fig. 3.

The offspring that undergo mutation are selected with uniform probability $Pm$=1. This means that all offspring are mutated but, in order not to lose the normal offspring, both the normal and mutated offspring remain in the resulting population. This avoids losing a good solution obtained by the crossing process as a mutation can provide a worse fitness value [27]. Then the two offspring (normal and mutated) are included in the population by replacing the two worst individuals in that population to leave a constant population size.

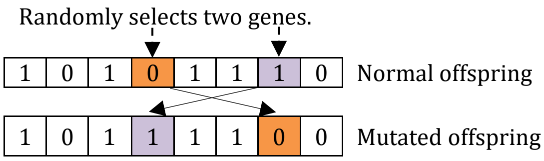


**Fig. 3** The Swap mutation operator

### 4.6 The matheuristic approach procedure

The best individual with the best fitness is selected at the end of the calculation time (stopping criterion) of the matheuristic GA. With this binary chromosome, MILP is launched.

In the evaluation function, MILP is relaxed to LP to reduce computational effort and to obtain a sufficiently good solution. To obtain a definitive solution, MILP is used, i.e., by removing relaxation and employing the binary chromosome of the individual with the best fitness provided by the GA.

The binary chromosome is set at the $Y_{ikt}$ variable of MILP. This means that the binary chromosome becomes a parameter for the model. Then the MILP model is launched, the solver solves the integer variables and the GA provides the binary variable

The advantage of using matheuristic, and not directly using the solver, lies in the search space of the MILP model being significantly reduced when a matheuristic is employed to deal with binary variables.

## 5. Results and discussion: Numerical experiment case study

In the present section, a set of synthetic data is used to evaluate our approach. In this type of problem, real data sets are generally large, which renders it unsolvable with many plants, products, outlets and periods. To assess how the matheuristic and the non-commercial solver perform, in computational tests we apply large instances, which are randomly generated according to the outlined parameters and formulations in Park [22]. To create these data, we created a synthetic data generator, which appears at: https://bit.ly/synthetic_data_generator.

Park [22] analysed large datasets with similar characteristics to those in Table 4. Park used CPLEX to solve MILP but did not present any results for large instances because of the problems' computational difficulty, which is why he applied this solver only for small instances. We use the same data for plant size (5), points of sales (from 40 to 65), products (5) and periods (from 10 to 12), as presented in the above-mentioned study.

The software followed in this research is a non-commercial optimisation solver from the Computational Infrastructure for Operation Research (COIN-OR) community called COIN-OR Branch and Cut Solver (CBC) [28]. This open-source solver is generally employed for MILP problems. The MILP model and matheuristic were implemented in Python with the Pyomo package [29]. Experiments were run by an Intel Core i7 2.80 GHz processor (6 GB RAM) in an Ubuntu 20.04.1 LTS operating system.

The performances of the matheuristic approach and the proposed MILP through computational experiments were compared to one another to identify the best performing method. The resulting GAP of the MILP solved by CBC and the matheuristic is calculated as indicated in Equation (12).

$$GAP(\%) = \frac{|UB \ - Best_{sol}|}{|Best_{sol}|} \tag{12}$$

Where UB indicates the upper solver bound, and $Best_{sol}$ refers to the best solution generated by either the mathematical model or the matheuristic approach.

### 5.1 Experimental results

In order to demonstrate the proposed approach's efficiency and performance, the computational experiments with different large instances are provided. Table 4 compares the solution's efficiency among the solutions obtained by solving MILP with CBC and the matheuristic one with CBC. The first column in this table denotes the name of the instance, followed by the number of plants (*I*), points of sale (*J*), products (*K*) and periods (*T*). For all the instances, the applied criterion is the same calculation time that corresponds to 14,400 seconds. We executed the matheuristic algorithm 20 times for each instance in order to evaluate and avoid atypical performance.

The MILP solved by CBC obtained solutions for two (I2, I4) of the six instances, but it was unable to find optimal or good solutions. The matheuristic gave good solutions for all the instances. Fig. 4 illustrates the total profit obtained by matheuristic and CBC. I2a and I4a show how the matheuristic approach evolves and converges towards good solutions, along with how CBC performs at around 7,200 computation seconds, while I4b and I4b show the behaviour of both the matheuristic and CBC at 14,400 processing seconds. For the I2 instance, CBC gave a feasible solution at 5,152.76 seconds (see Fig. 4) with GAP = 17.10 %. GAP improved up to 14,400 seconds by 0.02 %. For the matheuristic for the same instance, it obtained feasible solutions from 71.05 seconds, with GAP less than 10 % at 1,880 seconds (see Fig. 5).

**Table 4** Performance comparison between CBC and Matheuristic

| Instance | Problem | | | | CBC | | | Matheuristic | |
|---|---|---|---|---|---|---|---|---|---|
| | *I* | *J* | *K* | *T* | Total profit | Upper bound | GAP | Total profit | GAP |
| I1 | 5 | 40 | 5 | 12 | Unfeasible solution found | 5746740.5 | - | 5117847 | 12.28 % |
| I2 | 5 | 50 | 5 | 10 | 5873321 | 6876383.6 | 17.08 % | 6347862 | 8.33 % |
| I3 | 5 | 45 | 5 | 12 | Unfeasible solution found | 6785206.6 | - | 6157783 | 10.18 % |
| I4 | 5 | 60 | 5 | 10 | 6643133 | 8037979.9 | 21.00 % | 7487111 | 7.36 % |
| I5 | 5 | 50 | 5 | 12 | Unfeasible solution found | 6932259.4 | - | 6294622 | 10.13 % |
| I6 | 5 | 65 | 5 | 10 | Unfeasible solution found | 8272162.9 | - | 7640947 | 8.26 % |

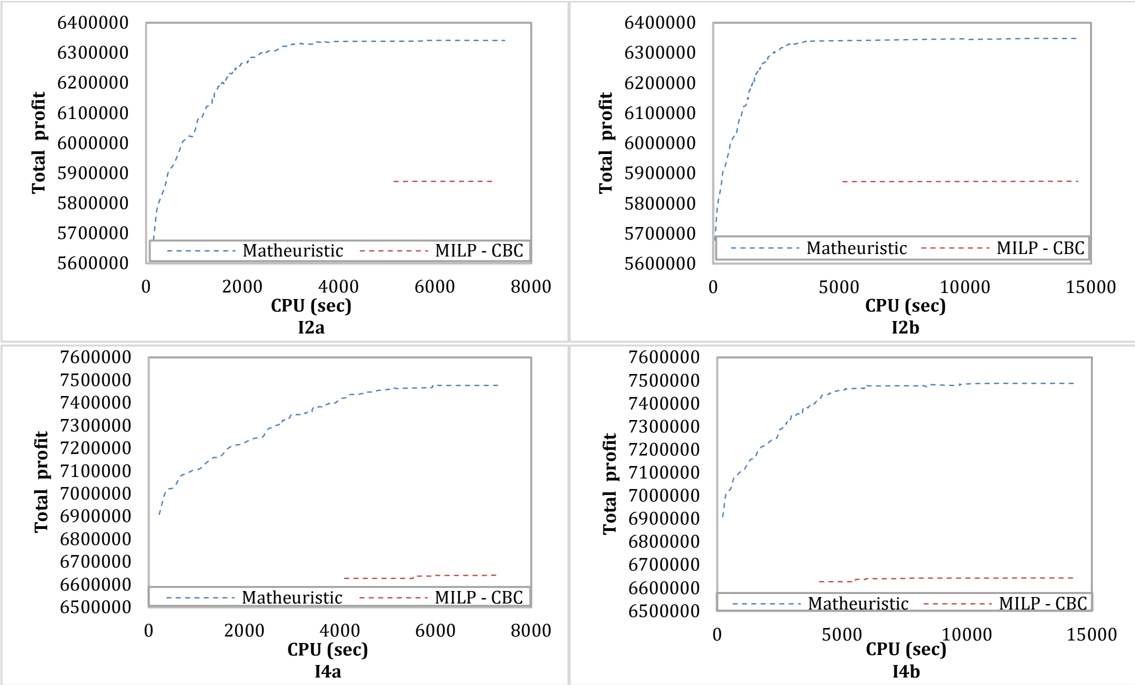


**Fig 4.** Time spent by matheuristic to find a feasible solution

With the I4 instance, CBC performance visibly improves. It obtains solutions in 4,097 seconds and becomes the best solution in 5,538 seconds (see Fig. 5). Matheuristic better performs than CBC by reaching feasible solutions in shorter computational times and reaches a GAP below 10 % after 2,735 seconds (see Fig. 5). This means that matheuristic outperforms CBC by 13.64 %.

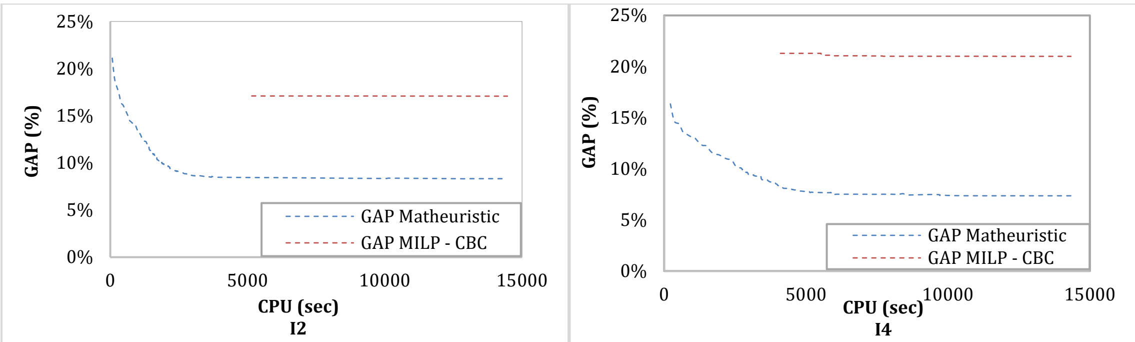


**Fig. 5** Comparison of matheuristic and MILP-CBC performance

The complexity of the instances and the size of the problem mean that CBC is unable to find feasible solutions. Nevertheless, the combination of a GA with CBC gives better results with feasible solutions in shorter computational times. A matheuristic's efficiency is linked with the solver's speed because the solver is in charge of evaluating solutions by the GA's evaluation function. Moreover, as the evaluation function is the principal component of GAs [30], employing a non-commercial solver combined with a GA offers good results, as herein shown, and the matheuristic is more efficient in solving problems with many variables and parameters, and can be a useful alternative for large instances. When utilising a non-commercial solver like CBC, a matheuristic can support the solver to find better solutions.

In order to further demonstrate the efficiency of the proposed matheuristic, we compare it to Gurobi 9.1.1, i.e., the MILP and LP of the matheuristic are solved with Gurobi. We employ the same aforementioned computational conditions and apply a processing time of 14,400 seconds. The computational results given by Gurobi are better than those of CBC. Thus Gurobi obtains feasible solutions in all the instances in much shorter solution times. However, the matheuristic is better for achieving a lower GAP than Gurobi in all instances (see Fig. 6).

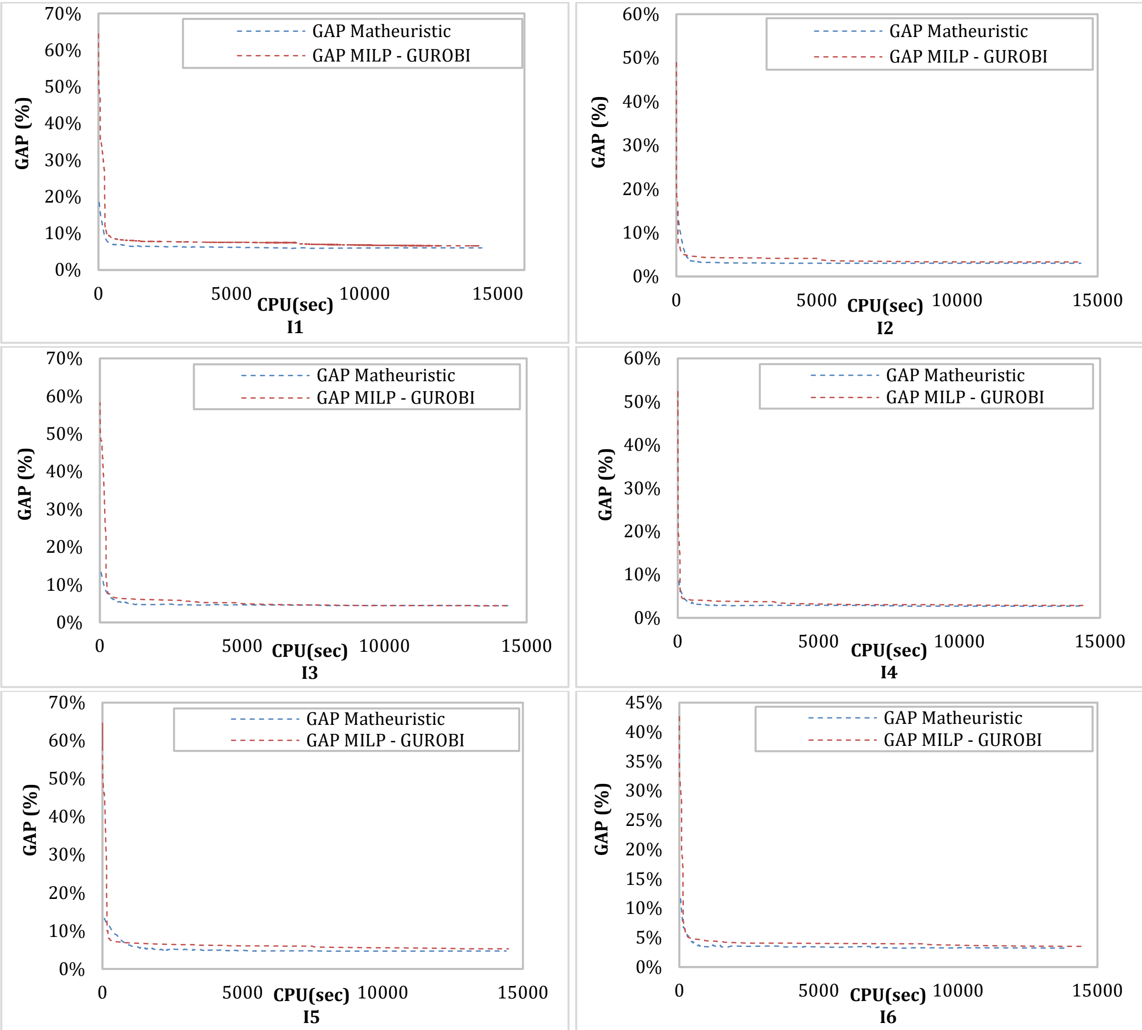


**Fig. 6** Comparison of matheuristic and Gurobi performance

## 6. Conclusion

The PDP problem has long since been studied for the practical applications that it can offer industry. One such case is enterprises with different manufacturing plants in several locations, perhaps in the same city or country, or in others, which must decide the amount of products to be produced in plants, the quantity of products to be stored in plants during each period, the number of products to deliver to various points of sale according to product demand and the inventory of finished products at points of sales. Although several resolution techniques have been used for this problem and its variations, heuristic and metaheuristic algorithms can provide excellent results as combined or hybrid approaches. Likewise, combinations between metaheuristic techniques and exact approaches can offer better results for real-life problems because these combinations make the most of the benefits of both techniques [7]. In this context, the present paper intends to solve the PDP problem in real-world large data sizes. The problem is modelled as MILP, and a matheuristic solution approach is presented that combines a GA and an LP model.

Computational tests were performed on a large dataset capable of simulating real-world problems. The development of this approach stems from SMEs having to use open-source tools and the need to digitise companies because they must compete in today's market. Many SMEs cannot have access to software with paid licenses, due to the high-costs they may have to adapt the software to the needs of the enterprises. The main research contribution is about applying a matheuristic approach by employing a non-commercial solver (CBC). We also tested the performance of the non-commercial solver with an NP-hard MILP model. The computational tests run on different instances showed that our approach offers markedly improved results than the exact method. Matheuristic obtained competitive results in a short time. When solving MILP, CBC is unable to acquire feasible solutions for four of the six computed instances. However with our proposed matheuristic, and by also using CBC for solving relaxed LP, our results were good for all instances. Matheuristic can perform better even when using a commercial solver like Gurobi. Therefore, matheuristic can offer a real technical and economical application and is affordable mainly for SMEs that cannot pay a commercial solver or do not recurrently resort to one. This approach is feasible thanks to the proposed model's simplicity. The matheuristic also offers the benefit of making the most of the solver's features, regardless of them being commercial or not, because the matheuristic improves the solver's performance. The proposed approach has the limitation that its effectiveness depends on the selected solver, since the solutions of the matheuristic with a commercial solver (Gurobi) are better than those obtained with a non-commercial solver (CBC).

Other metaheuristics can be used for future work, such as memetic algorithms, ant colony optimisation or tabu search, and other highly complex problems can also be tested. Other genetic operators can be evaluated, or specific heuristics can be used to improve the GA's performance.

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Research paper

# Enhancing manufacturing excellence with Lean Six Sigma and zero defects based on Industry 4.0

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**A B S T R A C T**

Improving quality, enhancing productivity, redesigning machining tools, eliminating waste in production, and shortening lead time are all objectives aimed at improving customer satisfaction and increasing profitability for manufacturing companies. This study combines lean manufacturing and six sigma techniques to form a technique called Lean Six Sigma (LSS) by using the DMAIC (Define-Measure-Analysis-Improve-Control) model. This study proposes to use statistical test models to analyze real data collected directly from the operator. The study proposes to use the Taguchi optimization technique to determine the optimal conditions for oil dipping tanks of molybdenum materials. In addition, the study also proposes a computer vision technique to recognize objects using color recognition techniques running on the LABVIEW software platform. This study builds a digital numerical control (DNC) model operating on digital signal processing techniques, linking the data of each process together. The results reduced the rate of defective parts in the whole processing stage from 6.5 % to zero defects, the whole processing line production capacity increased by 7.9 %, and the profit of the whole production line was USD 35762 per year. As a valuable external outcome, the conclusion of the LSS project fostered a spirit of continuous improvement. The utilization of research results from the research environment in the actual production setting is significantly enhanced for the operator. The LSS model is deployed with specific tasks and targets for each member of the LSS project team, and the processing conditions for each specific stage are optimized, such as the oil dipping process and hole grinding process. Industry 4.0 techniques, including computer vision, digital numerical control, and commercial software such as LabVIEW and MINITAB, are optimized for use, simplifying machining operations. Some proposed directions for future research are also presented in detail. For example, studying the improvement of the quality of the 220 V power supply through harmonic mitigation in processing factories is an intriguing area of investigation. Additionally, exploring data security for big data in the context of Industry 4.0 would be a valuable study to enhance customer satisfaction with big data technology in the future.

**A R T I C L E   I N F O**

*Keywords:*
Lean Six Sigma;
Industry 4.0;
Manufacturing;
Smart manufacturing;
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DMAIC (Define-Measure-Analysis-Improve-Control);
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## 1. Introduction

Industry 4.0 techniques develop strongly in the product factory environment [1]. Specifically, applying computer vision techniques is for object recognition and object classification, artificial intelligence (AI) techniques to create robots that work in place of humans and create high productivity. Using automate manufacturing operations to eliminate waste, shorten lead times, increase productivity, and move towards zero defect production [2-3]. The Six Sigma technique has been implemented and brought to great effect at Motorola since 1980 and is embraced by many other companies as a model of continuous improvement in the manufacturing company. Lean manufacturing tools and models are logically integrated into each phase of Six Sigma implementing a continuous improvement model that delivers efficiency, and that hybrid model is called Lean Six Sigma (LSS) [4-5]. General Electronic Company has implemented the LSS model into its continuous improvement activities since 1998 and has brought high efficiency. Specifically, the company's revenue is more than 1.2 billion USD, which shows to the world the high efficiency in business operations when applying the LSS model to continuous improvement activities.

### 1.1 Research question

The LSS model is implemented by manufacturing companies in continuous improvement activities to improve quality and productivity, enhance customer satisfaction. Holtskog [6] and Sony *et al*. [7] also highlight the limitations of the LSS model when deployed by manufacturing companies. However, many manufacturing companies implement the LSS model into continuous improvement activities with high efficiency while several companies also implement the LSS model but the results are not as required. The LSS is a project, so it is necessary to plan work specifically, clearly divide work for each member of the project, and describe in detail, specific goals. Completion time for each task is absolutely necessary [8-9]. This study details the process of implementing the DMAIC model of the LSS technique into the product production line at a mechanical company. The specific goals of this research are (1) Optimize production conditions at the oil dipping process, prevent defects and prevent delays for customers. (2) Automatic selection of production tools by Industry 4.0 or computer vision technology at hole grinding process, preventing mistaken selection of production tools caused by careless employees and shortening production time, simply optimize the work performance for operators, improving operator satisfaction on continuous improvement activities. (3) Digital signal technology is deployed to collect data of each individual line by barcode system, call machining programs for automatic machining machines by barcode system and measurement system to collect stored data into the SQL system to form big data in Industry 4.0 [10].

In production activities, there are several questions such as: (1) Determine the specific production conditions for semi-automatic and automatic processing machines such as Oil dipping tanks, and hole grinding machines; (2) Product quality is guaranteed throughout the entire processing stage, which method is appropriate and not too complicated in the operation of employees; (3) The factory is illuminated by LED lights, and the factory is operated by smartphones and computer systems. All of them are sources of harmonics in the power supply to the furnace, the circuitry that controls the semi-automatic and automatic machines, ensuring that harmonic components according to IEEE 519:2022 are essential. The main operating principle of the LSS model is based on manufacturing fundamentals. Lean manufacturing and six sigma techniques are also based on manufacturing fundamentals. The implementation LSS project model is effective in action process planning, operational process analysis, and action process assessment. In addition, the LSS project investigates, analysis, and identifies problems at specific production lines and proposes improvement plans. Werkema [11] detailed evaluation of the results of implementing the LSS model into continuous improvement activities at manufacturing companies and brought high results, enhancing the company's competitiveness. Lean manufacturing technique has not yet clearly formed the detailed structure of each solution corresponding to each specific problem [12]. The Six Sigma technique is highly effective in minimizing process variation but has not really cared about the time and speed completion of production process [13]. These two techniques are deployed in combination to overcome each other's weaknesses and improve efficiency [14].

### 1.2 Contribution of research

This article details the steps of implementing an LSS model that combines lean manufacturing and six sigma techniques in continuous improvement operations at a manufacturing company [15]. The research results show that the defective rate decreased from 6.5 % to zero defect, the production capacity of the whole production line increased by 7.9 % and the profit increased by 35762 USD per year. This study contributes to improve the working morale of machine operators, the spirit of applying techniques from research to the practical environment, and remove the thinking separating the research environment and the production practices. In this study, it is considered as a model for managers performing each step in the analysis to find out the origin problem. The DMAIC model is used as a guide for members of the continuous improvement project in a variety of companies [16]. The data in this study were collected directly at the production line by the operator at the mechanical product manufacturing company [17-18]. This study proposes the use of statistical tools such as descriptive statistics, statistical hypothesis testing in data analysis, and determination of the current status of the problem on the table of specific analysis results. The Taguchi optimization technique is implemented to specifically determine the optimal condition for the machining condition. Computer vision technology identify and classify objects by color is deployed to redesign production operating conditions at specific production stages. Digital signal processing techniques based on barcodes and QR Codes are developed for real-time data collection at each separate manufacturing process and create a close connection in terms of data between the stages [19].

This study is a big challenge for researchers because its data completely collected from reality at each specific production line. Analytical tools are deployed to analyze data such as PARETO charts, descriptive statistics tools, statistical hypothesis testing tools, fishbone charts, value stream mapping, failure tree analysis, techniques, Taguchi optimization techniques, computer vision techniques, and digital numerical control techniques. This paper details the implementation of the LSS model using DMAIC in continuous improvement and also serves as a reference model for LSS researchers, managers, and project members implemented as a model. The DMAIC model is applicable to many different environments and organizations and serves as a model.

The next structure of the research paper is organized as follows: Section 2 details the content of the literature review. Section 3 presents the research method in detail. Section 4 details the results of the experimental study and discusses the results from the experiment, and Section 5 presents the conclusion of this study.

## 2. Literature review

The Lean Six Sigma model combines Lean manufacturing and Six Sigma techniques [20-21]. The literature review for both Lean manufacturing and Six Sigma techniques is performed first. Next is the evaluation of the data for statistical techniques applied to actual data analysis techniques and numerical processing techniques in data collection and analysis.

### 2.1 Lean manufacturing

Key tools used in Lean manufacturing are Value Flow Mapping, Fishbone Diagram, Kanban System, Pareto Diagram, and Failure Tree Analysis [22]. These tools mainly perform analysis to confirm the wastes incurred in production activities and suggest improvement actions to eliminate wastes with the aim of increasing productivity and set goals to improve production methods [23]. Value Stream Mapping (VSM) details valuable and non-valued activities across each activity in the supply chain. The VSM tool identifies valueless activities (waste activities) to help managers easily decide on improvement proposals. The 5 Whys tool and fishbone diagram does the enumeration problem point causes and root cause selection. The system charting tool builds countermeasures based on weighting indicators [24-25]. In addition, Fault Tree Analysis combined with the 5 Whys tool adds extra power to root cause analysis. However, Fault Tree Analysis focuses on detailing the problem points according to the 5 whys method without focusing on finding the root cause and 5 whys analysis only focuses on the starting content of the problem point. A combination of failure tree analysis and 5 whys analysis makes a powerful analyze model and Kanban System is a fundamental tool in Lean manufacturing to control operations.

### 2.2 Six Sigma

Fluctuations in the production process stem from machining conditions, human factors, unstable machine accuracy, and power sources that generate many harmonic components that exceed IEEE 519:2022 standards. Six Sigma technique helps to eliminate fluctuations in the production process. Improve product quality, and customer satisfaction. Motorola Company pioneered the implementation of Six Sigma technology in the phones production line and achieved great results in controlling volatility and reducing defect rates below 1 Sigma. Six Sigma techniques use DMAIC (Define-Measure-Analysis-Improve-Control) model implemented as a model for performing problem analysis and measurement [26-27], using the actual database at the machining line. Define phase (D) presents an overview of the environment around the problem to be analyzed and analyzed to determine the content of the problem point using statistical charting tools such as Pareto chart, and bar chart. Measure phase (M) deploys statistical testing tools, and statistical hypothesis testing to measure and analyze real data at the production stage and find the root problem point. Analysis phase (A) deploys the Taguchi optimization technique to determine optimal production conditions for production conditions. Conduct experiments and collect experimental data by operators. Improve phase (I) deploy Industry 4.0 tools such as computer vision to identify and classify objects by color running LabVIEW software and digital numerical control techniques in digital signal processing by barcode or QR Code, data collected into the big data system in Industry 4.0 systems [28-30]. Control phase (C) deploys an online measurement system using digital numerical control (DNC) technology to control the system automatically and completely eliminate workers' skill. A comprehensive literature review of the Six Sigma technique is needed.

### 2.3 Lean Six Sigma (LSS)

The main goal of the Lean Six Sigma model is to eliminate the fluctuations of the production process and improve product quality by manufacturing according to the zero defects model to improve product quality, process quality, people quality, production capacity, and customer satisfaction [31-32]. Ensuring quality meets customer requirements and delivering products on time is a challenge. Pande *et al.* [33] pointed out level problem of responsiveness between providing services to customers and meeting customer requirements is a big challenge. Rathi *et al.* [34] specifically outlined 17 obstacles when implementing LSS projects for enterprises and the main content is data collection. Data is the backbone of the LSS project. The ability monitoring the LSS project to ensure that the projects are completed on schedule and project manager's target met is a challenge. Implementing LSS projects knowledge of team members is also an issue that needs attention. The main tools used in the DMAIC phase such as Process Flowchart, Data Collection Checklist, Fishbone Diagram, Histogram, 5 Whys Analysis, Statistical Hypothesis Test, Experimental Design, Taguchi method, and Statistical analysis are comparing results before and after improvement [35-36]. If the LSS project is not performed well, it can lead to loss of investment, time, and resources, customer trust and the image of the organization implementing the LSS project. Lean Six Sigma technique has been successfully applied in many companies. However, there are still a few companies that still do not give good results when applying Lean Six Sigma. Because of the inconsistent use of statistical techniques, Lean manufacturing techniques. Shokri [37] has implemented LSS technology in a mechanical manufacturing company with the goal of eliminating scrap to zero and achieving a profit of 98 USD per year. Guleria *et al.* [38] proposed to apply the LSS project to the gear component manufacturing process, the tools applied such as SIPOC (Supplier-Input-Process-Output-Customer) diagram, Pareto chart, Fishbone chart, reject results from 10641 to 3193 (PPM). Minh and Thu [39] proposed to apply the LSS project to the manufacturing process of mechanical components, apply tools such as the Pareto diagram, fishbone diagram, scatter plot, histogram, and lifting work of production capacity from 118 products in 8 hours to 155 products in 8 hours.

# 3. Research methodology

## 3.1 Research characterization

The company produces condensed products using many automatic processing machines and processing conditions, so the variation in the production process is very large. Controlling product quality means controlling fluctuations in production conditions. This study employs both quantitative and qualitative research methods. The quantitative method is to use statistical charts to analyze the data. De Boer [40] highlights the need for a large enough sample size to meet the requirements of statistical models. Qualitative research is seen as a management tool implemented to understand and find solutions for specific problems in the workplace. De Boer [40] demonstrates that quantitative research provides logical information about reasons without using mathematical equations, observable behaviors or problem-solving solutions. This study specializes in a particular mechanical production line, and conducts a process assessment of the status quo that generates problem points for waste and human skill-dependent operations. Hart [41] highlights the need for direct workers at each stage of the LSS project implementation process. Operators at the machining line understand the need for continuous improvement and implementation. The main goal of the project is to implement the research results into practice, the researcher directly participates in the implementation of the project's work together with the operator. Practice research projects, measure the results of practice directly at the production line, and evaluate their effectiveness. The researchers provide instructions on how to collect and analyze samples for LSS project workers and operators who perform direct sampling. The author directly participates in the implementation of the LSS project at a mechanical processing company from April 2021 to March 2022, participates in all project activities as the manager, and performs the works such as defining research, performing data collection, analyzing data to collect results after implementing the LSS project.

## 3.2 Scope of Lean Six Sigma application

The slow implementation of the tasks in the Lean Six Sigma project will waste the company's resources, so the LSS project management team needs to focus on controlling the progress of activities [42]. Changing the production process entails changing a lot of other things such as changing standards and technical conditions, changing operating methods and controls. This study presents a step-by-step implementation of Lean Six Sigma techniques with the DMAIC model as Table 1.

**Table 1** Activities development in DMAIC phase

| DMAIC phase \ Activities | Activities 1 | Activities 2 | Activities 3 | Activities 4 |
|---|---|---|---|---|
| Define | Present an overview of the environment surrounding the problem point to be analyzed and describe information about the problem point to be studied. | Using fishbone diagrams, the 5 whys or failure tree analysis details the causes of the problem score according to 4 aspects: Man-Machine-Method-Material. | Gather the opinions of the Lean Six Sigma project team members and identify the root cause of the problem. | The system diagram is implemented in the construction of improvement activities according to the rating scale. |
| Measure | Make surveys and check sheets to collect data directly from the production line by operators. | Planning, methods, and data collection directly on the line [43-44]. | Deploy statistical tools, and test statistical hypotheses to analyze data. | - |
| Analysis | Set up a specific implementation plan for each trial according to the GANTT and WBS diagrams. | Analyze the current status of each stage by video recording method and analyze the correlation between man and machine using a Man-Machine diagram [45-46]. | Set specific goals for each case according to S.M.A.R.T criteria. | - |
| Improve | Re-optimize production conditions at each soybean production line by the Taguchi method [47-48]. | Rebuild management standards, and work instructions according to ISO9001:2015 and IATF16949:2015. | - | - |
| Control | Build a digital processing system to control the operation of each operation at each corresponding production line, the Industry 4.0 system is built based on the POKA-YOKE theory. | Build an online measurement system using digital numerical control techniques [49-50]. | - | - |

## 4. Results and discussion

### 4.1 Define (D)

This phase outlines the Lean Six Sigma (LSS) project scope clearly and specifically. The fish bone diagram combined with the 5 Whys analysis lists individual causes of defects in 4 aspects as Man-Machine-Method-Material (Fig. 1). Failure tree analysis combined with the 5 Whys analysis are also reviewed and verified the cause of defects.

A survey questionnaire was established and researchers assessed the accuracy of each question, surveying the opinions of direct operators of the production line such as machine operators, chief and deputy shift staff of production, production line managers, machine maintenance technicians, production line design technicians, and factory managers. All comments show the general content is that there are no specific regulations on machine operating conditions, there is no connection of production data between stages, and employees choose production tools by experience, so they often give rise to defects. Evaluating the current state of the machining process by using the control plan sheet tool is easy to spot gaps in the manufacturing process. Managers who lack understanding of the production process and completely depend on the skills of workers. Interviews with workers of LSS project members contribute to enhancing the culture of sharing in the company. The LSS project needs to clearly show two goals: (1) Clearly define the goals of each specific task and (2) Form a plan table according to Gant and WBS (Works Breakdown Structure) diagrams for each specific task. From Fig. 1. This research paper has 3 main projects: Project A (Make sure to use the right tools to process the hole size of the product at the machining center). Project B (Determine the temperature conditions, time of the oil dipping, and the stabilization time based on the expansion of molybdenum) and Project C (Check the quality of power supply for the oil dipping machine).

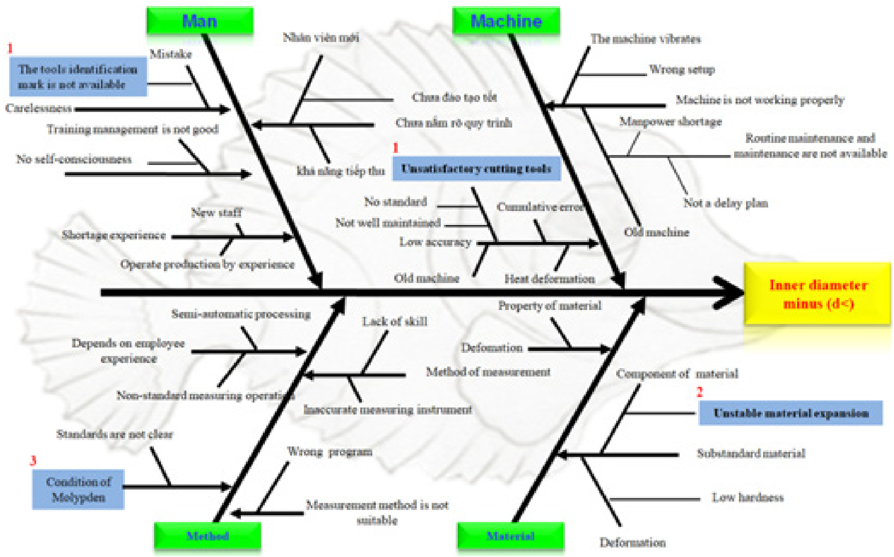


**Fig. 1** Fishbone diagram

### 4.2 Measure (M)

Project A is implemented experimentally at the product hole grinding stage. The product is manufactured with 2 different materials depending on customers' requirements. (1) Material type FC250 and molybdenum has a hardness of 196 HV, and (2) Material type copper and molybdenum has a hardness of 125 HV. The tool for hole grinding also depends on the respective material. Tools employing FC250 materials used blue-labeled tools, while those using SUJ2 materials used red-labeled tools. However, the shapes of the two types of tools are similar (Fig. 2), make their identification and differentiation is a challenge.

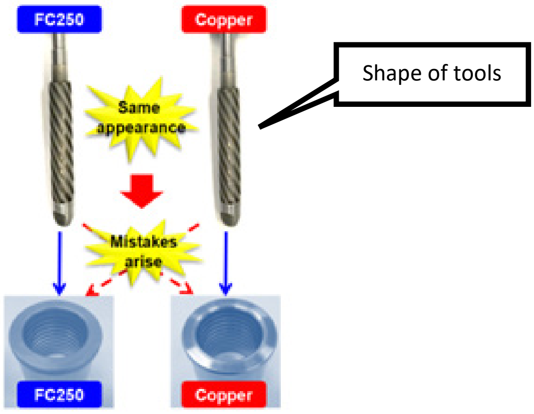


**Fig. 2** Shape of hole grinding tools

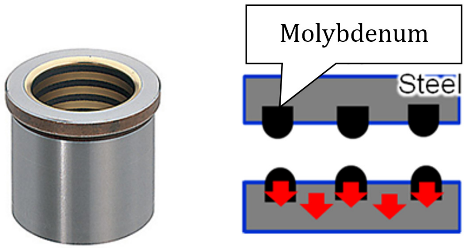


**Fig. 3** Molybdenum disulfide inside Bush product

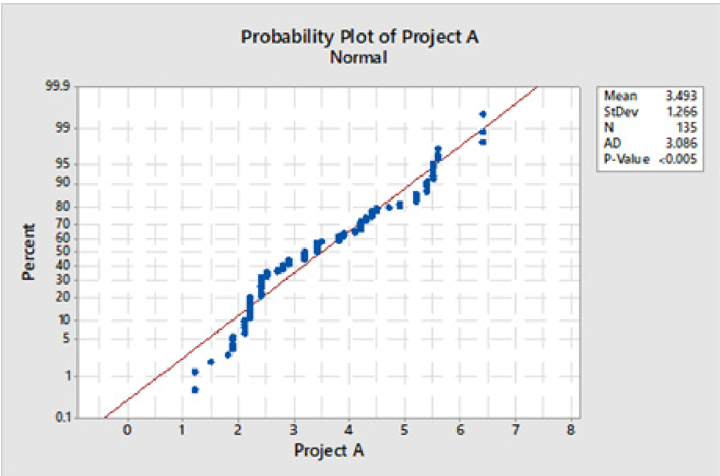


**Fig. 4** Probability plot of Project

Project B performs the task of determining the most optimal oil dipping conditions. Bush product line uses molybdenum material inserted into the groove inside the product hole (Fig. 3), the molybdenum material deforms in size according to thermal conditions and heat time. Molybdenum is manufactured by Sumi Steel Co, Ltd. manufacturing, its main ingredient is molybdenum disulfide. It is effective in reducing friction or wear in high-temperature and load-bearing environments, and is effective in grease-restricted environments. Optimizing conditions for oil dipping is a challenge for LSS project team members.

Project C performs quality control of the power supply for electronic boards and thermistor devices at the oil dipping stage. The factory uses a lot of LED lighting systems, computer systems, internal and external telephone systems, all the above devices are harmonic sources in the power supply, and harmonics make the image. The sine waveform of the power supply is distorted, and the system of power boards is unstable. Specifically, the extreme resistance of the oil dipping tank does not guarantee thermal stability and is the cause of defects. Designing systems for harmonic mitigation to ensure that total harmonic distortion (THD) falls within the IEEE 519:2022 standard is a major challenge.

The statistical testing method is applied to data analysis activities of the LSS project to meet the right objectives. The Anderson-Darling normalization method is performed to check the normality of the hole diameter data with an error of fewer than 3 microns using Minitab 18.0 software. The P-value of Project A), the P-Value of Project B), and the P-Value of Project C) are less than 0.005 (Fig. 4). The hypothesis H0 that data are normally distributed is rejected. A non-parametric method was used to analyze this data, as this data set is not normally distributed. The analyze results will be presented in the analysis phase contributing to the implementation of Project A, Project B, and Project C.

### 4.3 Analysis (A)

Project A (The identification of machine tools by color at the hole grinding process). The product hole grinder has 3 main parts: Mandrel, Nut, and Blade (Fig. 5). The FC250 and the Mandrel Synchronous Material Cutting Kit and the Nut Kit are the same and interchangeable. However, the hardness setting at the blade's cutting surface is different. It should be distinguished when using FC250 and copper materials for machining. Using the chi-square test is for association statistics running on Minitab 18.0 software to evaluate the similarity of the results of correct identification of the cutting tool's blade type H0 or the dissimilarity of the correct identification of the cutting tool blade type H1. Use the difference between the expected number $E_i$ and the actual number of observations $O_i$ to find the chi-square value (called a statistic), according to the Eq. 1.

$$x^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{1}$$

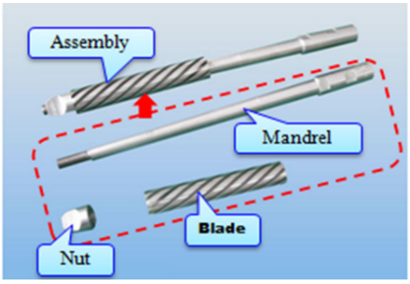


**Fig. 5** Structure of cutting tools

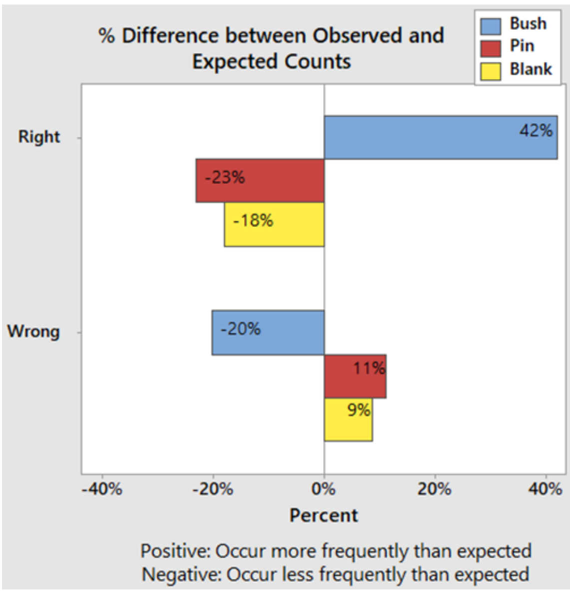


**Fig. 6** Difference between observed and expected counts

Randomly select 200 employees of 3 processing lines (65 Bush product line employees, 60 Pin product line employees, and 75 Blank processing line employees) to distinguish between the blade type used for FC250 material and the blade type used for copper material. The P-Value of the Chi-square test is 0.016 less than 0.05, H0 is rejected, and H1 is accepted. Indicating is the results of blade selection of tools cut are not uniform among 3 groups of 200 employees. Line Bush products that the rate of choosing the right type of Blade is 46 % and the rate of choosing the wrong type of Blade is 26 %. In line Pin, the right selection rate reaches 23 % and the wrong selection rate reaches 33 % in Line Blank the right selection rate reaches 31 % and the wrong selection rate reaches 41 %. The percentage difference between Observed and Expected Counts of Line Bush's right choice reaches 42 % and the wrong choice reaches negative 20 %. Line Pin's right choice reached negative 23 % and the wrong choice reaches 11 % and Line Bush correctly pick negative 18 % and the wrong choice reaches 9 %, see Fig. 6.

Project B (Re-designed of oil dipping tank processing condition). The oil dipping process of molybdenum-based products is done through 3 steps: Step 1) The product is neatly lined up and immersed in MG815 oil which is heated to 100°C by the thermistor. Step 2) Store products are in a warehouse environment with a temperature of 70°C. Step 3) Cool the product in a normal temperature environment from 28°C to 32°C for about 7 days. To evaluate the size expansion of molybdenum powder after implementing the 3 above conditions, with 5 factors and 2 levels for initial treatment conditions (Table 2). Taguchi method responds well to many factors in the system simultaneously, ensuring independent research and reliable influence of factors. The L32 (2^5) orthogonal matrix table designed for 5 elements is presented in Table 3. In this study, the quality characteristics of the molybdenum set size extension (E6) in the standard region are less than 3 microns. The test prototype is sampled directly from the production process, the results are converted to signal-to-noise ratio (S/N), according to Eq. 2.

$$S/_N = -10 \cdot \log[(\mu - m)^2 + S^2] \tag{2}$$

The molybdenum expansion dimension of 3 microns was measured with a Koshaka 3D profile tensile tester with a profile measuring distance of 80 mm. The results of the S/N analysis (Fig. 7) show that the product response of cooling time after oil immersion and oil immersion time strongly affects the quality of molybdenum size expansion. Next, the oil immersion temperature has a relative response and the drying time as well as the product drying temperature after oil immersion is responsive but not high. The results of the one-way ANOVA analysis (Table 4) show a 95 % confidence interval for the thermal conditions of the molybdenum product.

Project C (Quality control of power supply is for oil dipping tank). A supply voltage of 400V/3 phase/30A provides a thermistor (Fig. 8) to heat the oil bath (Fig. 9). Ensuring a constant and stable power supply to the thermistor is essential. Power meter type PQ3100 manufactured by HIOKI firm is used by the company to measure voltage source, current source for thermistor. Results of document search in the frequency of power quality testing by PQ31000 on Wednesday 7 weekly (shared work area) cleaning day before Sunday off. Measurement results are recorded manually on the test sheet to check the machine's status.

**Table 2** Experimental factors and their level for $L_{32}$

| Factor | Level 1 | Level 2 |
|---|---|---|
| E1: Oil dipping time (hours) | 1 | 3 |
| E2: Oil dipping temperature (°C) | 90 | 110 |
| E3: Dry time after oil dipping (hours) | 1 | 3 |
| E4: Dry temperature after oil dipping (°C) | 60 | 80 |
| E5: Cooling time after oil dipping (days) | 5 | 7 |

**Table 3** $L_{32}$ ($2^5$) orthogonal array experimental parameter

| Exp. | E1 | E2 | E3 | E4 | E5 | E6 | S/N |
|---|---|---|---|---|---|---|---|
| L1 | 1 | 90 | 1 | 60 | 5 | 4.1 | -12.26 |
| L2 | 1 | 90 | 1 | 60 | 7 | 3.0 | -9.54 |
| L3 | 1 | 90 | 1 | 80 | 5 | 3.7 | -11.36 |
| L4 | 1 | 90 | 1 | 80 | 7 | 2.9 | -9.25 |
| L5 | 1 | 90 | 3 | 60 | 5 | 3.6 | -11.26 |
| L6 | 1 | 90 | 3 | 60 | 7 | 3.1 | -9.83 |
| L7 | 1 | 90 | 3 | 80 | 5 | 3.2 | -10.10 |
| L8 | 1 | 90 | 3 | 80 | 7 | 2.9 | -9.25 |
| L9 | 1 | 110 | 1 | 60 | 5 | 3.5 | -10.88 |
| L10 | 1 | 110 | 1 | 60 | 7 | 2.9 | -9.25 |
| L11 | 1 | 110 | 1 | 80 | 5 | 3.2 | -10.10 |
| L12 | 1 | 110 | 1 | 80 | 7 | 2.6 | -8.30 |
| L13 | 1 | 110 | 3 | 60 | 5 | 3.5 | -10.88 |
| L14 | 1 | 110 | 3 | 60 | 7 | 2.6 | -8.30 |
| L15 | 1 | 110 | 3 | 80 | 5 | 3.5 | -10.88 |
| L16 | 1 | 110 | 3 | 80 | 7 | 2.6 | -8.30 |
| L17 | 3 | 90 | 1 | 60 | 5 | 3.2 | -10.10 |
| L18 | 3 | 90 | 1 | 60 | 7 | 2.1 | -6.44 |
| L19 | 3 | 90 | 1 | 80 | 5 | 3.7 | -11.36 |
| L20 | 3 | 90 | 1 | 80 | 7 | 2.9 | -7.60 |
| L21 | 3 | 90 | 3 | 60 | 5 | 3.1 | -9.83 |
| L22 | 3 | 90 | 3 | 60 | 7 | 2.5 | -7.96 |
| L23 | 3 | 90 | 3 | 80 | 5 | 3.6 | -11.13 |
| L24 | 3 | 90 | 3 | 80 | 7 | 2.6 | -8.30 |
| L25 | 3 | 110 | 1 | 60 | 5 | 3.2 | -10.10 |
| L26 | 3 | 110 | 1 | 60 | 7 | 2.7 | -8.23 |
| L27 | 3 | 110 | 1 | 80 | 5 | 3.5 | -10.88 |
| L28 | 3 | 110 | 1 | 80 | 7 | 2.3 | -7.24 |
| L29 | 3 | 110 | 3 | 60 | 5 | 3.1 | -9.83 |
| L30 | 3 | 110 | 3 | 60 | 7 | 2.3 | -7.24 |
| L31 | 3 | 110 | 3 | 80 | 5 | 3.2 | -10.10 |
| L32 | 3 | 110 | 3 | 80 | 7 | 2.1 | -6.44 |

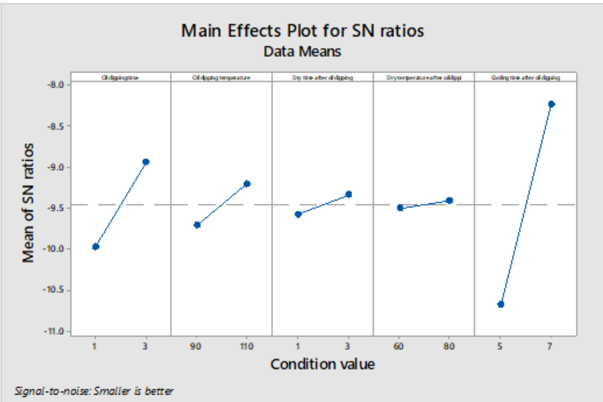


**Fig. 7** S/N analysis

**Table 4** The mean value of One-way ANOVA analysis

| Factor | N | Mean | StDev | 95 % CI |
|---|---|---|---|---|
| E1 | 32 | 2.00 | 1.02 | (-0.062, 4.062) |
| E2 | 32 | 100.00 | 10.16 | (97.94, 102.06) |
| E3 | 32 | 2.00 | 1.02 | (-0.062, 4.062) |
| E4 | 32 | 70.00 | 10.16 | (67.94, 72.06) |
| E5 | 32 | 6.00 | 1.02 | (3.938, 8.062) |
| E6 | 32 | 3.01 | 0.51 | (0.953, 5.078) |

Pooled StDev = 5.91340

**Fig. 8** Thermal resistance 3KW/33cm/380V

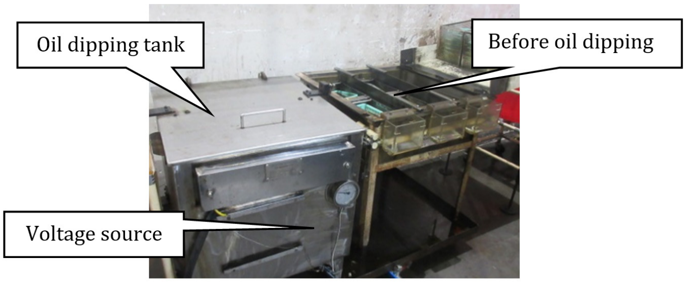


**Fig. 9** Oil dipping process

### 4.4 Improve (I)

Project A (The identification of machine tools by color at the hole grinding process). Propose a method to identify objects by color. The red and blue grading feedback system is much better than commercially available color sensors which have limitations. The camera system is designed and installed in the production process. A basic camera with 720p resolution is used for image acquisition tools. The color system of the tool's image, after being recorded by the camera, is transmitted to LabVIEW software running on PC to process and classify tools according to the system's requirements. The camera system is opened when scanning the barcode of the order on the Order sheet. Image processing tool is written in LabVIEW software (Fig. 10). The real-time database is deployed on the company's server hardware system developed with simple and fast programming applications in simplifying data access. The data connection model is between the server and the clients. The image processing algorithm in LabVIEW is implemented as a closed process (Fig. 11). The camera captures the image and image is processed on PC. The image with 3 RGB color systems (Red, Green, and Blue) is analyzed and converted to HSL color system (Hue, Saturation, and Lightness). The IMAQ Color Learn function learns the HSL color system and divides each cell containing each color system according to the color sensitivity selection. The FC250 material cutters are available in blue and red for copper tools and are divided into 16 color racks arranged from 0 to 15 (blue on the 6th color and red on the 15th color shelf). The reference value used is 0.4 for the purpose of improving accuracy in color selection and discrimination. In case where the return value at the 6th price is greater than 0.4, the evaluation is shown in blue, and the same process for the 15th price is identified in red. This cut-off value of 0.4 is obtained from the experiment during the observation of the value at each of the blue and red shelf boxes (Fig. 12).

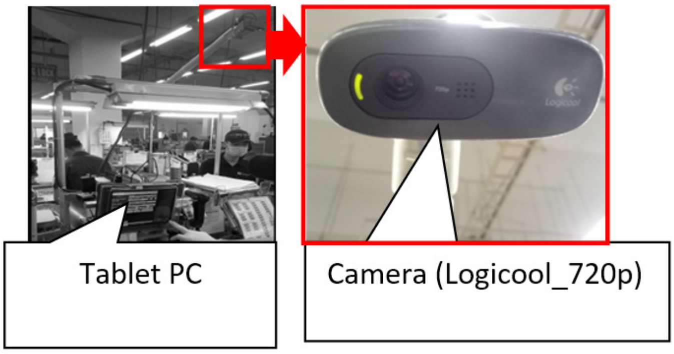


**Fig. 10** Actual camera system in process

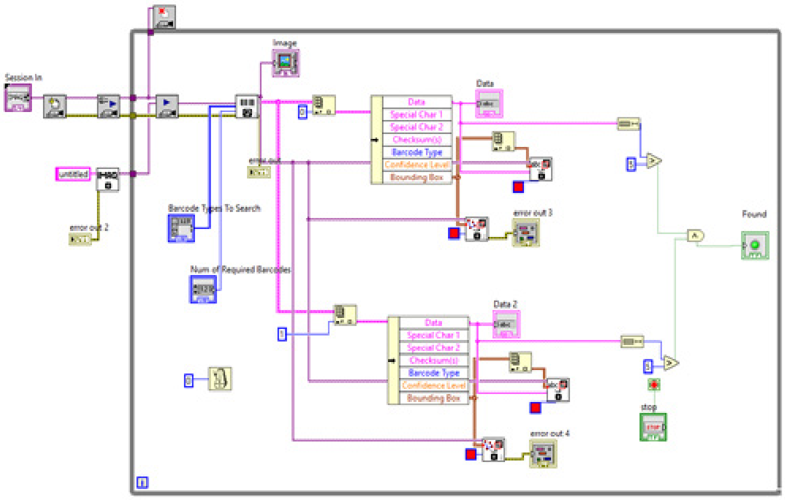


**Fig. 11** LabVIEW graphical programming environment

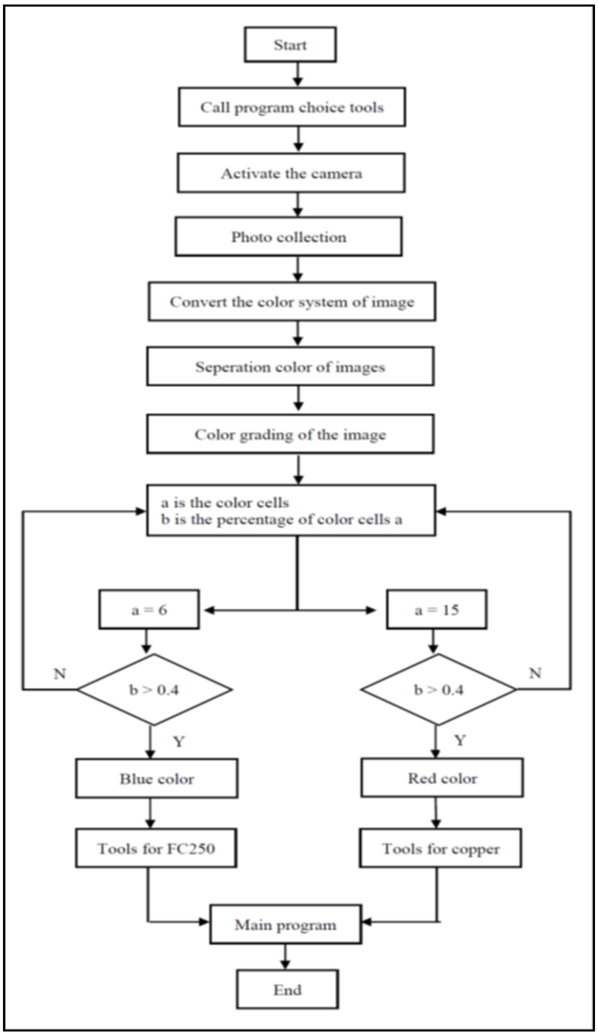


**Fig. 12** Image processing in LabVIEW

Project B (re-designed is oil dipping tank processing condition). The response of the oil dipping process includes the dimensional expansion of molybdenum $h$, the hardness of the molybdenum material $c$, the input variables for the oil dipping process including the oil dipping bath temperature $F$, heat temperature of molybdenum drying bath after oil dipping $F_1$, changing oil immersion time $F_2$, changing molybdenum drying time $F_3$, and changing molybdenum powder cooling time $F_4$. Building the mass balance equation and the composition balance equation in the oil immersion heat accretion process assuming conditions such as the density of MG 815 oil and the motion inertia of MG 815 oil in the tank are ignored. Construct the mass balance equation for oil MG 815 in the oil immersion tank (Eq. 3), and a simulation of the thermal operation of oil dipping (Eq. 4).

$$\rho V \frac{dc}{dt} + \rho c \frac{dV}{dt} = F_1 F_3 + F_2 F_4 - Fc \tag{3}$$

$$\frac{dc}{dt} = \frac{1}{\rho A h}(F_1 F_3 + F_2 F_4 - (F_1 + F_2)c) \tag{4}$$

The system of differential equations describing the thermal oil dipping process is built into, Eq. 5.

$$\frac{dy}{dt} = \frac{d}{dt}\begin{bmatrix} h \\ c \end{bmatrix} = \begin{bmatrix} \frac{1}{\rho A}(F_1 + F_2 - F) \\ \frac{1}{\rho A y_1}(F_1 F_3 + F_2 F_4 - (F_1 + F_2) y_2) \end{bmatrix} \tag{5}$$

The hypothesis at equilibrium working point taken from the mean of Table 4 (One Way ANOVA analysis) with 95 % confidence interval is $F_2$ = 2 hours, $F_3$ = 2 hours, $F_4$ = 6 days, and $\rho A$ = 0.001 m/kg. Proceed to solve Eq. 6 to find the optimal condition of oil dipping temperature $F$, optimum temperature condition $F_1$, and waiting time for molybdenum cooling after oil dipping $F_4$.

$$\begin{cases} \overline{F_1} + \overline{F_2} - \overline{F} = 0 \\ \overline{F_1}\,\overline{F_3} + \overline{F_2}\,\overline{F_4} - (\overline{F_1} + \overline{F_2})c \end{cases} \tag{6}$$

The optimal result of oil dipping temperature is that the oil dipping temperature $F$ is 100°C, the bath temperature $F_1$ is 70°C, the oil dipping time $F_2$ is equal to the drying time $F_3$ is 2 hours and the waiting time for molybdenum cooling after oil dipping $F_4$ is 6 days. Using the above condition in the oil dipping process to produce 110 products continuously, using the histogram to analyze the molybdenum size data measured by the Koshaka profiler. Standard molybdenum size expansion is less than 3 microns, analysis results show that the $C_{pk}$ stage capacity index reaches 1.16. Dimensional stability analysis of 110 continuously produced samples using the I-MR Chart and found the results to be within the norm but with large inter-series variability.

Project C (Quality control of power supply is for oil dipping tank). Connect the voltage measurement results and THD value to the measurement system at the oil dipping stage. The standard THD power supply for the thermistor is 5 % max and the mains voltage is 380 V ± 20 %. For each oil dipping order, the measuring system program is activated and the power supply measurement value is updated in the system, the results are processed by the system online (Fig. 13). If the value of the power supply (THD and Voltage) exceeds the standard, the system generates an alarm. Data is collected in real-time, and connected to the SQL (Structured Query Language) system.

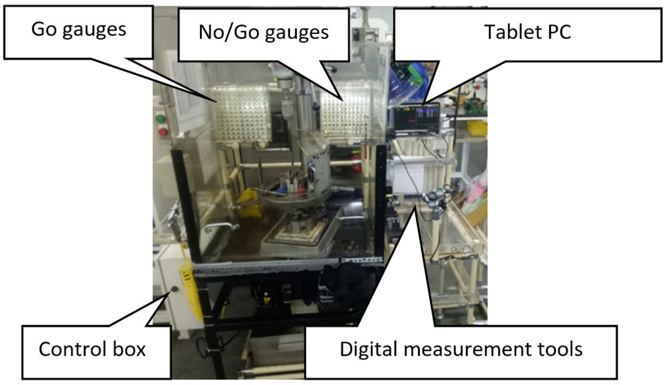


**Fig. 13** Actual digital measurement system in process

### 4.5 Control (C)

This study focuses on controlling the molybdenum size variation in the production line and is a long-term development strategy of the enterprise. Enhancing workers' confidence in tool improvement from the improvement department is a very important step forward. Applying lean tools, statistical tests, and experimental design methods as well as applying quality 4.0 techniques such as computer vision, digital numerical control, and inspection system have contributed to bring great success for Lean Six Sigma projects. The team leader of the Lean Six Sigma project is a member of the company's technical committee (an engineer) and the project members are employees working directly at the product processing line. The lessons learn from failed experiments as well as from successful experiments are valuable that help improve the capacity of engineers as well as research team members. Helps build new knowledge and develops team leadership skills for project members. Engineers become leaders in the future, for machine operators, accumulate experience, and apply quality 4.0 technology to improve process and product quality. Achieves the goals set out from the beginning of the project implementation. This study has relevant contributions to researchers, managers, engineers, and even direct machining machine operators. These key results are presented step-by-step by phase in the DMAC (Table 5).

**Table 5** Description of research results through each phase of DMAIC

| Phase \ Results | Result 1 | Result 2 | Result 3 |
|---|---|---|---|
| **D**efine | It is necessary to redesign the process of applying Industry 4.0 technology to the operation and controlling production line of products using the special raw material molybdenum. | The Lean Six Sigma (LSS) project specifies a specific target, a specific timeline for each task, and each member according to each specific project. | Enhancing the morale of employees through continuous improvement activities to improve productivity and quality. |
| **M**easurement | Using statistical techniques, statistical hypothesis testing to analyze data collected directly at the machining line by the operator | | |
| **A**nalysis | Specify each activity in the LSS project and deploy the corresponding analysis tool for each activity. Namely, the Optimization of machining conditions by the Taguchi optimization technique. Object recognition and classification by computer vision technique with color processing function. Real-time data acquisition by digital signal processing with RFID barcode scanning and digital numerical control technology to control the corresponding object. | Many noise factors in the factory environment affect machining conditions. | Link data of individual stages into a common data block. |
| **I**mprove | Industry 4.0 techniques and computer vision technology are deployed directly to the production line and operated by workers. | Digital numerical control technology is deployed to the direct processing line to collect data in real-time. | The processes are linked together. |
| **C**ontrol | Tasks in each project are completed. Re-engineered the production line from semi-automatic to fully automatic operation. Machining operation is simple. | The research results are that the defect rate decreased from 6.5 % to zero, the productivity increased by 7.9 % per year and the profit increased by 35762 USD per year. | Improve the working spirit of workers and employees in the company. Connecting and implementing research results into practice brings high results. |

## 5. Conclusion

All members of the outsourcing line participate in the Lean Six Sigma (LSS) project, the goal of the LSS project is to improve the internal capabilities of the organization within the company. This study implements the implementation of the LSS project on rebuilding the production process at the mechanical product processing line and redesigning the production conditions at each specific production process. The specific result is optimizing the conditions for the oil dipping process, creating a system that links data from individual processes into a system and processes that can access and recognize each other's data. The measurement and data collection system by barcode scanning tool using Industry 4.0 techniques is deployed at each line, the operation is simplified, and the operation changes from semi-automatic to automatic operation. The Industry 4.0 system follows the principle that if the fieldwork quality is not completed, the next stage will be locked and the industrial system will not work, which means the processing line is stopped by the leader and transferred to the employee card (Fig. 14).

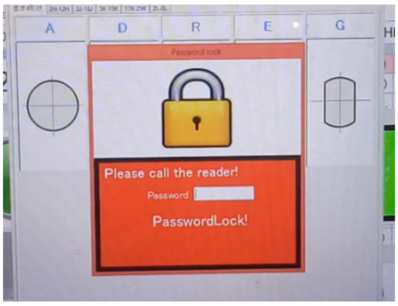


**Fig. 14** Lock system screen

This study serves as a project planning and reporting model for activities in companies. However, this study raises the issue of data security systems in Industry 4.0 systems and is a promising research direction for future researchers. This study implements the LSS project implemented directly at the production line at the mechanical manufacturing company and the data is collected at the production site by the operator. This is also considered a promising data set for researchers carrying out new studies on improving productivity and product quality in the future.

The research results are that the defect rate decreased from 6.5 % to zero defect, the total production capacity increased by 7.9 % and the profit was 35762 USD per year, reaching the set target compared to the LSS implementation plan. Another result is to improve the working spirit of employees, and at the same time remove prejudices about the gap between research results and application of research results in practice. Enhance the spirit of implementing continuous improvement activities in the company.

However, it is necessary to reanalysis each specific tool when applying the DMAIC model to each specific process to promote the strongest. Because some companies only define the goal without really paying attention to the empirical research and the research method is not enough. This study establishes a model for the application of statistical tools, statistical hypothesis testing, and optimal experimental design Taguchi in data analysis to meet organizational development goals. This research paper provides a scientific research model for organizations applying directly to their production processes in order to develop and bring good results. It is also worth noting that computer vision technology is applied to the process of continuous improvement to deliver results that exceed expectations. This model is considered as the foundation for research and application of artificial intelligence in improving production processes and production operations.

Some recommendations are for further studies. It is proposed to extend this research model to apply to all departments in the company. Improve power quality by minimizing and controlling harmonics generated in the power supply for the signal processing sensor operating boards, the thermostat power supply, and the actuator circuit power supply in the processing line. Real-time data security is also considered a promising research direction.

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# Spatial position recognition method of semi-transparent and flexible workpieces: A machine vision based on red light assisted

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**A B S T R A C T**

In the automatic sorting process, overlapping translucent and flexible workpieces on the conveyor belt, blurring the imaging edge features of translucent and flexible workpieces is a challenge to locate the upper and lower workpieces spatially, we propose a method for locating translucent and flexible workpieces spatially under the overlapping environment in conjunction with the most common automatic sorting of translucent and flexible workpieces such as infusion tube drip buckets. Firstly, we propose a rectangular surface light source based on 650 nm band and monocular CCD for imaging translucent workpieces such as infusion tube drip buckets and optimize the imaging parameters. Secondly, we study a feature matching recognition algorithm for flexible workpieces that are prone to deformation, construct a mapping relationship between the position of overlapping layers and imaging quality of translucent and flexible workpieces such as infusion tube drip buckets based on clarity and information entropy, and establish The mapping relationship between the position of the overlapping layers and the imaging quality of translucent and flexible workpieces such as infusion tube drip buckets is constructed based on clarity and information entropy, and a local spatial coordinate conversion model is established. Finally, the spatial positioning coordinates of overlapping and non-overlapping translucent and flexible workpieces in the local coordinate system are identified, and the results show that the imaging method and theory can be effectively applied to the identification of overlapping and spatial positioning coordinates in the automatic sorting of translucent workpieces such as infusion tube drip buckets.

**A R T I C L E  I N F O**

*Keywords:*
Machine vision;
Image processing;
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Feature matching;
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## 1. Introduction

In the fields of food processing [1], manufacturing job-shops [2], health care, electrical and electronics, architectural design, and resource recovery [3], sorting means have been automated, especially for translucent flexible workpieces. Translucent and flexible workpieces such as infusion tubes and drip buckets (abbreviated as TFW-TDB) occupy a larger market for medical products (13 billion tubing and drip buckets are used annually in the Chinese medical field [4]). For the reason of used in medical, their sorting and assembly processes have more stringent standards and specification systems than other similar products [5, 6].

Machine vision has flourished and applied well in modern sorting systems for detection and sorting, and automated mechanical technology for control [7, 8]. Accurate workpiece posture information is a prerequisite for accurate sorting by automated machines, mechanical grippers can be guided quickly and accurately to carry out grasping work, thus achieving the purpose of sorting [9]. When there is a large number of targets, it is also necessary to judge the spatial position of each target and select the most suitable workpiece among the stacked workpieces. Therefore, visual recognition and position detection technology is one of the key technologies in the field of machine vision automation [10, 11].

As early as the 1950s and 1960s, foreign research was conducted on the recognition and understanding of two-dimensional images and the recovery and coordinate mapping of three-dimensional images, and its application scenarios included aerial images [12], workpiece surface defect detection [13]. By the 1980s and 1990s, CCD and CMOS camera technology progressed rapidly [14], and machine vision technology was better supported. China started late in this area, but has achieved good results in various fields. The most popular method for a large number of target recognition is template matching [15, 16], which is widely used in various fields such as license plate detection [17], fingerprint recognition [18], font recognition [19, 20], distance estimate [21]and even waveform classification [22] by virtue of its simplicity, stability, and accuracy. However, the following challenges exist in imaging the characteristics of TFW-TDB. (1) Blurred edges: Its translucent nature makes the edge features of TDB in imaging inconspicuous, which will affect the performance of the image algorithm and lead to difficulties in distinguishing spatial relationships when multiple TDB overlap; (2) Flexible and easily deformed: TDB are too soft and the stacked workpieces are prone to deformation during the sorting process, making it more difficult to accurately identify their positioning coordinates. Therefore, the sorting and assembling of TDB is still done manually, which makes it difficult to control the efficiency and quality effectively in the long run. Therefore, we propose a method that can be adapted to the inspection of workpieces with this feature. Since the object-oriented objects in this paper are standard artifacts, the template matching method is considered. Template matching is performed by creating a template similar to the target image, translating, rotating, and 3D transforming the template image to overlap with the target image as much as possible, and then quantifying the comprehensive similarity degree by comparing the pixels of each point in the overlap region, corner features and light and shadow changes. When the similarity degree is higher than a set threshold, the target is recognized and the spatial pose information of the target is returned.

The mode of image pixel matching and image feature matching are two common template matching methods. The former matches the template pixels directly with the pixels of the image to be measured, while the latter constructs a template by finding the relationship between the target features and the coordinates of the corner points, and then extracts the features of the measured image for matching. Korman *et al*. [23] proposed a matching algorithm capable of performing arbitrary affine transformations by calculating the sum of the absolute differences between the template and the affine changed region and finding the minimum value for matching, but this process is only effective for the deformation on the perspective, and will result in large errors if the target sample itself changes. Zhang *et al*. [24] solve the problem that the original template matching method based on NCC (normalized correlation) is too slow for rotated images, and propose a sub-NCC-based template matching method, which selects rotationally invariant edge points from rotationally invariant pixels and uses the selected points for rough matching to quickly filter out the mismatched regions, improving the anti-interference ability and matching speed of the algorithm. Zhang *et al*. [25] proposed a multi-scale template matching method based on nearest neighbour (NN) search, which provides scale adaption by extending the diversity similarity DIS and explicitly penalizing deformation to deal with the situation that the size of the candidate window is fixed and cannot solve the object scale changes greatly. Experiments show that the proposed method is robust in terms of extended variation as well as other challenging aspects and outperforms state-of-the-art methods using both colour and depth features. Ye *et al*. [26] proposed a fast and robust template matching framework integrating local descriptors of multimodal images to cope with the multimodal data problem, and proposed a novel pixel feature for images using oriented gradients (CFOG) with excellent performance in image matching and computational efficiency. Consider the disadvantages of the existence of over-segmentation and image interference by reflected light, Wu and Li [27] proposed an improved watershed algorithm based on morphological gradients. The method obtains the component gradients of colour images in a new colour space without interference from reflected light. The gradient image is reconstructed by turning on and off, and the final gradient image is obtained. Additionally, deep learning-based matching algorithms are the mainstream in recent years. Wang *et al*. [28] proposed such algorithm to achieve the recognition of different types of track profiles. The template-matching driven spatio-temporal context tracking algorithm is used to achieve fast tracking of laser stripes on the rail head. The method effectively solves the problem of profile measurement of passing trains at the crossing, and achieves precise positioning and fast tracking of various types of laser stripes. Hikosaka and Tonooka [29] proposed a new method for automatic image-to-image alignment, which performs image-to-image alignment by applying template matching to road masks extracted from images using a two-step deep learning model. Chen *et al*. [30] proposed a new MC-UNet, which expands the depth of MC-UNet layer to 2 layers and reduces the maximum number of channels to 32/31 compared to the classical U-Net. Using average pooling and embedding channel attention in the hopping process between encoder and decoder layers of the same network depth, the computational speed and accuracy are improved.

In the actual production process, the spatial relationship of the target under the camera still needs to be clarified. Especially in the stacked state, it is more difficult to achieve matching when there is a target that is partially occluded. Currently, there is a class of methods to determine the part space relationship by calculating the edge integrity. In the edge extraction algorithm, Sangeetha and Deepa [31] improved on the basis of Canny algorithm and proposed a new Canny algorithm without any loss in detecting edges at the block level to solve the traditional. The edge detection method is complex, time-consuming, and has high hardware cost. Goyal *et al*. [32] proposed an improved version of local binary mode LBP, namely ILBP, to overcome the limitations of basic LBP.ILBP replaces the fixed weighting matrix of basic LBP with a pixel difference matrix. Results show that ILBP has superior performance and is very effective for noisy, blurred and low pixel value images. Mittal *et al*. [33] proposed a robust edge detection algorithm using a multi-thresholding approach (B-Edge) to compensate for the edge connectivity and edge thickness problems encountered in edge detection, and successfully detected robust and continuous thin edges with a small percentage of noise. Furthermore, there is also the use of three-dimensional reconstruction to make judgments, and such methods are more accurate although the computational complexity of the algorithm is increased. He *et al*. [34] solve the problem of overlapping and mixing workpieces, which makes it difficult for robotic arms to grasp workpieces. Take advantage of 3D laser scanner to obtain the point cloud features of the workpiece. The point cloud is first filtered and segmented, and then fed into RS-CNN network for recognition and classification. According to result, different models are used to record the point clouds in the scene. Finally, the final pose of the workpiece to be grasped is obtained to realize the unordered grasping of various workpieces. Chen *et al*. [35] proposed a novel stereo matching algorithm combining polar geometry and cross ratio invariance (CMEC) to reconstruct the workpiece in 3D by fitting the plane with least squares. The matching accuracy reaches 3 % and the measurement accuracy reaches 99.0 mm. Wang [36] proposed an improved LIDAR point cloud surface reconstruction algorithm to achieve fast 3D surface reconstruction from a given scattered point cloud. The idea of classification is also incorporated into template matching and 3D reconstruction to better obtain the spatial information of stacked parts.

With the continuous development of neural networks, deep learning-based methods are becoming more and more mature, which has become an important trend in the field of sorting. Han and Han [37] proposed a detection method based on an improved Faster R-CNN model, improved the Faster R-CNN feature network, and selected ResNet combined with SENet for feature extraction, which improved the important feature layer and suppressed the non-significant feature layer is suppressed. The Soft-NMS algorithm was introduced to optimize the NMS algorithm to reduce the problem of missed and false detection of overlapping or adjacent targets. Li *et al*. [38] proposed an improved artifact recognition method based on YOLOV5. By adding an attention module to the backbone network, the feature extraction capability of the network is enhanced. Secondly, the SIoU loss function is used to speed up the convergence speed, improve the regression accuracy and enhance the network accuracy. The phenomenon of missed detection, false detection and overlap can be effectively avoided.

In the infusion tube processing process, the material is flexible, translucent and other physical properties, the general machine vision feature matching algorithm is difficult to cope with, the biggest problem is that the infusion tube valve bubble itself is not fixed. General template matching algorithm can only be applied to the traditional perspective deformation, when the measured target itself deformation is difficult to identify; and deep learning algorithms are generally more complex, hardware chips and data sets require a certain cost to build, real-time is also relatively poor.

When it comes to the overlapping grasping of the infusion tube valve bubble, considering that the infusion tube valve bubble is not a perfectly straight line, as well as for its translucent nature characteristic, the exact edge position of the bubble extracted using the general edge detection algorithm is limited, it leads to a large error between the center of the workpiece and the grasping point. At the same time, the complexity of the algorithm based on 3D reconstruction and deep learning is too high, and it is difficult for ordinary embedded chips to achieve real-time detection, so most of them are not applicable to the application scenario of the spatial positioning of the infusion tube valve bubble in this paper.

Therefore, we propose a visual recognition method for the infusion tube valve bubbles; our method is improved and designed as follows.

- Adopt backlighting for overexposure type illumination, and use contrasting red light to solve the problem of unstable imaging quality of infusion tube valve bubbles in overlapping state.
- An improved template matching algorithm based on deformation is proposed, and reasonable matching greediness and distortion thresholds are set to realize the segmentation and identification and localization operations of infusion tube valve bubbles in the overlapping state.
- To construct a coupled model of spatial position and imaging quality of infusion tube valve bubbles by using clarity coefficient and information entropy to realize the determination of spatial position of infusion tube valve bubbles.

## 2. The principle and methods

### 2.1 Composition of TFW-TDB visual positioning system

The TFW-TDB vision positioning system is mainly composed of conveyor conveying subsystem, sorting actuator, optical imaging subsystem, information processing subsystem and motion control subsystem (shown in Fig. 1). The optical imaging system consists of CCD camera, auxiliary light source, and imaging posture adjustment mechanism. In the TFW-TDB imaging on the conveyor subsystem, although the coaxial light source and other methods can image the TFW-TDB better and reduce the interference between the imaging device and the sorting execution device, there are problems such as insufficient contrast of edge features and difficulty in judging the upper and lower layers of overlapping features in the TFW-TDB imaging process. Therefore, the back-projected rectangular red light source backup drug-assisted imaging. the working principle of the visual positioning system in the TFW-TDB sorting process is as follows.

Firstly, the conveyor belt in the conveyor belt transport subsystem is set to transparent color, and the TFW-TDB is continuously transported by the conveyor belt to the preset imaging position, and the CCD obtains the TFW-TDB image on the conveyor belt according to the fixed adoption frequency with the assistance of the light source. Secondly, the dynamic feature matching algorithm and the TFW-TDB overlap layer determination algorithm are used to obtain the feature points in the coordinate system of the TFW-TDB image Secondly, the dynamic feature matching algorithm and TFW-TDB overlap layer determination algorithm are used to obtain the feature points in the coordinate system of TFW-TDB image and the overlap layer of TFW-TDB. Finally, the spatial positioning coordinates in TFW-TDB sorting are obtained by combining the positioning coordinates of TFW-TDB feature points in the image coordinate system, the camera calibration parameters and the mapping relationship between the measurement point coordinates and the sorting global coordinate system.

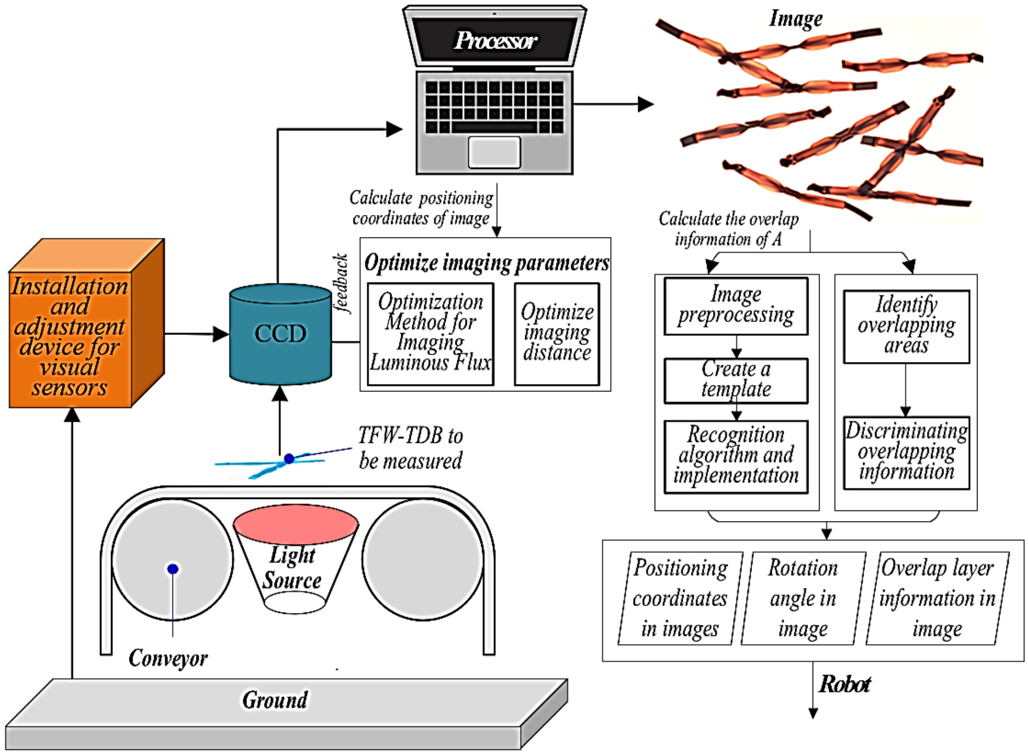


**Fig. 1** Schematic diagram of TFW-TDB visual recognition system

### 2.2 Optimization of TFW-TDB vision system parameters

TFW-TDB imaging system is composed of CCD, auxiliary light source, light source controller, industrial control machine, transparent conveyor belt and other modules. For liquid tube drip bucket, which are easy to overlap on the conveyor belt, the back-projection type of auxiliary light illumination is proposed (shown in Fig. 1). In the imaging process, the light intensity directly affects the prominence of features in TFW-TDB imaging, reasonable imaging distance parameters can ensure TFW-TDB images each layer clearly under overlapping conditions and the features of interest occupy the highest pixel density, the TFW-TDB imaging light flux and imaging distance parameters are optimized.

A) Establishment of lighting system luminous flux optimization method

To output clear edge imaging of TFW-TDB and reduce background interference, we objectively judge the imaging results of the infusion tube drip bucket based on the information entropy image information evaluation index with the rule, that the greater the information entropy in the image, the more information the image contains [39]. The optimization method of imaging parameters in terms of information entropy is as follows:

We assume that the acquired image of the TFW-TDB region is $Image_1$, in which the gray values of each pixel point are independent of each other, its binarized distribution is as follows:

$$rel = \{rel_0, rel_1, \ldots, rel_i, \ldots, rel_n\}, n = 1,2, \ldots, 255 \tag{1}$$

where, $rel_i$ denotes the ratio of the number of pixels with gray value i to the total number of pixels in the image. On the basis of the above equation, Eq. 2 calculates the information entropy of $Image_1$:

$$Ent = -\sum_{0}^{n} rel_i \cdot \log_2 rel_i \tag{2}$$

To investigate the effect of auxiliary light source brightness on the imaging quality of TFW-TDB, the CCD camera aperture is adjusted to the maximum, the shutter time is set to 1/20 s, and the IPC controls the light source controller through the RS232 communication port to change the brightness of the auxiliary light source, assuming that the brightness level of the auxiliary light source is $j$ ($j = 1, 2, 3, \ldots, 242$), the image acquired under different brightness levels $j$ is $\text{Image}_{1j}$. The information entropy of TFW-TDB images acquired at different brightness levels $j$ is recorded as $\text{Image}_{1j}$. The information entropy of image $\text{Image}_{1j}$ under different luminance levels is calculated based on Eqs. 1, 2, and the curves are shown in Fig. 2. Then the curve continues to decline until the end. The reasons for the change of information entropy $\text{Ent}_j$ under different luminance levels $j$ are as follows: when the luminance of the auxiliary light source increases, the red backlight light source gradually overexposes the image, and the information of the surrounding environment is gradually lost, and the curve starts to decline, when the luminance level $j = 92$, the structural features of TFW-TDB gradually reveal, and the image information increases, and when the luminance level $j = 114$, the image becomes completely overexposed due to the increase of illuminance. At luminance level $j = 114$, the image becomes completely overexposed due to the increase in illuminance, so the best imaging effect is achieved at luminance level $j = 114$.

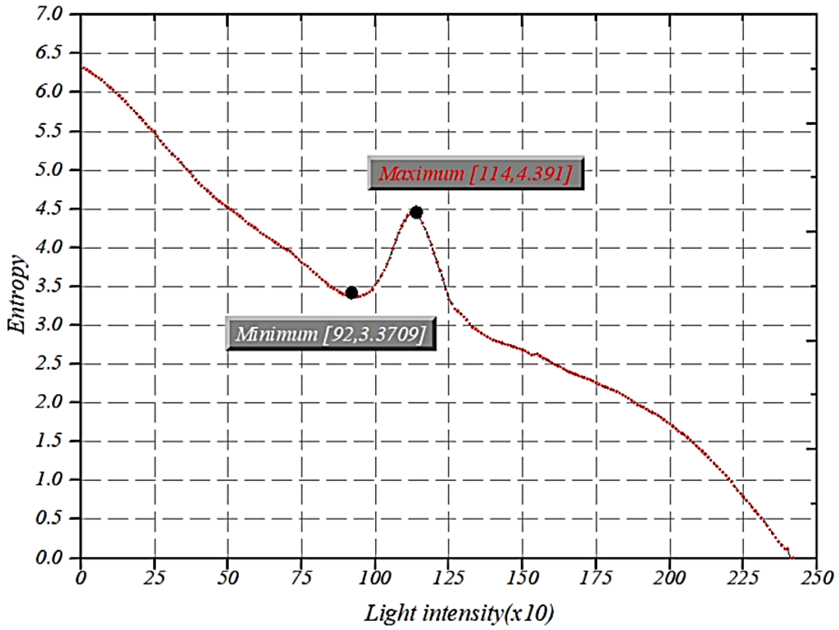

**Fig. 2** Information entropy curves under different illuminances

B) Establish the camera imaging distance optimization model

In the imaging process of TFW-TDB, the imaging method of vertical transmission of lens with surface is used, and the imaging distance $L$ directly affects the depth of field $\Delta L$ of imaging, that is, the overlap thickness of TFW-TDB. We suppose that the maximum thickness of a single TFW-TDB is $H$, and the overlapping thickness of TFW-TDB in the sorting process does not exceed $m$ layers, the following equation needs to be satisfied:

$$\Delta L \geq (m + \lambda) H \tag{3}$$

where, λ is the compensation factor for camera installation error and other effects, through the experiment to take λ = 0.5. TFW-TDB will be placed on the conveyor belt for several experiments can be known $m$ = 3. Assume that the camera shooting aperture value is $F$, the lens focal length is $f$. From the imaging principle of camera, it is known that the camera depth of field $\Delta L$, focal length $f$, aperture value F satisfy the following formula:

$$\begin{cases} \Delta L_1 = \dfrac{FdL^2}{f^2 + FdL} \\ \Delta L_2 = \dfrac{FdL^2}{f^2 - FdL} \end{cases} \tag{4}$$

Simplify above:

$$\Delta L = \Delta L_1 + \Delta L_2 = \frac{\alpha L^2}{\beta + \alpha L} + \frac{\alpha L^2}{\beta - \alpha L} \tag{5}$$

where, $\Delta L_2$ is the depth of field, $\alpha = F \cdot d$, $\beta = f^2$, $d$ is the allowable dispersion circle diameter and the camera frame, based on the size of the camera imaging frame in the experiment (480×360 mm) and the literature [40] can be known, we take $d$ = 0.146.

From Eq. 3 and Eq. 4 can be established Eq. 5 to find the camera imaging distance $L$ need to meet the Eq. 6:

$$L \geq \left(\frac{(m+\lambda) H\beta^2}{2\alpha\beta + (m+\lambda) H\alpha^2}\right)^{\frac{1}{2}} \tag{6}$$

It is known from the imaging theory that when the imaging distance is reduced, the pixel density occupied by the TFW-TDB imaging target features is higher and the recognition accuracy is higher, so the minimum value of Eq. 6 can be taken as the optimal imaging distance.

### 2.3 TFW-TDB visual recognition

*Construction of a flexible target matching template*

Template matching algorithm is an effective method to achieve target feature localization. Due to the existence of flexible deformation and other characteristics of the infusion tube drip bucket, it causes the traditional rigid workpiece matching template construction algorithm to be difficult to apply. This study adopts a global-local contour line fusion matching template construction method, and the related theory and algorithm are as follows.

A) Image pre-processing

Due to the factors such as the imaging environment lighting, TFW-TDB itself material inhomogeneity, there is noise in the imaging process of TFW-TDB, it is necessary to perform certain pre-processing operations on TFW-TDB image to eliminate the noise and initially filter the infusion tube drip bucket which is not qualified in shape and color or has serious deformation, the related algorithm is as follows:

(1) If the pixel values of any pixel point $P(i,j)$ in $Image_1$ in R,G,B channels before preprocessing are $P_R(i,j)$, $P_R(i,j)$, $P_B(i,j)$, respectively, and the value after binarization is $P_{Gray}(i,j)$, the calculation formula for binarization of $Image_1$ is as follows:

$$P_{Gray}(i,j) = a_1 \cdot P_R(i,j) + b_1 \cdot P_G(i,j) + c_1 \cdot P_B(i,j) \tag{7}$$

where, $a_1$, $b_1$, $c_1$ are the weight coefficients of R, G, B triple pass at the time of binarization. The information entropy is used as the evaluation index of imaging quality after binarization, and the $a_1$,$b_1$,$c_1$ weights are obtained when the information entropy of TFW-TDB $Image_1$ is maximized after binarization, and then $a_1$ = 0.299, $b_1$ = 0.587, $c_1$ = 0.114 are determined by fitting with the least squares method. The TFW-TDB region after binarization is shown in Fig. 3(a). The TFW-TDB region is shown in Fig. 3(b) after binarization of Image2 with grayscale inversion.

(2) The two ends of TFW-TDB show irregular deformation. When the TFW-TDB image matching template is established, under the condition that the rectangular region of interest (ROI) completely contains the bubble chambers to the left and right of TFW-TDB, considering that the bubble chambers to the left and right of TFW-TDB have small deformation relative to the spatial position in the actual process, the rectangular region of interest (ROI) shown in Fig. 3(c) is set as the boundary line by deviating 10 pixel points from the bubble chambers to the left and right of TFW-TDB, and the irregular ends of the standard sample are removed to segment the feature region as shown in Fig. 3(d).

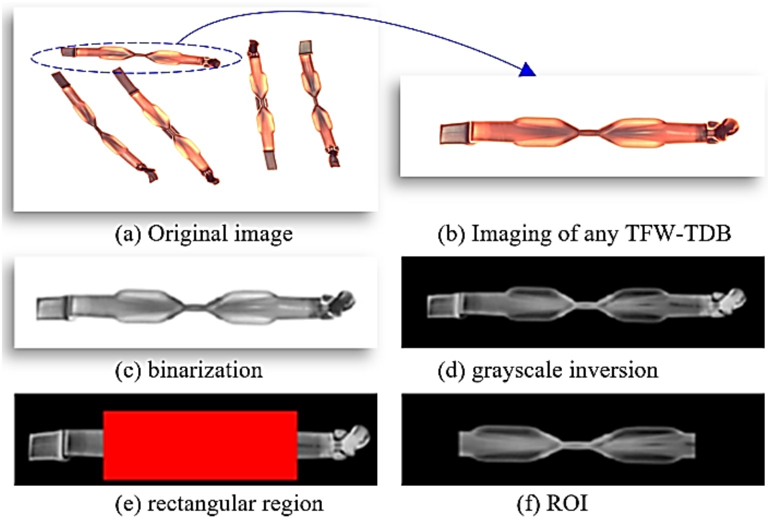


**Fig. 3** Preprocessing images

B) Creating templates

TFW-TDB will cause small deformation easily between the left and right bubble chambers in the overlapping state, but the left and right bubble chambers themselves do not change shape easily, the method of global-local contour line feature fusion is used to create the TFW-TDB matching template (shown in Fig. 4). The matching template contains two parts of features, the global features are two global contour lines in red and purple, and the local features are four local contour lines in green, blue, light blue and yellow. The global contour lines are clear and complete, reflecting the main features of the infusion tube valve bubble. The local contour lines reflect the structure of the two bubbling chambers and present an asymmetric structure, which can prevent a template from repeatedly matching the same workpiece.

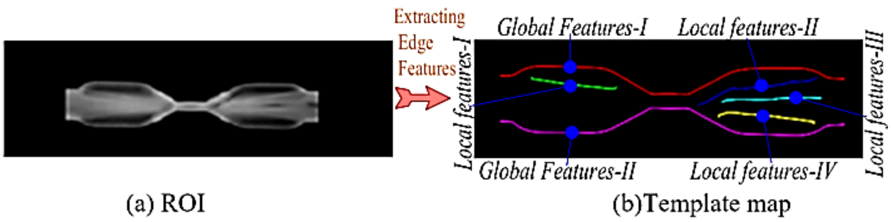


**Fig. 4** Template map

*TFW-TDB matching algorithm and implementation*

Achieving the matching of TFW-TDB features with the created template is one of the key steps to realize the irregular TFW-TDB image localization, and the recognition algorithm based on template matching is developed for the features of TFW-TDB and the above created template as follows:

Step1: Using the above image pre-processing algorithm, the $Image_1$ is binarized and grayscale inversion operation is performed to obtain image $Image_2$.

Step2: Using morphological algorithm to denoise $Image_2$ is to obtain $Image_3$, based on which the number $t$ of corresponding single or overlapping TFW-TDB is identified in conjunction with the connected domain algorithm, and the identified TFW-TDB are segmented and encoded, where any one segmentation region is noted as $Image_{3\text{-}j}$ $(j = 1, 2, \dots, t)$.

Step3: The matching template operator in the literature [29] is used, and the search greediness parameter is set to 0.9, the minimum threshold score parameter is between 0.5 and 0.55, the overlap coefficient is 0.3, and the maximum number of matches parameter is calculated as follows:

$$N = \frac{S_{roi}}{S_{unit}} + 1 \tag{8}$$

where, $S_{roi}$ is the area of the region, $S_{unit}$ is the area reference value of a single workpiece, the output result of the matching template operator is the row coordinate $Row_j$, column coordinate $Column_j$, rotation angle $Angle_j$, scaling $Scale_j$, matching $score_j$ of the upper left vertex of any TFW-TDB$_j$ of the rectangular image Image$_{4\text{-}j}$ matched in Image$_1$. This matrix carrying the template matching pose information is then applied to the template contour image to form the matching contour image, and the matching effect is shown in Fig. 5.

Step4: Since the result of TFW-TDB matching may have deviation, it needs to be corrected. First, take the minimum outer rectangle of any TFW-TDB$_j$ matching contour line as in Fig. 6(a); then merge the rectangle shapes, and then take the minimum outer rectangle on the basis of the merged shapes as in Fig. 6(b), and output the minimum outer rectangle row coordinates of the upper left vertex of TFW-TDB$_j$ Image$_{4\text{-}j}$ matching after correction $Row_j'$, column coordinates $Column_j'$, rotation angle $Angle_j'$, outer rectangle length and width respectively are $Lenght_0'$, $Width_0'$.

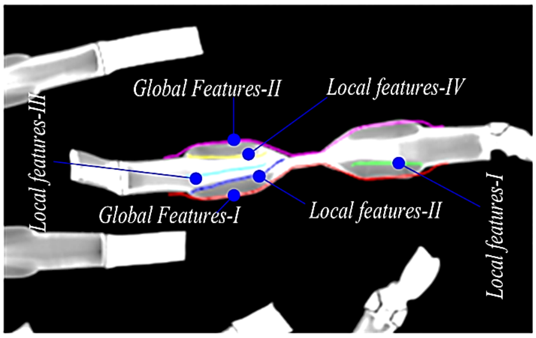


**Fig. 5** Matching effect display

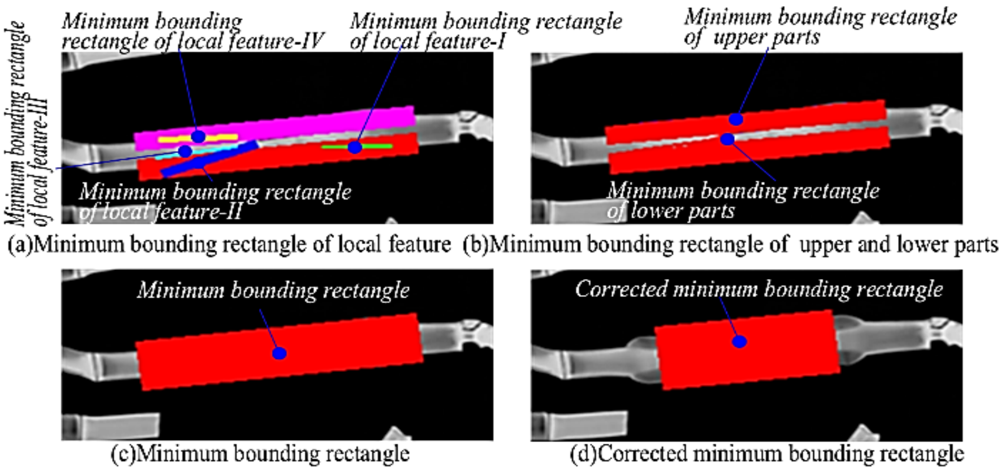


**Fig. 6** Matching result correction

*Establishing TFW-TDB spatial overlap state discriminant model*

After image processed, the planar coordinates and rotation angle of the TFW-TDB on the conveyor belt can be accurately obtained, but the characteristics of the TFW-TDB such as translucency and overlap make it difficult to obtain the height information on the conveyor belt, which restricts the realization of automated sorting and assembly of the TFW-TDB. Therefore, spatial determination of the overlap where the TFW-TDB is located is needed. This study establishes a coupling model between the overlapping layer and the imaging quality of TFW-TDB, and identifies the overlapping layer of TFW-TDB by its imaging quality.

A) Constructing the overlap region of interest model

The positioning of feature points in the left and right bubble chambers of TFW-TDB is the key factor to realize its sorting and assembly, however, the complete imaging and segmentation accuracy of the left and right bubble chambers of TFW-TDB determine the accuracy and reliability of TFW-TDB positioning. The corrected matching area can accurately locate the area where TFW-TDB is located, but the complete imaging of TFW-TDB left and right bubble chambers is incomplete. Therefore, the corrected matching area is used as the basis to construct the overlap area of interest, which provides the image basis for the analysis of the overlap layer where TFW-TDB is located. If the percentage of the aligned contour lines in the TFW-TDB image along the length and width directions is $H_1$%, $W_1$%, respectively, and the extension rate of TFW-TDB in the length and width directions is $H_2$%, $W_2$%, respectively, and the length and width of the outer truncated rectangle of the matching template are $Length_0$, $Width_0$, respectively, the row coordinates $Row_j'$, column coordinates $Column_j'$, rotation angle $Angle_j'$ of the upper left vertex of the TFW-TDB overlapping rectangle region of interest, the outer truncated rectangle .

The length and width are $Lenght_0'$, $Width_0'$ respectively, then the parameters of TFW-TDB$_j$ overlapping region of interest ($ROI_j$) are calculated as shown in Eq. 9.

$$\begin{cases} \dfrac{Row_j^{ROI} - Row_j'}{0.5 \cdot (Length_j^{ROI} - Length'_j)} = \cos\,(Angle_j^{ROI}) \\ \dfrac{Column_j^{ROI} - Column_j'}{0.5 \cdot (Width_j^{ROI} - Width'_j)} = \sin\,(Angle_j^{ROI}) \\ Length_j^{ROI} = \dfrac{Length_0 \cdot Scale_j \cdot (1 + H_2\%)}{H_1\%} \\ Width_j^{ROI} = \dfrac{Width_0 \cdot Scale_j \cdot (1 + W_2\%)}{W_1\%} \\ Angle_j^{ROI} = Angle_j' \end{cases} \tag{9}$$

In the experiment, the percentage of TFW-TDB images along the length and width directions $H_1$%, $W_1$% are 80 % and 95 %, respectively. The extension rate of TFW-TDB in the length and width directions $H_2$%, $W_2$% are 20 % and 5 %, respectively. The overlap region of interest of TFW-TDB$_j$ is shown in Figs. 7 and 8 when the value is taken into Eq. 9.

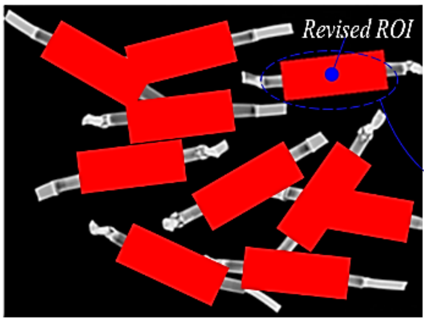


**Fig. 7** Region of interest

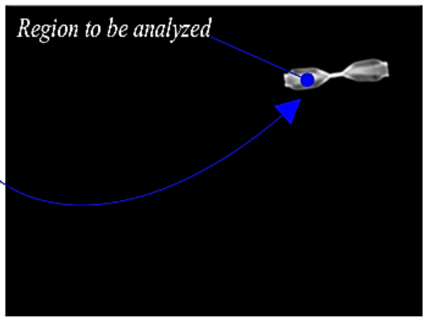


**Fig. 8** Overlapping analysis area

B) Establishing an overlap layer discrimination model based on imaging quality

In the TFW-TDB overlap region of interest, the Sobel operator is applied to extract the edge features in the left and right bubble chambers of the TFW-TDB, shown in Fig. 9.


(a) Edge extraction of unoverlapped regions (b) Edge extraction of overlapping regions

**Fig. 9** Edge extraction

As can be seen from the figure, the TFW-TDB is imaged after overlapping, the upper layer features are clear and the lower layer features are blurred, so the feature imaging quality evaluation function of the TFW-TDB can be constructed, and then the spatial layer in which the TFW-TDB is located is coupled with the feature imaging quality model, which works as follows.

(1) The feature imaging quality evaluation function of TFW-TDB was constructed. When TFW-TDB is overlapped, there are certain differences in the imaging clarity of upper and lower TFW-TDB and the contrast of TFW-TDB features in the image. Therefore, the sharpness coefficient *Sharpness* and information *Entropy* are used as the feature imaging quality evaluation index of TFW-TDB in $ROI_j$.

First, the image variance is calculated in $ROI_j$ of TFW-TDB$_j$ and flipped in the interval [0, 100] to obtain the sharpness coefficient $Sharpness_j$ of TFW-TDB$_j$, which is calculated by the equation:

$$Sharpness_j = 100 - \sqrt{\frac{\sum_{p=1}^{n}\left(g(p) - \sum_{p=1}^{n} g(p)/n\right)^2}{n}} \tag{10}$$

where, $p$ is any pixel point within $ROI_j$, $g(p)$ is the gray value of $p$, and $n$ is the total number of $ROI_j$ pixel points. Secondly, the information entropy is calculated at $ROI_j$ of TFW-TDB$_j$, which is given by:

$$Entropy_j = \sum_{p=1}^{n}\left(g(p_k) \cdot \log_2 g(p_k)\right) \tag{11}$$

where, $p_k$ denotes the probability that the grayscale value is $k$. The calculated sharpness coefficients are normalized and multiplied by the weighting factor $\alpha$. The information entropy is also multiplied by the weighting factor $\beta$, and then summed up to obtain the imaging quality assessment coefficient $OverlapScore_j$ of TFW-TDB$_j$ as follows.

$$OverlapScore_j = \alpha \cdot \frac{Sharpness_j}{100} + \beta \cdot Entropy_j \tag{12}$$

(2) Establishing the spatial layer discriminant rule for TFW-TDB. When TFW-TDB$_i$, TFW-TDB$_j$ is identified in the image and judged to be overlapping, the discriminative rules for the spatial location of the upper and lower layers of TFW-TDB$_i$, TFW-TDB$_j$ are shown in the following terms.

$$\begin{aligned} &OverlapScore_i > OverlapScore_j,\ TFW\text{-}TDB_i \text{ is located on the upper layer} \\ &\text{else, } TFW\text{-}TDB_j \text{ is located on the lower layer} \end{aligned} \tag{13}$$

## 3. Experimental results and analysis

### 3.1 Experimental method

To verify the above theory and model, an experimental platform was built as shown in Fig. 10, in which a Daheng 5-megapixel USB3.0 interface CCD (MER-500-7UC) was used, and the auxiliary light source was illumination system using a red surface array light source (TSD-FL300200FRLED) and a digital light source controller (TSD-DPA6024V-2S). The experimental process is as follows:

- To place a transparent glass plate above the surface array light source for simulating a transparent conveyor belt.
- Selecting a batch of TFW-TDB to be identified at any time and putting them onto the upper surface of the transparent glass plate, so that there is no overlap, overlap and other phenomena.
- Simulate the change of TFW-TDB density on the conveyor belt during the recognition process by increasing and decreasing TFW-TDB and simulate the random overlapping state by changing the overlapping posture of TFW-TDB.
- The camera acquires images of TF0W-TDB workpieces containing no overlap and with overlap in the random state.
- The images are processed by the algorithm in this study to identify the image positioning coordinates of TFW-TDB and the overlapping layer they are in.

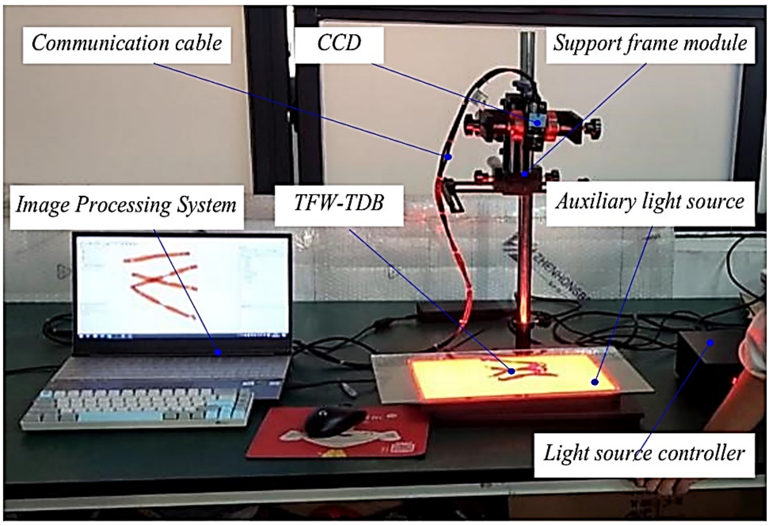


**Fig. 10** Experimental setup diagram

### 3.2 Data sets

In the actual working condition, the variation of the surrounding light intensity is strong, in order to overcome the environmental defects and improve the robustness, accuracy and efficiency of the reliability of the algorithm, 300 samples of TFW-TDB images under different lighting environments are collected in this paper, which contain different ambient lighting, no overlap and with overlap. The relevant sample data are shown in Table 1.

**Table 1** Composition of training set and test set

| | Low light environment | Medium light environment | Intense light environment |
|---|---|---|---|
| No overlap | 1494 | 1240 | 1125 |
| Overlap | 1494 | 1240 | 1125 |

### 3.3 Evaluation indicators

In order to objectively evaluate the recognition results of different methods in the overlapping layer where TFW-TDB is located, four evaluation indexes are used: Recall value, Precision value, F-measure value, and FPS value, which are calculated as follows: manually mark the actual overlapping layer where TFW-TDB is located, the total number of which is defined as NP, mark the predicted as upper layer, the actual also in the upper layer is marked as TP, predicted as the lower layer, actually the upper layer is marked as FP, predicted as the lower layer, actually also the lower layer is marked as TN, predicted as the lower layer, actually the upper layer is marked as FN. in addition, when there is no overlap in TFW-TDB, it is recorded as the upper layer.

- Recall and Precision: Given an IoU threshold, two parameters, Recall and Precision can be determined. If the true value of IoU and ground overlap of the bounding box exceeds 0.5, Recall $R$ and Precision $P$ are expressed as follows:

$$\begin{cases} R = \dfrac{TP}{NP} = \dfrac{TP}{TP + FN} \\ P = \dfrac{TP}{TP + FP} \end{cases} \tag{14}$$

- $F_{measure}$ value: $F_{measure}$ value is the weighted value of precision and recall, and its equation is as follows:

$$F_{measure} = \frac{(1 + \alpha) \cdot P \cdot R}{\alpha \cdot P + R} \tag{15}$$

  where, α is a non-negative real number that represents the weighting factor between precision and recall, which in our work is empirically set to 0.8 [22]. It is important to note that the higher the value of $F_{measure}$, the better the performance of our method.
- FPS value (Frame Per Second): In addition to the accuracy of TFW-TDB upper and lower recognition, another important performance index of TFW-TDB recognition algorithm is speed, only fast can achieve real-time detection, which is extremely important for some application scenarios. A common metric to evaluate the speed is Frame Per Second (FPS), which is the number of TFW-TDB that can be processed in each second.

### 3.4 Experimental data and analysis

Develop TFW-TDB visual recognition algorithm and localization system with the help of OpenCV, C# and other software platforms. In this system, the calibration method in the literature [43] is used to calibrate the internal and external parameters of the camera, and the optimal imaging distance $L = 100$ of the camera is solved based on the obtained information of the internal and external parameters of the camera by Eq. 3. Then, the proposed algorithm is used to realize the binarization of the image and ROI region acquisition and create the matching template. Secondly, the proposed matching algorithm is used to realize the TFW-TDB. Finally, the image coordinate system OUVW is established with the top left of the image as the origin, the horizontal direction as the V-axis and the vertical direction as the U-axis, and the coordinates of the center point of the right bubble chamber of TFW-TDB and the angle with the V-axis are identified and output, the imaging quality evaluation coefficient, and part of the identification results are shown in Fig. 11.

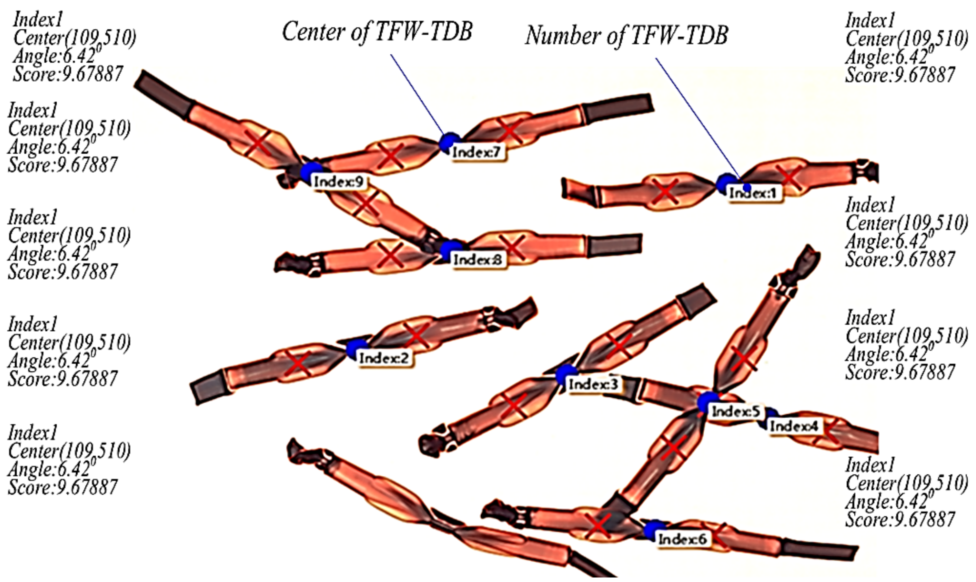


**Fig 11** Experimental setup diagram

Initially, the coordinate center information of the TFW-TDB left and right bubble center images are located in the sample image. Then, the image positioning coordinate center information of the left and right bubble centers of TFW-TDB in the sample image is extracted by our method. Finally, the errors of the two recognition results are calculated as shown in Fig. 12. The recognition result of the algorithm in this paper has been basically with the manually one. For some of the waste material in the workpiece, the results have large differences in the deformation between the left and right bubble chamber, resulting the calculation results by our method are zero. Similar identification results can be used as a basis for rejecting scrap.

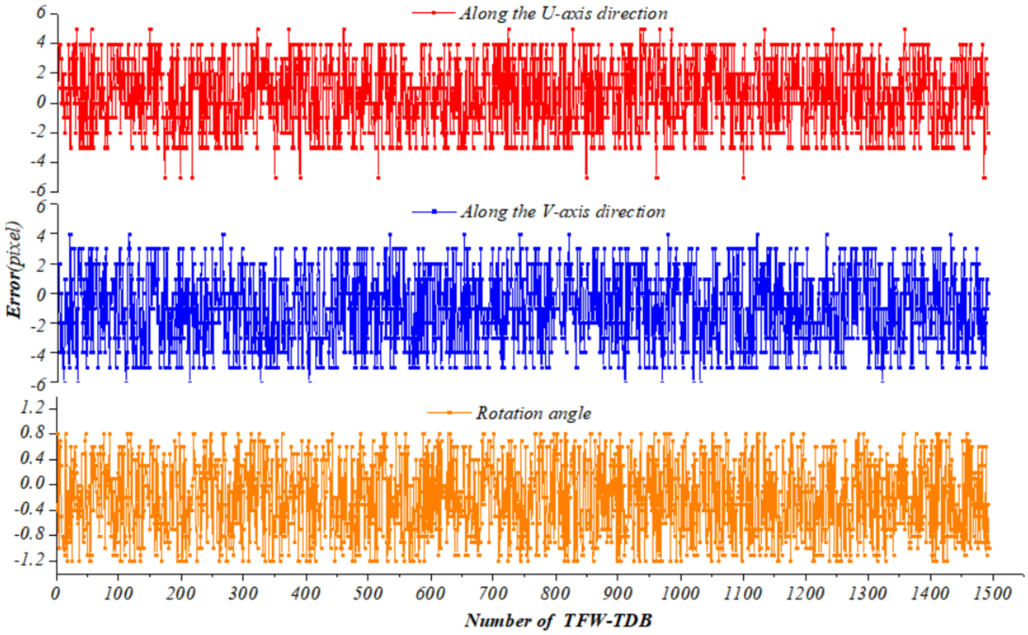


**Fig 12** Error of recognition results

**Table 2** Results of different algorithms for identifying the layer of TFW-TDB

| | | Our Method | | | the literature 35 algorithm | | | the literature 36 algorithm | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Actual layer | Prediction layer Upper layer | Prediction layer Lower layer | Sample number | Prediction layer Upper layer | Prediction layer Lower layer | Prediction layer | Prediction layer Upper layer | Prediction layer Lower layer | Prediction layer |
| Low illumination | Upper layer | 1238 | 3 | 1241 | 1237 | 4 | 1241 | 1235 | 6 | 1241 |
| | Lower layer | 4 | 249 | 253 | 3 | 250 | 253 | 5 | 248 | 253 |
| | recall | | 82.86 % | | | 82.80 % | | | 82.66 % | |
| | precision | | 99.76 % | | | 99.68 % | | | 99.52 % | |
| | F-measure | | 91.47 % | | | 91.40 % | | | 91.25 % | |
| | FPS | | 10 | | | 8 | | | 9 | |
| Medium illumination | Upper layer | 1016 | 1 | 1017 | 1015 | 2 | 1017 | 1012 | 5 | 1017 |
| | Lower layer | 2 | 221 | 223 | 1 | 222 | 223 | 3 | 220 | 223 |
| | recall | | 81.94 % | | | 81.85 % | | | 81.61 % | |
| | precision | | 99.90 % | | | 99.80 % | | | 99.51 % | |
| | F-measure | | 91.03 % | | | 90.94 % | | | 90.67 % | |
| | FPS | | 12 | | | 9 | | | 10 | |
| High illumination | Upper layer | 956 | 5 | 961 | 954 | 7 | 961 | 957 | 4 | 961 |
| | Lower layer | 5 | 186 | 191 | 4 | 187 | 191 | 8 | 183 | 191 |
| | recall | | 82.99 % | | | 82.81 % | | | 83.07 % | |
| | precision | | 99.48 % | | | 99.27 % | | | 99.58 % | |
| | F-measure | | 91.41 % | | | 91.21 % | | | 91.50 % | |
| | FPS | | 9 | | | 7 | | | 7 | |

In this experiment, the upper and lower layers information in which the TFW-TDB annotations are located in the sample images is obtained manually. Then, the information such as the overlapping layers in which the TFW-TDB left and right bubbles are located in the sample images is extracted by using the literature [41] algorithm, the literature [42] algorithm, and the algorithm in this paper, respectively, and the recognition results are shown in Table 2, which lists the recognition results under different lighting environments. For the properly illuminated environment, we identified a total of 1240 TFW-TDB from the 300 image samples obtained, among which two lower TFW-TDB were incorrectly identified as upper TFW-TDB. One upper TFW-TDB was incorrectly identified as lower TFW-TDB in 222 cases where lower TFW-TDB were identified. The F-measure of the sample was 91.03 %, which verified the validity of the method. We also compared our method with two state-of-the-art algorithms, the literature 35 algorithm and the literature [36] algorithm. Compared with our method, the literature 35 algorithm consumes 33 % more time and reduces the recall, accuracy and F-measure values by 0.11 %, 0.10 % and 0.09 %, respectively. Meanwhile, the literature 36 algorithm consumes 20 % more time and reduces the recall and accuracy by 0.40 %, 0.39 % and 0.40 %, respectively. The algorithm proposed in this paper achieves the computation of ground complexity based on guaranteed computational accuracy and reliability. Similar results are shown in dark and bright lighting environments, and it can be observed that our method still has stable performance in terms of recall, accuracy, and F-measure values as the ambient lighting changes.

## 4. Conclusion

Our paper presents an automatic spatial position recognition system for picking and assembly of translucent and flexible workpieces. For the spatial position recognition of TFW-TDB in the automatic sorting process, the imaging parameters are optimized by jointly using imaging modelling and translucent and flexible workpiece features, the ROI method and target matching algorithm are used to quickly acquire TFW-TDB in images and then complete image localization. However, the recognition algorithm based on machine vision has certain limitations. When the type of translucent and flexible workpiece changes, it is necessary to reset the edge matching features based on the specific characteristics of translucent and flexible workpieces, and the ROI region. In the future research, we will further explore the adaptive matching algorithm and adaptive ROI region algorithm to realize the intelligent extraction of spatial position of any type of translucent and flexible workpieces without human-machine interaction.

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# Hierarchical hybrid simulation optimization of the pharmaceutical supply chain

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**A B S T R A C T**

In this paper, a global simulation optimization approach is developed to imitate and optimize the performance of the Pharmaceutical Supply Chain (PSC). Firstly, a hierarchical hybrid simulation model is developed in which aggregate and detailed data levels are addressed simultaneously. The model consists of two types of interdependent paradigms: the system dynamics paradigm, which depicts the echelons of pharmacies and wholesalers in the PSC, and the discrete event paradigm, which simulates the manufacturers with their detailed production operations, as well as the echelons of suppliers. Secondly, the "As is" scenario analysis and a screening process are performed to extract significant input parameters as well as sensitive outputs of the model. The final step optimizes the performance of PSC. The proposed approach validity is appraised by being applied to the PSC of a leading pharmaceutical company in Jordan. As a result, the opportunity loss cost has considerably decreased for both the manufacturer and wholesalers' echelons and the service level has improved throughout the PSC.

**A R T I C L E   I N F O**

*Keywords:*
System dynamics;
Discrete-event;
Simulation optimization;
Hybrid simulation;
Scatter search;
Tabu search;
Artificial neural networks (ANN);
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## 1. Introduction

Pharmaceutical supply chain (PSC) is a very complicated supply chain due to heterogeneous stakeholders, internal and external environments, and distinct related characteristics of healthcare industry such as pharmaceuticals, medical equipment, and patients' flow. PSC is also very sensitive, as it must guarantee that the right drug reaches the right people at the right time and in the right condition. Typically, PSC network consists of multi echelons including pharmacies, drugs wholesalers, drugs manufacturers, and raw material (RM) suppliers. Yet, PSC networks are continuously evolving with increasing number of customers, different types of products, increasing number of suppliers and manufacturers. Over the past decades, PSC has faced tremendous challenges such as lack of coordination, shortage or excess of drugs, and high demand uncertainty [1, 2]. Shortage of drugs is not a simple incident that can be diagnosed by one or more explicit sources; rather, it is a dynamic crisis caused by multiple interrelated aspects.

Low manufacturing velocities, multi-procedures of quality assurance, and supply chain dynamics are the key players in PSC drug shortage [3].

Optimizing the PSC can be carried out analytically [4] or heuristically [5]. However, these approaches are generally applied under simplification assumptions such as sole stage or product and restricted variability [6]. In real situations, PSC is a complex system with multi-product and multi-echelon. It operates under a high level of stochasticity in which analytical optimization may fail. Additionally, similar to other SC, PSC includes manufacturing and non-manufacturing functions, encompasses different planning scopes at various management levels, and involves dissimilar data details [7]. In such turbulent circumstances, simulation would be the optimal approach that gives practitioners the ability to imitate such complex systems using different scenarios without altering processes on ground [8].

Mostly, single simulation methodology, including discrete-event (DE) [9, 10] or system dynamics (SD) [11, 12] is adopted in literature for PSC simulation modelling. However, considering the combination of discrete and continuous issues within the PSC, as well as the challenges related to different abstraction levels, relying solely on an individual simulation approach proves inadequate in accurately capturing the PSC system [13]. Lately, hybrid simulation, where two or more traditional simulation modelling paradigms are integrated into one model, has proved excellent capabilities in resolving complicated scenarios such as PSC [7, 13]. According to Eldabi *et al.* [14], interest in hybrid simulation has experienced remarkable growth in the last decade. With its evolving complications, Brailsford *et al.* [15] highlighted the need to explore the application of hybrid simulation in the modern operation management area.

Simulation optimization (SO) can be defined as the process of testing various variables' values in order to find the most desirable combination of values from simulation models [16]. The valuable advantage of SO is the ability to handle stochasticity and complex interactions at a level that can hardly be formulated by traditional optimization [17]. The early initiatives to embed optimization in simulation modelling were either non-generic and based on ad hoc approaches or were heavily dependent on users to implement "seat of the pants" analysis [17]. Later, intelligent search procedures have been implemented within SO to find optimal or near-optimal solutions by exploring a small portion of available alternatives [18]. For PSC literature, SO is rarely adopted, mostly, the PSC entities are considered as disjoint systems to be locally controlled and optimized. Chen *et al.* [19] proposed a DE-SO approach for the clinical SC that included patient demand, demand scenario forecast, and mathematical programming-based planning. Franco and Alfonso-Lizarazo (20) developed a SO approach based on the sample path method for optimizing tactical and operational decision levels in PSC. They considered uncertainty in demand, cost, and lead-time in the pharmacy-hospital echelon.

This study develops a global SO approach to optimize the PSC performance at different data levels using hierarchical hybrid (HH) simulation modelling. The developed HH simulation model can holistically imitate multi-echelon multi-product PSC. In this model, both aggregate, such as material and information flow between the PSC entities, and detailed data levels, including production process details are taken into consideration. Particularly, the proposed model allows for the integration of different sub-models with different data levels into an overall global SO model, hence, avoiding inconsistencies resulted from combining models with different data levels [21, 22]. Moreover, the proposed HH simulation model handles the dynamic nature of stochastic market demand on daily basis, at the same time, it can simulate the discrete detailed processes occurring in real PSC (e.g., replenishment and production processes).

## 2. The hierarchical hybrid simulation optimization (HH-SO) approach

The proposed SO approach consists of three main steps. First, a HH simulation model is developed to simultaneously address aggregate and detailed data levels in the PSC. Then, the "As is" scenario analysis is performed, and a screening process is applied via sensitivity analysis in order to extract major effective parameters as well as sensitive outputs. The performance of PSC concerning sensitive outputs is optimized in the third step. Fig. 1 depicts the major steps in the proposed approach while the next subsections further discuss them.

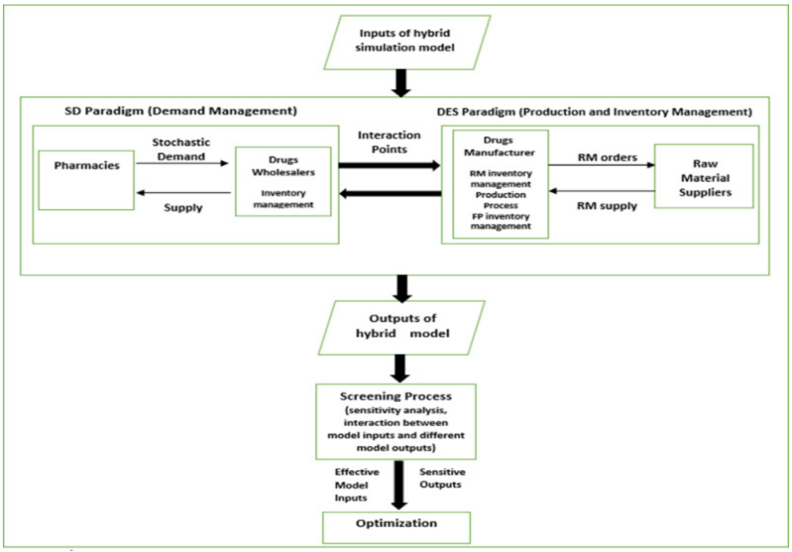


**Fig. 1** The proposed approach flowchart

## 2.1 The hierarchical hybrid (HH) simulation modelling

Fig. 1 depicts the hybridity in the proposed simulation model while the hierarchy in the simulation model is described in Fig. 2. The HH simulation model consists of two types of interrelated paradigms: SD paradigm that depicts the pharmacies and wholesalers' echelons in the PSC, and DE paradigm that simulates the manufacturers with their detailed production operations, order receiving, order fulfilment, inventory management, replenishment, and storage processes, and the suppliers' echelons. SD is used to depict the dynamic and stochastic nature of market demand due to its capabilities in buffering and self-adaptation to turbulence in market demand, which is considered a frequent situation in PSCs. On the other hand, DE is adopted to emulate discrete physical and business processes such as production, order fulfilment, and inventory management. It is worthy to recap how critical inventory management is for effective PSC due to its enormous effect on both cost-related and service-related KPIs [23]. However, multi-echelon inventory management is strongly dependent on the performance of drugs suppliers and distribution centres [24]. Consequently, optimizing the PSC operations while considering inventory levels would be beneficial to achieve higher profit margins as well as higher service levels [25].

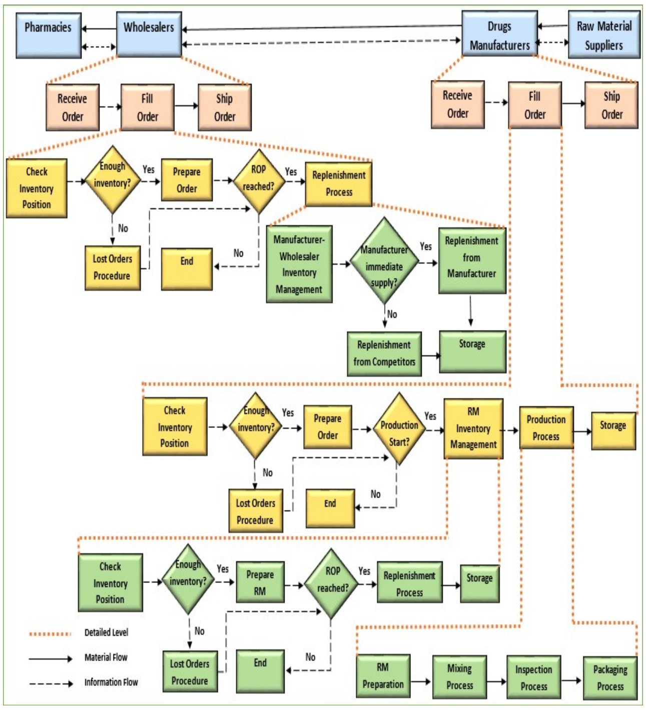


**Fig. 2** The proposed hierarchical simulation model

*Model building, verification, and validation*

All PSC processes are simulated by either SD or DE sub models. Each sub model is verified and debugged separately. In addition, control variables are used to test and verify sub models' logic and outputs. Then, the sub models are combined and aggregated gradually until the global HH simulation model is completely developed and verified. Regarding model validation, the proposed model/approach is validated by being used to simulate the PSC performance of a leading pharmaceutical company in Jordan. Major model outputs are compared to actual values obtained from the model's implementation. The results are comparable with an acceptable level of accuracy. Hence, the model is considered to be validated. More details about this step are presented in Section 3.

*Model inputs, outputs, and assessment*

The model input parameters are classified into three categories, as illustrated in Table 1, input parameters for SD sub models, input parameters for DE sub models, and input parameters for both paradigms. The third type of inputs is called interaction points since they affect and connect the SD and DE paradigms concurrently. The inputs include the number of entities, number of materials (both raw and finished), market demand, variables related to the inventory management system at different echelons, and production process variables. Table 2 shows the model outputs, which include different cost items, service level, lost orders, and different profit measures for different echelons.

Two distinct types of KPIs for both the wholesalers and manufacturers' echelons assess the model: the cost-related KPIs is represented in the opportunity loss cost while the service-related KPIs is expressed in the service level. Both measures are essential not only because they are highly related to the drugs' shortage critical challenge in PSC, but also due to their direct influence on the market share and competencies of PSC entities. In the developed model, the annual opportunity loss cost is calculated based on stochastic daily demand. While the average service level is estimated as the proportion of the annual supply to the annual demand for each PSC entity in the wholesalers and manufacturers' echelons.

**Table 1** Inputs for the HH simulation model

| Parameter | Symbol | Sub model | |
|---|---|---|---|
| | | SD | DE |
| Number of drugs | $I$ | √ | √ |
| Number of drugs wholesalers | $J$ | √ | √ |
| Number of drugs manufacturers | $K$ | √ | √ |
| Number of RMs | $L$ | | √ |
| Number of RM suppliers | $M$ | | √ |
| Number of RMs needed to produce drug $i$ | $Ni$ | | √ |
| Pharmacies stochastic demand for drug $i$ from wholesaler $j$ | $DPij$ | √ | |
| Wholesaler $j$ order quantity of drug $i$ from drugs manufacturers $k$ | $Wjik$ | √ | √ |
| Other demand of drug $i$ from drugs manufacturers $k$ | $Diks$ | | √ |
| Other demand selling price (per unit) of drug $i$ from drugs manufacturer $k$ | $SPik$ | | √ |
| Wholesaler $j$ reorder point of drug $i$ | $Rji$ | √ | √ |
| Wholesaler $j$ initial inventory of drug $i$ | $Vji$ | √ | √ |
| Wholesaler $j$ holding cost (per unit) of drug $i$ | $Hji$ | √ | |
| Wholesaler $j$ ordering cost (per order) of drug $i$ | $Oji$ | √ | |
| Wholesaler $j$ purchasing cost (per unit) of drug $i$ from drug manufacturer $k$ | $Pjik$ | √ | |
| Wholesaler $j$ opportunity loss cost (per unit) of drug $i$ | $Cji$ | √ | |
| Drugs manufacturer $k$ lead time distribution for drug $i$ | $Tki$ | √ | √ |
| RM $l$ order quantity for drugs manufacturer $k$ form RM supplier $m$ | $Alkm$ | | √ |
| RM $l$ reorder point for drugs manufacturer $k$ | $Blk$ | | √ |
| RM $l$ initial inventory at drugs manufacturer $k$ | $Elk$ | | √ |
| RM $l$ holding cost (per unit) at drugs manufacturer $k$ | $Flk$ | | √ |
| RM $l$ ordering cost (per order) at drugs manufacturer $k$ from RM supplier $m$ | $Glkm$ | | √ |
| RM $l$ purchasing cost (per unit) at drugs manufacturer $k$ from RM supplier $m$ | $Qlkm$ | | √ |
| Amount of RM $l$ needed to produce 1 batch of drug $i$ | $Ul$ | | √ |
| RM supplier $m$ lead time distribution for RM $l$ | $Vml$ | | √ |
| Drugs manufacturer $k$ initial inventory of drug $i$ | $Wki$ | √ | √ |

**Table 1** (Continuation)

| | | |
|---|---|---|
| Drugs manufacturer *k* production start point of drug *i* | *Xki* | √ |
| Drugs manufacturer *k* production batch size of drug *i* | *Yki* | √ |
| Drugs manufacturer *k* number of mixing machines | *NMk* | √ |
| Drugs manufacturer *k* number of packaging machines | *NPk* | √ |
| Drugs manufacturer *k* mixing time to produce 1 batch of drug *i* | *MTki* | √ |
| Drugs manufacturer *k* packaging time to produce 1 batch of drug *i* | *PTki* | √ |
| Drugs manufacturer *k* setup and inspection time to produce 1 batch of drug *i* | *STki* | √ |
| Drugs manufacturer *k* mixing cost to produce 1 batch of drug *i* | *MCki* | √ |
| Drugs manufacturer *k* packaging cost to produce 1 batch of drug *i* | *PCki* | √ |
| Drugs manufacturer *k* setup and inspection cost to produce 1 batch of drug *i* | *SCki* | √ |

**Table 2** Outputs of the HH simulation model

| Parameter | Symbol | Parameter | Symbol |
|---|---|---|---|
| Wholesaler *j* lost orders of drug *i* | *WLOji* | Drugs manufacturer *k* service level of drug *i* | *MSLki* |
| Wholesaler *j* service level of drug *i* | *WSLji* | Drugs manufacturer *k* opportunity loss cost of drug *i* | *MLCki* |
| Wholesaler *j* opportunity loss cost of drug *i* | *WLCji* | Drugs manufacturer *k* total lost orders | *MLOk* |
| Wholesaler *j* total lost orders | *WLOj* | Drugs manufacturer *k* total holding cost | *MHCk* |
| Wholesaler *j* total holding cost | *WHCj* | Drugs manufacturer *k* total ordering cost | *MOCk* |
| Wholesaler *j* total ordering cost | *WOCj* | Drugs manufacturer *k* total purchasing cost | *MPCk* |
| Wholesaler *j* total purchasing cost | *WPCj* | Drugs manufacturer *k* total opportunity loss cost | *MLCk* |
| Wholesaler *j* total opportunity loss cost | *WLCj* | Drugs manufacturer *k* total production cost | *MPrCk* |
| Wholesaler *j* service level | *WSLj* | Drugs manufacturer *k* service level | *MSLk* |
| Wholesaler *j* revenue | *WRj* | Drugs manufacturer *k* revenue | *MRk* |
| Wholesaler *j* profit | *WPj* | Drugs manufacturer *k* profit | *MPk* |
| Wholesaler *j* profit margin | *WPMj* | Drugs manufacturer *k* profit margin | *MPMk* |
| Drugs manufacturer *k* lost orders of drug *i* | *MLOki* | | |

### *Model structure*

As can be seen in Fig. 2, four hierarchical levels are presented in the proposed model with different levels of details. The highest or aggregate level, shown in blue, controls the material and information flow between the PSC echelons. The next highest level, shown in pink, controls the order fulfillment processes in the echelons of wholesalers and manufacturers. It receives input data from the lower level regarding inventory details, processes it, and then provides the necessary outputs and actions to the next higher level in the HH simulation model. The third level, shown in yellow, simulates inventory management of produced drugs in wholesalers and manufacturers' echelons. Finally, the lowest level, shown in green, is simulating the replenishment process for wholesalers' echelon as well as RM inventory management and production process in manufacturers' echelon. The system checks the inventory level, if there is enough inventory, the order will be prepared to be shipped, and the new inventory level will be compared to the reorder point (ROP), if it is reached, a signal will be sent to the replenishment sub model in level four. If there is not enough inventory, a signal will be sent to the lost orders sub model.

A basic feature of this HH simulation model is its capability to handle aggregate data such as material and information flow between the PSC entities, at the same time; it handles detailed data related to the drugs production process. This is achieved by employing the hierarchy concept in parallel with simulation hybridity. As mentioned earlier, most scholar work concentrates on one part while ignoring the other due to modelling complexity and computation time constraints.

It is worth noting that most activities, represented as rectangular boxes in Fig. 2, are entire processes that are simulated separately by either SD or DE sub models. For example, as shown in Fig. 2, the replenishment process is composed of multi sub-activities in which information related to inventory position and immediate replenishment ability is exchanged between wholesalers and manufacturers' echelons. If the manufacturer with the lowest prices has enough inventory to fulfil the wholesaler order immediately, then the order is purchased from this source. Otherwise, the wholesaler will look for other manufacturers (competitors) with different prices and lead time distributions to fulfil the order.

## 2.2 Screening process of the model's inputs and outputs

In a global simulation model, like the one developed in this study, the number of input parameters is too large to be directly fed into an optimization step. Moreover, the targets of the optimization process are considerably diversified than to be gathered in one objective function and optimizing such objective function would not be attainable due to potential conflict between these targets and/or computation time constraints. For such a complicated scenario, a screening process is proposed, first, to select the influential model inputs and hence use them as decision variables in the optimization step. Second, to specify the sensitive outputs of the HH simulation model that are highly influenced by the variation in input parameters. One practical way to perform this screening process is to use sensitivity analysis or "What-if" scenarios. In sensitivity analysis, a large number of simulation trials are performed in which the model outputs are monitored while varying the model inputs in order to decide which outputs are more sensitive to these variations (sensitive outputs) and which inputs variation has significant effects on these outputs.

In theory, the screening process is a sensitivity analysis or "What-if" scenarios when all the HH simulation model inputs are varied to monitor the resultant change in all the HH simulation model outputs. In other words, the theoretical screening process would include the following steps: firstly, instead of using one value for each input of the simulation model, a range of values is used for each input (one value at a time), secondly, the simulation model is run at each value and the simulation model outputs are monitored. The outputs that significantly vary with the variation in the input parameters are considered as sensitive outputs, accordingly, they will be chosen to be the optimization targets or the objective function terms for the optimization step. However, in reality, not all input parameters can be changed because not all of them are under control. For instance, in a real existing PSC, the number of entities (e.g., wholesalers, manufacturers, suppliers) are fixed and not subjected to changes in normal situations. As a result, there is no use in varying the number of PSC entities and monitor the sensitive outputs since the number of entities is already fixed in a certain PSC. Another example is the inputs whose values are determined externally, hence cannot be practically varied by the decision makers such as market demand. Based on that, the prospect decision variables to be fed to the optimization step are defined as all the input parameters that can be controlled by decision makers in a certain PSC. These prospect decision variables (shaded in Table 1) are chosen based on the authors' experience with real-world PSC in parallel with experts' opinions. They include reorder point, initial inventory, and order quantity for different entities in the PSC plus the production start point for the drugs' manufacturers. It is worth mentioning that the algorithm is generic enough to choose different prospect decision variables based on studied cases.

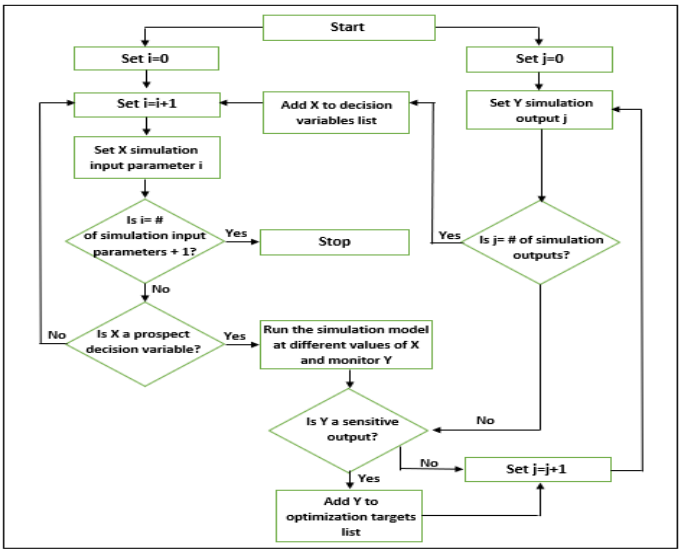


**Fig. 3** The screening process flowchart

To perform the screening process a code is programmed within the used simulation toolkit, the algorithm behind this code is shown in Fig. 3. The user enters an array that consists of the prospect decision variables (variable X in Fig. 3) with the selected range of variation. The program will start scanning the input parameters, if the input parameter is in the prospect decision variables list, the simulation model will perform multi-simulation runs according to the pre-specified range of variation and monitor the simulation model outputs (variable Y in Fig. 3). Then, the model will check the variation range in all the simulation model outputs to decide if the output is sensitive or not. If it is, it will be added to the optimization targets. After the screening process is completed, two lists of variables are ready to be fed to the optimization step, the decision variables list, which contains the influential inputs of the HH simulation model, and the optimization targets list that includes the sensitive outputs of the HH simulation model.

### 2.3 Optimization of the model sensitive outputs

Due to the complexity and stochasticity nature of simulation systems, an analytical expression for the objective function does not exist in SO, instead, it is estimated as a function of the stochastic simulation outputs either if the decision variables are discrete or continuous. In case of continuous decision variables, gradient-based methods such as stochastic approximation are used. Yet, in discrete decision variables with finite feasible region, ranking and selection methods could be used. If the feasible region is finite but significantly large, metaheuristics such as Tabu search, genetic algorithm, simulated annealing, neural networks are used (18).

In this paper, OptQuest optimization package, which is included in AnyLogic simulation software, is used. This optimization package uses scatter search, Tabu search, and neural networks algorithms to search within, the simulation runs, for optimal or near-optimal solutions [26]. Essentially, OptQuest used adaptive memory of the search history to guide the solution searching process, preventing evaluating pre-investigated alternatives. In practice, the user should create an optimization experiment by determining the optimization targets (which are in our case the sensitive outputs obtained from the screening process), the decision variables (which are the influential inputs of our simulation model obtained from the screening process), the constraints, and the stopping criteria of the optimization process.

Fig. 4 illustrates the interaction between the simulation and optimization packages which can be summarized in the following points:

- The simulation software performs simulation runs based on decision variables, obtained from the optimization package, and exports simulation outputs to the optimization package.
- Based on the embedded search methods, the optimization package guides the subsequent simulation iterations to ensure that the new solution is closer to optimal than the previous one.

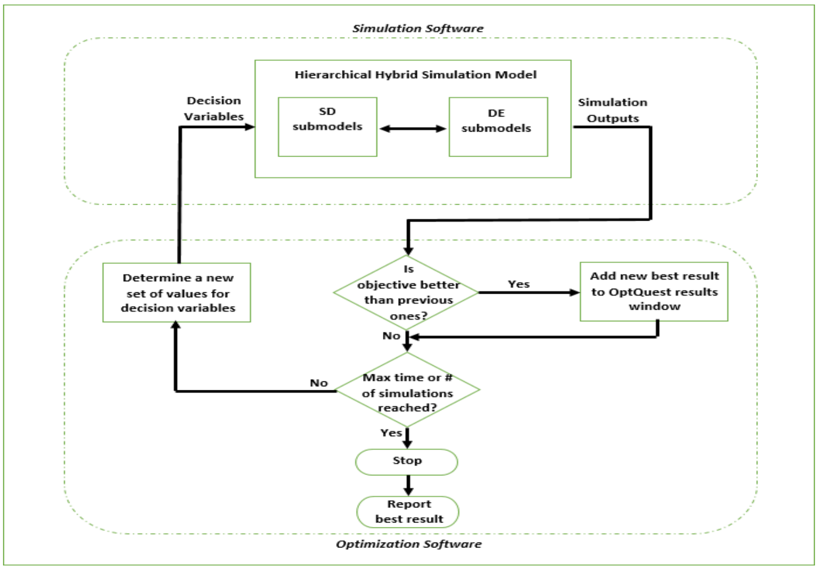


**Fig. 4** The interaction between the simulation and optimization packages

- The process will end when the stopping criterion is reached which could be based on simulation time or number of simulation iterations.

## 3. Implementation, results, and discussion

To validate the proposed approach with its three steps shown in Fig. 1, it was applied to the PSC of a leading pharmaceutical company in Jordan. The considered PSC network is described in Subsection 3.1 while Subection 3.2 illustrates the analysis and results obtained by applying the proposed approach to this PSC.

### 3.1 The PSC network

Generally, Jordanian pharmaceutical companies concentrate on the secondary pharmaceutical production process, which is taken into account in the current study, in which the active ingredient of the drug is processed and mixed with excipients to produce the drug in its commercial form. Since the core of any PSC is the drugs' manufacturer, the authors contacted one of the largest pharmaceutical companies in Jordan. Multi structured and semi-structured interviews were conducted with employees at different levels in order to collect qualitative as well as quantitative data to be used in this study. The first route of interviews was dedicated to qualitative analysis in order to determine the major obstacles the company is facing regarding with the SC arena. The results of this step showed that for a certain type of drugs, which is injectable, the company's PSC suffers from a shortage problem, which leads to relatively high opportunity loss cost (8.5 % of the annual revenue). Based on the results obtained from the elementary qualitative analysis, the second route of interviews focused on gathering all the necessary data needed to simulate the PSC of injectable drugs.

The considered PSC network for injectable has two parallel material flows, the primary is a four-echelon and the other is a three-echelon. The first echelon is the RM suppliers' echelon that provides the drug's manufacturer with RMs including active pharmaceutical ingredients (APIs), excipients, vials, labels, and boxes. Five local suppliers are responsible for supplying the company with RMs at different prices and stochastic lead-time distributions. However, based on practical data given by the pharmaceutical company, RM supply is regular with no shortage occurrence. Consequently, RM feed is assumed to be unlimited in the HH simulation model. The second echelon is the manufacturer echelon. The considered pharmaceutical company produces three different types of injectable. The preparation stage includes receiving and storing RMs in the RM warehouse at the pharmaceutical company. The production process is composed of four main stages, which are RM preparation, mixing, inspection, and packaging. Since the production process is secondary, the main operation is the dilution of the APIs with the specified types and amounts of excipients to produce the commercial form of the three injectable. The dilution or mixing is a batch production process that produces different batch sizes for each injectable. After the mixing process, various quality control procedures are applied in order to collect and test samples from the products to check different measures such as the concentration of the API in the produced injectable. This inspection process is followed by the final step, which is the packaging process. The company has two identical production lines each with mixing and packaging machines. Also, each line can produce the three types of injectable interchangeably. Since the company has two different types of customers (the public health sector and the wholesaler), two slightly different packages are used for each injectable. Finally, the finished products (FPs) are stored in the FP warehouse at the company.

The third echelon comprises two entities, the wholesaler that is responsible for providing pharmacies with injectable, and the public health sector that provides hospitals with the injectable. The public health sector demand is deterministic, and it is replenished via periodic tender protocols. It is important to mention that if the company inventory is not enough to satisfy the wholesaler demand, the wholesaler replenishment would occur from other pharmaceutical companies (competitors) at different prices and stochastic lead time. Finally, the fourth echelon following the wholesaler represents the pharmacies with stochastic daily demand.

### 3.2 Results and analysis

Based on the qualitative and quantitative data collected from the company as well as the wholesaler entities, a HH simulation model, like the one shown in Fig. 2, was built to imitate the "As is" scenario for the injectable supply chain. The software package used to build the hybrid simulation model is AnyLogic, a multimethod simulation modelling tool that supports DE, SD, and agent based (AB) methodologies [27]. Moreover, it supports Java coding which enabled authors to develop customized and complex events and subprograms for this HH simulation model. AnyLogic optimization package, used in the third step of the proposed approach, is built on top of the OptQuest Optimization Engine, which is considered one of the most powerful optimization tools available [26, 27].

The HH simulation model, with its various sub models, was constructed gradually until it was totally developed. Throughout the developing process, each sub model was verified and debugged separately in parallel with numerical and graphical testing of some variables to check the logic as well as accuracy. A good example of the graphical testing and representation of the HH simulation model outputs is shown in Fig. 5. Fig. 5 is a screenshot of the graphical interface constructed to check the behavior of the HH simulation model through monitoring the plots of major variables and outputs versus simulation time. These include the wholesaler inventory status and lost orders, the drug's manufacturer FP inventory status (with its two components of wholesaler package and public health sector package for each injectable), and the drug's manufacturer lost orders and accumulative lost orders. Meanwhile, the tested sub models were continually aggregated into the HH simulation model until it was completed and totally verified. The major outputs of the "As is" scenario are illustrated in Table 3, based on a one-year run (in the model's time unit: 365 days).

**Table 3** Comparison between the major outputs of the "As is" scenario and the "After optimization" scenario

| Simulation model output | Unit | "As is" scenario | "After optimization" scenario | Change (%) |
|---|---|---|---|---|
| The wholesaler lost orders | box | 887 | 346 | -61.0 |
| The wholesaler ordering cost | JD* | 85,000 | 72,000 | -15.3 |
| The wholesaler opportunity loss cost | JD | 483,380 | 190,101 | -60.7 |
| The wholesaler service level | % | 98.8 | 99.5 | 0.7 |
| The pharmaceutical company lost orders | box | 9920 | 8480 | -14.5 |
| The pharmaceutical company RM holding cost | JD | 1,819,799 | 1,767,452 | -2.9 |
| The pharmaceutical company opportunity loss cost | JD | 3,478,500 | 3,147,000 | -9.5 |
| The pharmaceutical company service level | % | 86.6 | 88.9 | 2.3 |

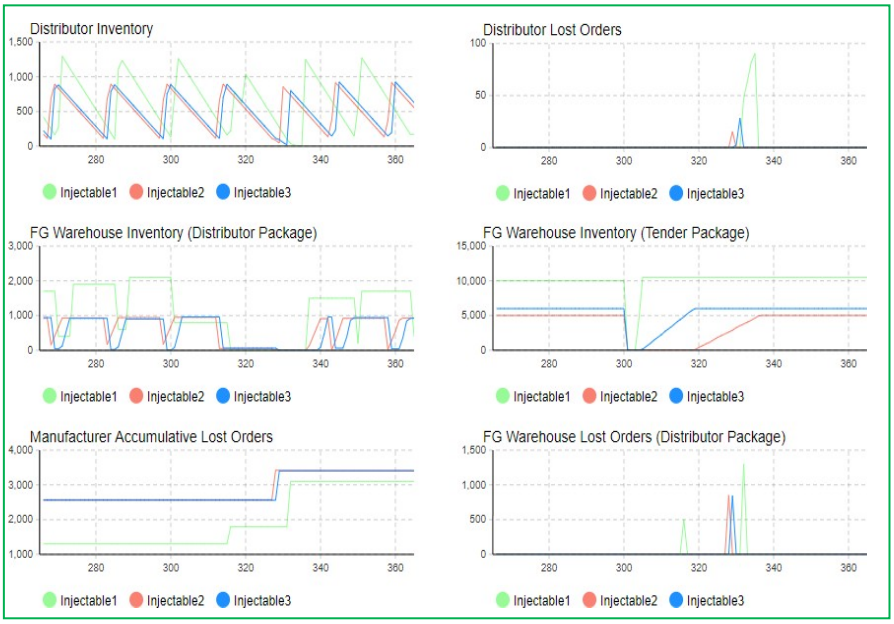


**Fig. 5** The graphical interface used to monitor major variables and outputs of the simulation model

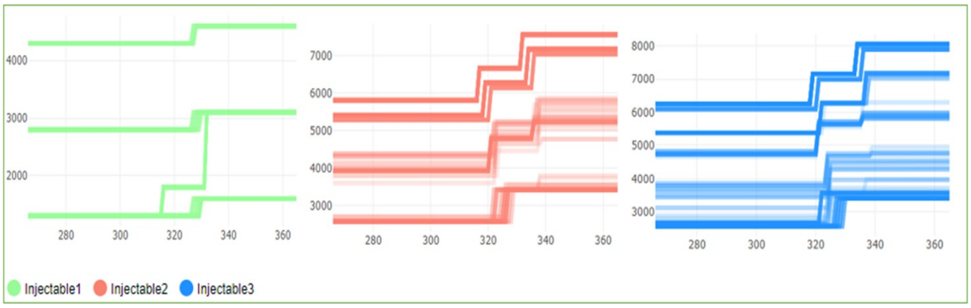


**Fig. 6** The pharmaceutical company lost orders (boxes) versus simulation time (days) at different values of the wholesaler order quantities

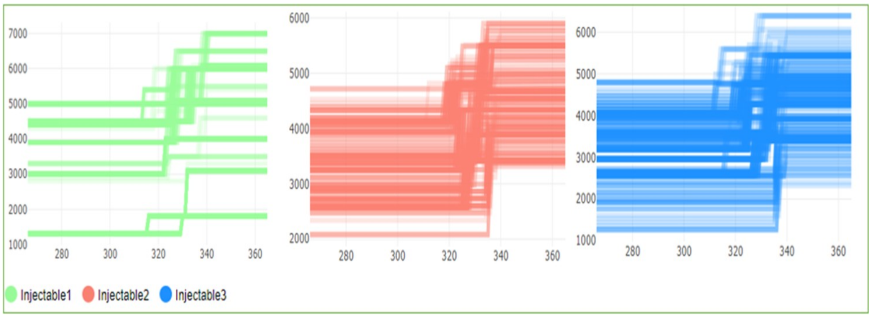


**Fig. 7** The pharmaceutical company lost orders (boxes) versus simulation time (days) at different values of the wholesaler reorder points

To check the HH simulation model validity, the "As is" scenario major outputs were compared to their actual values obtained from the company and the wholesaler. For instance, the annual opportunity loss costs for both the company and the wholesaler were compared to those calculated by the HH simulation model. The difference was found to be less than 5 %, which is considered to be within the acceptable level of accuracy.

To perform the second step of the proposed approach which is the screening process, the "As is" scenario inputs and outputs were fed into the screening process algorithm described in Fig. 3. Figs. 7 and 8 are graphical representations of the screening process's significant outcomes. Each one of the six plots in the Figs. shows the sensitive simulation outputs (which are the pharmaceutical company lost orders) of multiple "What-if" scenarios for each injectable. For instance, the green plot in Fig. 6 is the pharmaceutical company lost orders versus simulation time (in days) at different values of the wholesaler order quantity from injectable 1. While the green plot in Fig. 7 is the pharmaceutical company lost orders versus simulation time (in days) at different values of the wholesaler reorder point of injectable 1. The same is true for injectable 2 (red plots) and injectable 3 (blue plots). It could be seen clearly in the Figs that the pharmaceutical company lost orders are sensitive and highly dependent on the replenishment process of the wholesaler, represented in the order quantities and reorder points of each one of the three considered injectable. As mentioned earlier in the case description, the pharmaceutical company suffers from high annual opportunity loss cost for the injectable products, actually, the "As is" scenario results have assured this issue. However. It could not give explanations or possible reasons for this problem. The screening process outcomes have revealed that this shortage problem is not related to the company's internal factors such as production scheduling or RM availability. Instead, it is closely related to the lack of information sharing between the pharmaceutical company and the wholesaler entities.

As described in Section 3, the screening process results in two key results: influential inputs and sensitive outputs. In the considered implementation, the screening process has revealed six influential simulation inputs, as shown in Figs. 7 and 8, which are the wholesaler order quantity and reorder point for each one of the three injectable products. On the other hand, there are three sensitive simulation outputs which are the pharmaceutical company's lost orders for each

injectable. For optimization purposes, the opportunity loss cost was used rather than the number of lost orders, since it is more meaningful and representative to decision makers.
In summary, the objective function of the optimization model was set to minimize the pharmaceutical company opportunity loss cost for each injectable and the decision variables are the wholesaler order quantity and reorder point for each injectable. It is worth noting that the decision variables lower and upper bounds are set based on the capabilities and available possibilities discussed with the wholesaler.

After the optimization model (the objective function and decision variables) is specified, the optimization experiment was performed, with 500 iterations, on OptQuest Optimization Engine of AnyLogic. The new values of the decision variables, obtained from the optimization step, were used to simulate the PSC performance. Table 4 compares the influential inputs of the "As is" scenario and the "After optimization" scenario. It could be seen in the table that the wholesaler order quantities have increased by 23.1 %, 11.1 %, and 44.4 % for injectable 1, 2 and 3, respectively. While the reorder point has increased by 500 % and 100 % for injectable 1 and 3, respectively.

Furthermore, Table 3 compares the major outputs of the "As is" scenario and the "After optimization" scenario. Obviously, the lost orders have considerably dropped by 14.5 % for the pharmaceutical company and 61 % for the wholesaler. As a result, the opportunity loss cost has lowered by 9.5 % for the pharmaceutical company and 60.7 % for the wholesaler. Moreover, the service level has improved for both the pharmaceutical company and the wholesaler, with a 2.3 % and 0.7 % increase in turn. Another plus point is that other costs such as RM holding cost and the wholesaler ordering cost have also declined after performing the optimization process.

**Table 4** Comparison between the influential inputs of the "As is" scenario and the "After optimization" scenario

| Simulation model output | Unit | "As is" scenario | "After optimization" scenario | %Change |
|---|---|---|---|---|
| The wholesaler order quantity from injectable1 | box | 1300 | 1600 | 23.1 |
| The wholesaler order quantity from injectable2 | box | 900 | 1000 | 11.1 |
| The wholesaler order quantity from injectable3 | box | 900 | 1300 | 44.4 |
| The wholesaler reorder point of injectable1 | box | 100 | 600 | 500 |
| The wholesaler reorder point of injectable2 | box | 100 | 100 | 0 |
| The wholesaler reorder point of injectable3 | box | 100 | 200 | 100 |

## 4. Conclusion and future research

The current study has presented a HH-SO approach that simulates the aggregate as well as the detailed levels in PSC. A three-step procedure has been proposed that develops a HH-SO model to mimic the processes within a four-echelon PSC, including material and information flow, order receiving, order fulfillment, inventory management, replenishment, and storage processes. Also, the production process, which is frequently ignored or simplified when SCs are simulated in related literature, is minutely modeled. A screening process is then performed to filter influential inputs as well as sensitive outputs of the simulation model. Later, the outputs of the screening process are used to optimize the performance of the PSC.

Using a case study, the proposed approach has depicted validity in handling real PSC implications such as multi echelons and multi products, stochasticity in demand and lead times, and variation in data granularity levels. The results obtained have shown that although this approach is designed to optimize the sensitive outputs of the simulation model, such as opportunity loss cost and service level at different PCS echelons; the values of other outputs are indirectly improved after applying the proposed approach. It is important to note that the suggested approach can be used with supply chains other than those for pharmaceuticals. This would alter the "discrete event simulation" paradigm's modelling of the particulars of the other supply chain's production process. But the fundamental structure of the "system dynamics" paradigm would hold.

Regarding future work, the utilization of agent-based modeling (ABM) in a hybrid simulation environment would enhance the interaction among PSC entities, thereby increasing the responsiveness and autonomy of hybrid simulation models. The employment of ABM, with its intelligent characteristics such as reaction, evolution, and adaptation, would facilitate the study of complex adaptive systems, wherein the intricate behavior of the entire system emerges from the interaction of a large number of components capable of adjusting their performance over time based on their own experiences.

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# Supply chain engineering: Considering parameters for sustainable overseas intermodal transport of small consignments

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**ABSTRACT**

An increasingly environmentally conscious global economy is placing new demands on supply chain engineering, with a focus on sustainable approaches to modelling transport chain. In addition to the price and time efficiencies that characterize agile and lean supply chains, strategies for low-carbon and energy-efficient external transport must also be incorporated. This research therefore focuses on the challenges of organizing the supply of small overseas shipments to define how the relationship between land and sea transport in the selected intermodal chain affects environmental and energy performance. Understanding the input parameters and their impacts is a prerequisite for planning $CO_2$, $NO_x$, $SO_2$ and NMHC emissions, as well as energy efficiency (EE) of overseas transportation. The number of individual transport legs and their characteristics are crucial parameters for sustainable transport chains. The applicability of the proposed research framework is carried out on the example of outbound supply chains of the southern part of the Baltic-Adriatic Corridor using intermodal transport chains of small shipments via the ports of Koper and Genoa. The results of the case study show that an additional transport leg representing only 2 % longer land transport to the port of Genoa significantly affects the carbon footprint of the whole supply chain's compared to chains via the port of Koper. Moreover, other results also require special attention in supply chain modeling. The study enriches the field of supply chain engineering, as there is a lack of such studies. The study is part of the project "Green port – Developing a sustainable model for the growth of the green port", co-founded by the Slovenian Research Agency.

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## 1. Introduction

Transporting small shipments is becoming an increasingly important way to operate global supply chains. Purchasing habits, optimization of transportation means, specialization of NVOCC (Non-vessel Operating Common Carrier) on LCL (Less than Container Load) services are some of the basic requirements for efficient use of intermodal transportation in organizing overseas transportation of small shipments. In add-on to the time and price components of overseas supply chains, the necessity to harmonize with the environmental component of the acceptability of transport chain operations is becoming more apparent [1]. Supply chain engineering must incorporate the environmental aspect of optimal intermodal transportation organization, based on the elements of transportation energy efficiency (EE) and lower GHG (Green House gas) emissions. Limiting $CO_2$, $SO_2$, $NO_x$, and NMHC (non-methane Hydro Carbon) emissions is the primary focus, and the impact on the implementation of logistics processes must be considered [2]. Particular challenges arise in the operation of complex intermodal chains from a green and lean supply chain perspective [3]. An adequate support for lean overseas supply chains is provided by general cargo transportation, where several smaller shipments are consolidated in one container to one logistics destination, with cargo from different shippers and destined for different consignees. NVOCCs organize regular LCL services only through selected ports and set up consolidation depots for the provision of LCL containers in environments with a strong and wider gravitational hinterland while maintaining good infrastructural connectivity to the port [4]. Consequently, the commercial and operational implementation of regular weekly services are the basis for service operations, while the environmental aspect is often neglected.

The research contributes to the understanding of these elements that have a significant impact on supply chain engineering from an environmental perspective when relying on complex intermodal transportation chains. The need for a systematic assessment of the elements of environmental impact, time and price is highlighted. The scientific contribution is demonstrated through the prism of designing a more comprehensive approach to sustainable supply chain (SSC) planning in overseas operations, as there is a dearth of such scientific studies [5]. The applicability of the research is expressed in the case study of export supply chain operations using LCL services on the southern course of Baltic-Adriatic Corridor, where the volume of shipments is increasing, also due to the de-rotation of export shipments from northern European ports to the northern Adriatic port of Koper or the Italian port of Genoa. Export-oriented supply chains in the southern part of the Baltic-Adriatic transport corridor are becoming increasingly complex as it is a vast area with hinterland markets that generate regionally fragmented volumes of smaller overseas shipments [6]. Such shipments are routed to only two or three loading ports in outbound LCL services. The distances between loading ports (POL) are as long as 400 km, which has a significant impact on the price and time levels and the environmental components generated by the transport. There are also important differences between sea liner services, vessel size, liner connections and hub ports. Therefore, the applicable part of the research highlights the technological and operational diversity of outbound LCL services for small overseas shipments of Central Europe and Western Balkans and the need to consider environmental components in supply chain engineering. On this basis, the study pursues two research hypotheses:

- H1: A supply chain orientation towards general cargo transport that emphasizes only the most direct maritime link may lead to less environmentally and energy efficient supply chain operations.
- H2: In LCL services, land transport is an important factor for more environmentally friendly overseas transport of small consignments, even if it represents only a small share of the total transport route in the established supply chain.

## 2. Research background

SSC are based on three pillars: social, economic and environmental. Craig and Easton [7] point out that SSC engineering depends on emphasizing the content of these pillars. Suring [1] notes a greater emphasis on the environmental aspect of supply chain deployment, with global supply chain engineering being highly dependent on transportation infrastructure and logistics processes [8]. Infrastructure elements, POL, and warehouse locations influence the efficient organization of land links [9] and the cost aspect of supply chain performance [10]. It is also necessary to consider the exceptional political and economic conditions that affect the organization of transportation and supply chains. The pandemic COVID -19 showed how vulnerable the transportation system and transportation chains are. It is very difficult to adapt quickly, but sea and land freight transport has not come to a standstill. Colicchia *et al.* [3] analyze broader elements in the context of operating lean and green supply chains through efficient use of intermodal transportation. Indeed, lean global supply chains need to pay special attention to intermodality and LCL transport as part of it. Jamrus and Chien [11] highlight the fundamentals for optimal operation of global supply chains in intermodal transportation, such as higher freight space utilization, stuffing the container as close as possible to the source of the shipments, reducing the shipment handling along the chain, etc. Achieving economies of scale for organising direct LCL services and higher cargo space utilisation is easier and faster in economic areas with higher levels of production and demand [12]. In such environments, NVOCC operators are quicker to decide to establish LCL services [4], contributing to the development of new logistics networks and the possibilities of price and time optimization in supply chains [13].

In addition to operational excellence, reflected in supply chain shortening and price optimization, it is necessary to consider the environmental parameters [14], especially in intermodal transportation, which combines different modes and units of transportation. Liu *et al*. [2] state that increasing the speed of goods movement in supply chains has an impact on the increase in GHG emissions. Therefore, Lopez-Navarro [15] emphasizes the need for a comprehensive development of approaches to estimate the pollutant components, time and cost of intermodal transport, so that focusing on only one component does not have too great a negative impact on the others. The same attention is called for by Žic and Žic [16] when analyzing transport deliveries through distribution centers. A cross-comparison of sustainably oriented transport and logistics processes can only be made by an appropriate evaluation of emissions and time periods [17]. In determining these parameters, information about modern ships and road freight vehicles, the length of overseas connections and reduced travel speeds play a very important role [18-19]. Of particular importance for efficient LCL transport is the operation of the liner service, the container precarriage from the warehouse to POL, which directly affects the total cost of the intermodal chain and GHG emissions [20]. The environmental aspects of port performance also need to be considered [21], not only in terms of emissions generated, but also in terms of wider inclusion in the circular economy [22]. Understanding all parameters and measuring their impact in complex intermodal chains, where last mile delivery is also requested, is a very challenging process [23]. According to Herold in Lee [5] and Qian *et al*. [24] emphasize the lack of such studies in the operation of global supply chains for strategic and operational decisions of cargo owners. Evangelista *et al*. [25] expose the need for research to determine measurement standards and comparability of data between chains, which dictates the need to deepen the knowledge of input variables of environmentally oriented transportation chains. As a result, the engineering of SSC would be simpler and more transparent for all stakeholders.

## 3. Research methodology

### 3.1 Research basis

The study is based on previously identified challenges and differences in the operation of complex intermodal transport chains in the Central Europe region and the Eastern Adriatic region supporting export-oriented supply chains on the southern part of the Baltic-Adriatic Corridor [6]. The challenges lie in the management of land transport links between economic production areas and collection depots for overseas shipments to consumer markets. The study is based on the results of a study of container services in the Adriatic Sea and liner services in the Mediterranean Sea, which highlight the importance of container ship size, direct liner shipping, navigation speed, and ship space occupancy for the cost, time, and environmental efficiency of intermodal transport chains and, consequently, supply chains [26]. These elements have a significant impact on sustainable transportation in FCL (Full Container Load), which is directly reflected in sustainable LCL transportation.

The input variables of LCL transportation are much more complex than in FCL transportation, as it is necessary to combine cargo from different shippers and from different locations, with different goods and for different final destinations. Consolidation warehouses, which properly manage cargo flows, play an important role in the operation of the transport chain. Namely, they direct the further flow of goods according to the final locations of the loads, the possibility of packing goods in the same container, and the possibility of stacking them at multiple heights. From an operational point of view, they combine cargo quantities in such a way as to ensure at least one weekly dispatch of LCL containers.

A general and simplified LCL transport chain consists of at least five consecutive transport stages. It starts with the delivery of small consignments to consolidation warehouses by LTL (Less than Truck Load) or FTL (Full Truck Load) transports and continues with the transport of one or more full containers (FCL) to POLs. This is followed by sea transport organized by the container line (CL) to the booked POD and land transportation to the NVOCC operator's consolidation warehouse at the destination. Finally, the NVOCC takes care of the delivery of the shipments to the consignee or organizes the takeover of the shipments in a warehouse (Fig. 1).

The complexity of the commercial-operational process increases the goal of using the largest container, with 40' HC containers with a maximum volume of 76 $m^3$ being the most commonly used, although 45' containers with a volume of 86 $m^3$ can also be used. The goal of the NVOCC operator is to use at least 80 % of the selected container volume to achieve profitability of the transport. Indeed, the transport price is formed by volume or weight (weight/measure – w/m), using the higher value ($m^3$ or ton). The time component is less important for LCL transport, as overseas transportation for more distant markets takes more than 30 days; however, NVOCC operators disclose the total transportation time, as there can be significant time differences between services.

In most cases, elements of EE and GHG emissions are not reported in NVOCC operators' general offers, even though complex intermodal chains between the same POL and final destinations generate different amounts of $CO_2$, $NO_x$, $SO_2$, and NMHC emissions [27]. To ensure sustainably oriented complex intermodal chains in general cargo transport, it is necessary to analyse and properly classify the environmental usurpation values and the commercial components of time and price. It is important to analyse in detail the input variables and their impacts depending on the characteristics of the intermodal transport chain (Table 1).

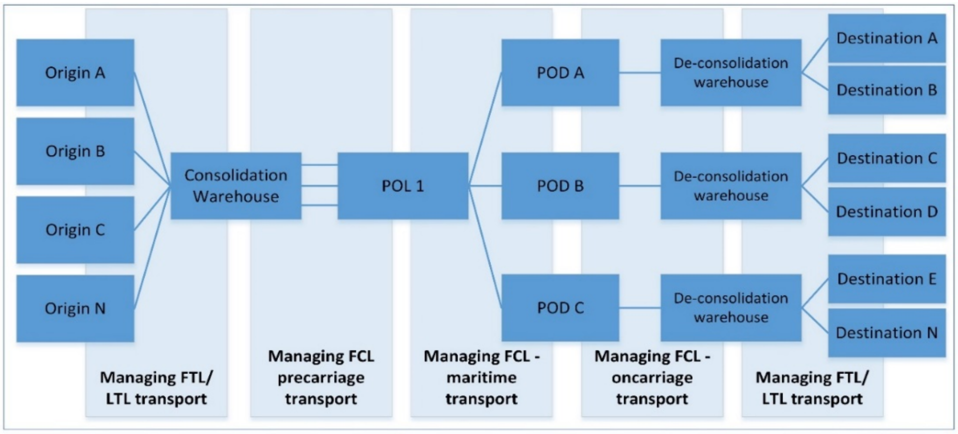


**Fig. 1** Simplified LCL transport on direct lines with a larger volume of LCL shipments

**Table 1** Input variables and influence parameters of SSC operation from the point of view of intermodal transport chain performance

| Input variable | Decision approach | Input variable impact |
|---|---|---|
| Place of consignment generation | Determination of land connections and mode of land transport | Distance, type and mode of land connection, number of individual land transport routes |
| Consignment characteristics | Orientation of the shipment to the land and sea part of a transport | Weight, volume |
| Location of consolidation warehouse | Direction of incoming and outgoing goods flows | Distance, mode of land transport, number of separate land transport legs |
| Type of land transport | Selection of optimal technological design, capacity, frequency | Occupancy of the cargo space, frequency, type of engine, ecological standard of the engine |
| POL location | Routing and grouping of shipments, LCL services operation | Distance, method of land connection |
| POD location | Direction of export flows of small overseas shipments | Length of sea route between ports, number of individual maritime transport legs |
| Direct or indirect LCL transport | Combination of sea transport to regional groupage warehouses | Length of sea route, additional handling, number of individual sea transport legs |
| Sea transport | Choice of CL and liner service | Vessel occupancy, vessel size, sailing speed |

Output parameters or comparison results are EE of the supply chain, GHG emissions ($CO_2$, $NO_x$, $SO_2$, NMHC), price, and transport process time. The output parameters can be calculated according to the input parameters (Table 1) and the characteristics and number of transport legs *(k)* of the selected intermodal transport chain. The overall energy efficiency $EE_T$ depends on the size of the transport vehicle, cargo space occupancy, engine, etc. and depends on the partial EE of the transport process $TL_{EEk}$.

$$EE_T = \sum_{k=1}^{n} TL_{EEk} \tag{1}$$

Total GHG emissions depend on the values of $CO_2$, $NO_x$, $SO_2$ and NMHC emissions. Their value depends on the type of transport, the length of each transport leg, the type of engine, etc. The total $CO_{2T}$ emissions depend on the $CO_2$ emissions of each transport leg $TL_{CO2k}$.

$$CO_{2T} = \sum_{k=1}^{n} TL_{CO2k} \tag{2}$$

The same is valid for $NO_{xT}$, $SO_{2T,}$ and $NMHC_T$ emissions. They mainly depend on the characteristics of maritime transport, where $TL_{NOxk}$ is the $NO_x$ value of single transport leg emissions, $TL_{SO2k}$ is the of $SO_2$ value and $TL_{NMHCk}$ is the NMHC value of single transport leg emissions.

$$NO_{xT} = \sum_{k=1}^{n} TL_{NOxk}; \qquad SO_{2T} = \sum_{k=1}^{n} TL_{SO2k}; \qquad NMHC_T = \sum_{k=1}^{n} TL_{NMHCk} \tag{3}$$

The total price of $C_T$ is made up of the price of land transport, handling and stowage, port handling, and sea transport, where $TL_{Ck}$ is the value of each of these processes.

$$C_T = \sum_{k=1}^{n} TL_{Ck} \tag{4}$$

The total delivery time of $T_T$ goods in the supply chain is also composed of several time components of individual transport legs and logistics services $TL_{Tk}$.

$$T_T = \sum_{k=1}^{n} TL_{Tk} \tag{5}$$

Service A is more sustainable and still lean than Service B if the condition is met: $EE_{TA} \leq EE_{TB}$; $CO_{2TA} \leq CO_{2TB}$; $NO_{xTA} \leq NO_{xTB}$; $SO_{2TA} \leq SO_{2TB}$; $NMHC_{TA} \leq NMHC_{TB}$; $C_{TA} \leq C_{TB}$; $T_{TA} \leq T_{TB}$.

### 3.2 Methodology

The methodology is based on a multiphase approach to the analysis on the sustainable operation of LCL services on the southern part of the Baltic-Adriatic Corridor. The basic research problem aims to understand the environmental performance of LCL services in order to find more balanced transport solutions that do not negatively impact the concept of lean supply chain operations at the same time (Fig. 2). Based on the characteristics of the LCL service, it is possible to simulate EE and the GHG emissions generated. The quantity of LCL shipments for a given destination, the type and mode of inland transport, the location of POL, the location of the regional LCL hub, the operation of container liner services and the size of the vessels and finally the utilisation of the container vessels shape a LCL service.

The study on the LCL services was conducted prior to the epidemic COVID-19 that significantly changed the way supply chains and intermodal transportation chains functioned due to access to empty containers, rising maritime prices, and the unreliability of maritime transportation services and delivery times for LCL shipments.

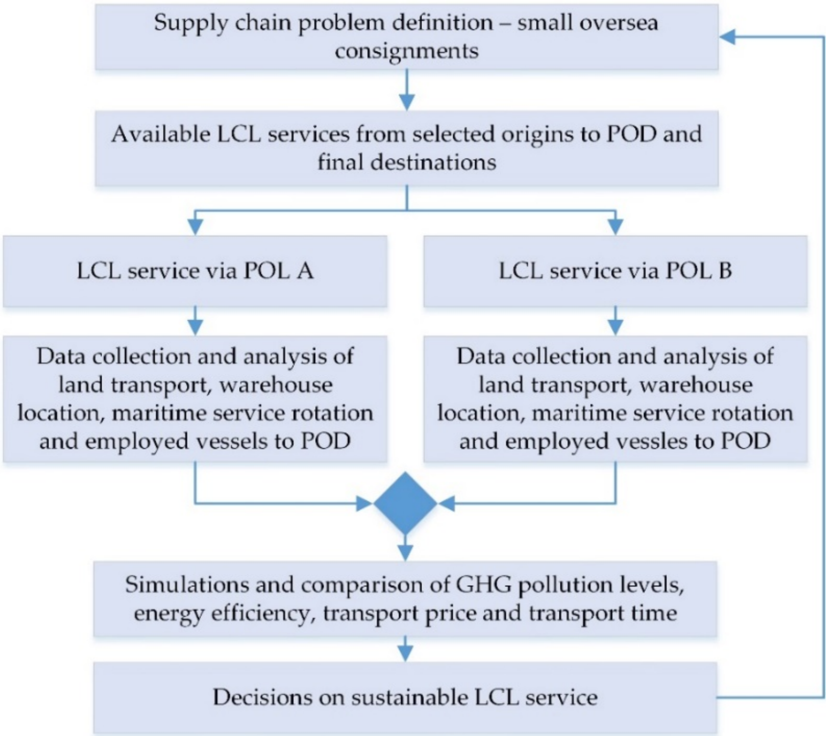


**Fig. 2** Research workflow on SSC for small and frequent consignments

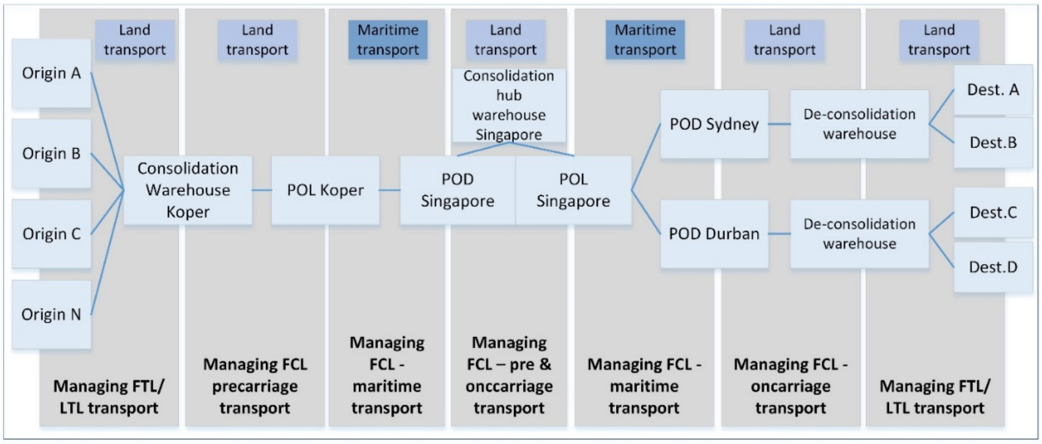


**Fig. 3** Case study: LCL service from POL Koper to POD Durban and Sydney

Six places of origin were included in the study: Belgrade (Serbia), Zagreb (Croatia), Sarajevo (BIH), Banja Luka (BIH), Ljubljana (Slovenia) and Budapest (Hungary). In the first part of the transport process analysis, an FTL transport was chosen for the shipment delivery to the consolidation warehouse. In the second transport leg a FCL transport was analysed, as POL Koper and Genoa are used by NVOCC operators for outbound LCL services. The third transportation section of FCL transportation by sea is very complex, as the booking of sea services depends on the regional consolidation location, the rotation of the vessel on a particular liner service, and the number and location of hub ports on route to POD. The elements of price and frequency of the liner service are also important. Selected destinations are Shanghai, Durban, Sydney and Jeddah, which are served by an LCL service via Koper and via Genoa. The selected destinations ensure the spread of the transport networks and thus the relevance of the comparisons.

The ongoing shipping process can be more complex than shown in Fig. 1, as for destinations with less regular shipments the LCL container is un-stowed in a regional consolidation warehouse of an intermediate hub. From there, a new full LCL container is formed for the POD, which is an additional fourth and fifth leg of the transportation process management (Fig. 3). This applies to shipments from POL Koper to Sydney and Durban, where the shipments are brought in a single container to POD Singapore and separated in Singapore into different containers for POD Durban and POD Sydney. The latter has a major impact on EE and GHG emissions from LCL services as the shipment is de-routed from the optimal conventional liner service and additional feeder connections are requested. This is followed by a series of transport process management that includes FCL transport to the final deconsolidation warehouse and on to the final destination.

The price analysis consists of FTL transportation prices from Q3 2018 as well as sea transportation prices of LCL shipments at Incoterms CFR parity, which were much more stable before the COVID-19 epidemic. The input parameters of sea transportation are the chosen CL, the container service between ports and the size of vessels between ports in liner service. An important parameter is the location of the regional hub LCL warehouse as an input for planning the required combination of maritime services. LCL services via Genoa do not require additional handling and grouping of shipments in regional hub warehouses, while LCL hub points in Singapore and Dubai are used for services via Koper for markets with less frequent shipments (Table 2).

To calculate EE and GHG emissions, the EcoTransIT World calculator developed by EWI (Ecotransit World Initiative) is used, which provides a transparent way to calculate projected GHG emissions in intermodal transport [28]. The calculation of EE and GHG emissions is based on the standard EN 16250, which specifies the methodology for calculating EE and GHG emissions for freight transport [29]. The following input parameters are defined for land transport: transport volume 1 ton, diesel engine and EURO 5 standard, 80 % cargo space utilization and no empty transport share. For sea transport, the following parameters are used: 1 ton of cargo, vessel's size as specified in Table 1, load factor 70 %, and slowing down the sailing speed by 25 %, which is also recommended by the IMO, as underwater noise pollution is reduced by more than 66 % and collisions with larger fish are reduced by more than 78 % [30].

**Table 2** Input variables and influence parameters of the simulation of SSC operation from the point of view of intermodal transport chain operation

| POD | Direct LCL service | Via regional LCL hub | Preferred carrier | Maritime service | Employed vessel capacity (TEU) |
|---|---|---|---|---|---|
| | | | POL Koper | | |
| Shanghai | YES | - | CMA | Direct | 12.500 |
| Durban | NO | Singapore | CMA | Port Klang, Singapore, Tanjung Pelepas | 12,500; 5,100; 2,500; 8,100 |
| Sydney | NO | Singapore | CMA | Port Klang, Singapore | 1,500; 5,100; 5,700 |
| Jeddah | NO | Dubai | MSC | King Abdul, Jebel Ali, Jeddah | 15,200; 18,000; 5,600 |
| | | | POL Genova | | |
| Shanghai | YES | - | COSCO | Direct | 13,600 |
| Durban | YES | - | MSC | Las Palmas | 5,700; 6,400 |
| Sydney | YES | - | MSC | Gioia Tauro | 8,800; 9,200 |
| Jeddah | YES | - | CMA | Direct | 11,300 |

## 4. Results

The study of LCL services in the analyzed supply chains shows the greater complexity of services through POL Koper due to the lower number of LCL shipments on selected destinations. Therefore, the services have to be routed to regional LCL hubs (Singapore or Dubai). At these points, containers are filled with additional shipments to the final destination. This does not apply to the Shanghai service as the weekly shipment volume is sufficient to organize a direct LCL service. The analysis shows that the sea transport route of the LCL service via Koper is more complex due to the sea container services. On the service to Durban and also to Jeddah, the container is reloaded three times. This is because the LCL services via POL Genoa are direct and the shipments remain in the container. Moreover, as shown in Table 2, on the way to Durban and Sydney, the container is transhipped only once at Las Palams (for Durban) and Gioia Tauro (for Sydney). The vessels used do not belong to the largest class of ULCVs (Ultra Large Container Vessels), which achieve lower GHG emissions per container transported at the same load factor.

Higher efficiency of sea transport has a significant impact on the low total $NO_x$, $SO_2$ and NMHC emissions of LCL services to Durban, Sydney and Jeddah via Genoa. On the whole transport route, $NO_x$ levels to Sydney are on average 8.5 % lower than via Koper, to Durban 12 % lower and to Jeddah even 50 % lower. The difference is even greater for $SO_2$ emissions, as levels are 12% lower via Genoa to Sydney, 14 % lower to Durban and 18 % lower to Jeddah. NMHC levels are also lower via Genoa than via Koper, with the exception of the direct service to Shanghai (Table 3).

**Table 3** Emission level of $NO_x$, NMHC and $SO_2$ via Genova vs. via Koper (in % Genova to Koper)

| | $NO_x$ via GEN vs. via KOP | | | | NMHC via GEN vs. via KOP | | | | $SO_2$ via GEN vs. via KOP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SHA | SYD | DUR | JED | SHA | SYD | DUR | JED | SHA | SYD | DUR | JED |
| BEG | 106.52 | 91.50 | 78.55 | 50.78 | 110.79 | 96.67 | 84.71 | 63.36 | 100.19 | 87.67 | 75.55 | 41.88 |
| ZAG | 106.74 | 91.28 | 78.05 | 48.30 | 111.66 | 96.46 | 83.80 | 58.90 | 100.19 | 87.60 | 75.42 | 41.22 |
| SAR | 106.52 | 91.50 | 78.56 | 50.82 | 110.79 | 96.67 | 84.71 | 63.36 | 100.19 | 87.68 | 75.58 | 42.05 |
| B. LUKA | 106.64 | 91.38 | 78.28 | 49.48 | 111.26 | 96.55 | 84.21 | 60.98 | 100.19 | 87.63 | 75.49 | 41.57 |
| LJU | 106.82 | 91.21 | 77.87 | 47.41 | 111.96 | 96.39 | 83.50 | 57.30 | 100.19 | 87.73 | 75.66 | 42.47 |
| BUD | 106.58 | 91.45 | 78.43 | 50.20 | 111.03 | 96.61 | 84.45 | 62.15 | 100.19 | 87.65 | 75.51 | 41.70 |

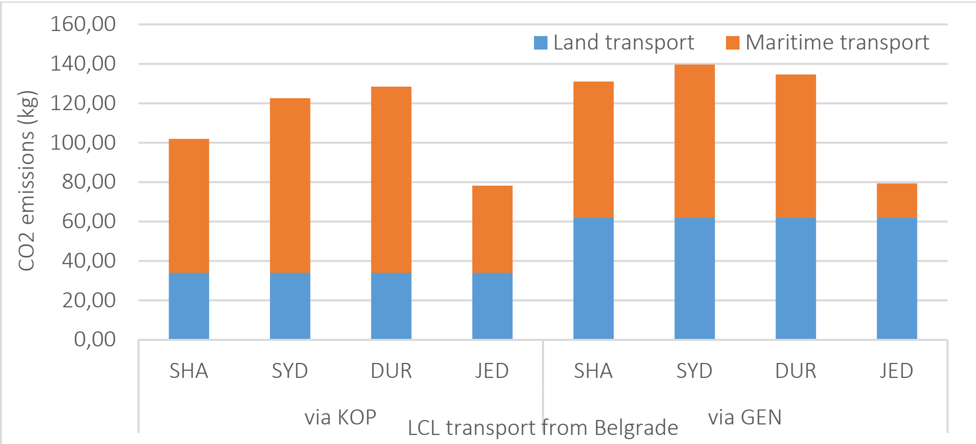


**Fig. 4** Comparison of $CO_2$ emissions from Belgrade via POL Koper and Genoa to final destinations

The analysis of $CO_2$ emissions also highlights the lower value of the maritime transport leg via Genoa, with the exception of the service to Shanghai, which is direct through both ports. The total emissions are significantly influenced by the road transport from Koper to the LCL warehouse in Milan and then to POL Genoa. As shown in Fig. 4, the land transport of a 1-tonne shipment from Belgrade to Sydney and Durban via Milan-Genoa causes 20 % of the total $CO_2$ emissions and as much as 35 % of the total $CO_2$ emissions when transported to Jeddah. Consequently, land transport to Milan and on to Genoa has a significant impact on total $CO_2$ emissions and LCL transport EE per tonne of each shipment. Due to the direct service to Shanghai, it is not environmentally justifiable to route shipments to Genoa. However, $CO_2$ emissions to Sydney, Durban and Jeddah via Genoa are also higher. An LCL shipment of one tonne of freight results in up to 18 % more $CO_2$ emissions to Sydney, up to 6 % more when shipping to Durban and 2 % more $CO_2$ emissions to Jeddah. From the perspective of EE, LCL transport via Genoa is also less efficient, although LCL shipments routed via Koper are additionally handled at several transshipment ports. As shown in Table 4, LCL transport via Genoa to Sydney is up to 21 % more inefficient and up to 9 % more inefficient for transport to Durban and Jeddah.

The cost aspect illustrates the price advantage of LCL transport via Koper, even if sea freight rates for FCL containers are somewhat higher. The additional cost of land transport to Genoa cancels out the advantages of the cheaper sea connections. The cost of transporting an LCL shipment weighing 1 ton and less than 1 $m^3$ is 16-19 % higher via Genoa to Shanghai, 12 % higher on average to Sydney and Durban, and 7 % higher to Jeddah (Fig. 5).

**Table 4** Emission level of $CO_2$ and EE levels via Genova vs. via Koper (in % Genova to Koper)

| | $CO_2$ via GEN vs. via KOP | | | | EE via GEN vs. via KOP | | | |
|---|---|---|---|---|---|---|---|---|
| Origin | SHA | SYD | DUR | JED | SHA | SYD | DUR | JED |
| BEG | 128.48 | 114.00 | 104.79 | 101.41 | 131.43 | 116.69 | 107.36 | 105.76 |
| ZAG | 136.31 | 117.06 | 105.77 | 101.96 | 140.11 | 120.37 | 108.89 | 108.01 |
| SAR | 128.48 | 114.00 | 104.79 | 101.41 | 134.93 | 116.69 | 107.36 | 105.76 |
| B. LUKA | 132.28 | 115.52 | 105.28 | 101.66 | 135.62 | 118.50 | 108.12 | 106.80 |
| LJU | 139.52 | 118.24 | 106.15 | 102.21 | 144.01 | 121.92 | 109.53 | 109.16 |
| BUD | 130.26 | 114.72 | 105.02 | 101.52 | 133.02 | 117.39 | 107.66 | 106.14 |

The time component is particularly important for supply chain engineering, because shortest delivery time is one of preferences the in fast expanding on-line market [31]. The comparison of the total transport time highlights the higher competitiveness of LCL services via Genoa. For the service to Shanghai, the time is very similar, the only difference being the additional land transport to Milan and Genoa. LCL transport to Sydney takes on average more than 50 days via both selected POLs. Important differences exist for the transport to Durban and Jeddah, as for the service via Koper the shipment for Durban has to be brought to Singapore first and the shipment for Jeddah to the LCL hub warehouse in Dubai. Transport via Koper to Durban takes 25 days longer (+67 %) and transport to Jeddah takes 13 days longer or 50 % of the transport time.

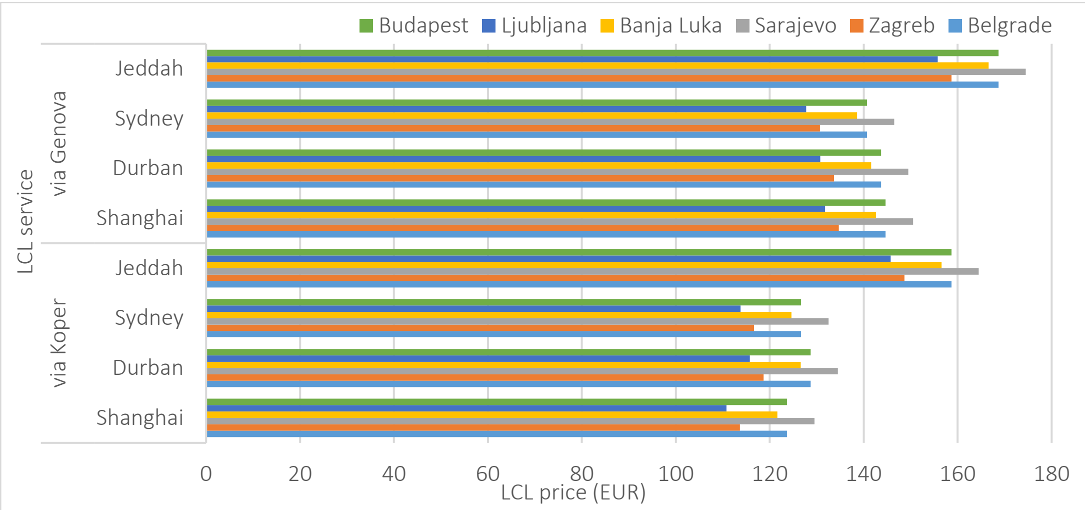


**Fig. 5** Price level for LCL shipment of 1 ton and volume less than 1 m3 per destination

## 5. Discussion and implications for modeling sustainable supply chains with sustainable intermodal transport

Lean supply chains are based on the efficient operation of intermodal transportation and incorporate many elements of modern supply chain engineering. The results of the study highlight the importance of environmental sustainability of overseas transportation. An understanding of the identification and placement of consolidation warehouses and selected POLs is required in SSC engineering. The study highlights the importance of mainland efficiency to ensure low-carbon and higher EE of global supply chains. Total $NO_x$, $SO_2$ and NMHC emissions in overseas supply chains mainly depend on the optimal implementation of port access and vessel characteristics (size, load, speed).

If only the time component is pursued in lean supply chain modelling to reduce inventories and financial liquidity, LCL service via Genoa offers better solutions. Thus, shipments are frequently routed through this port, resulting in more direct traffic and greater export freight volumes. In terms of price, transporting a single shipment weighing 1 tonne and with a volume of less than 1 $m^3$ via Genoa, which is further away, is 10 to 20 EUR more expensive, which represents an average difference of about 50 EUR for a medium-sized shipment of 4 tonnes and up to 4 m$^3$ in volume. This difference is acceptable for exporters and importers, as they get up to 50% shorter delivery times. On the other hand, 44.6 kg more $CO_2$ is generated and 300 kWh more energy is consumed to transport such a shipment to Sydney.

Due to fragmentation of overseas consolidated cargoes to various final destinations, LCL transport to less frequent destinations in the southern Baltic-Adriatic Corridor are still routed via Milan and POL Genoa. However, carbon footprint results, EE, and price comparisons do not support these activities. This is reflected in the data on the LCL transport from the most distant location, Belgrade, to selected destinations (Fig. 6). The matrix representation of the main indicators can be a transparent tool for commodity owners in the decision model of supply chain modelling (Table 5).

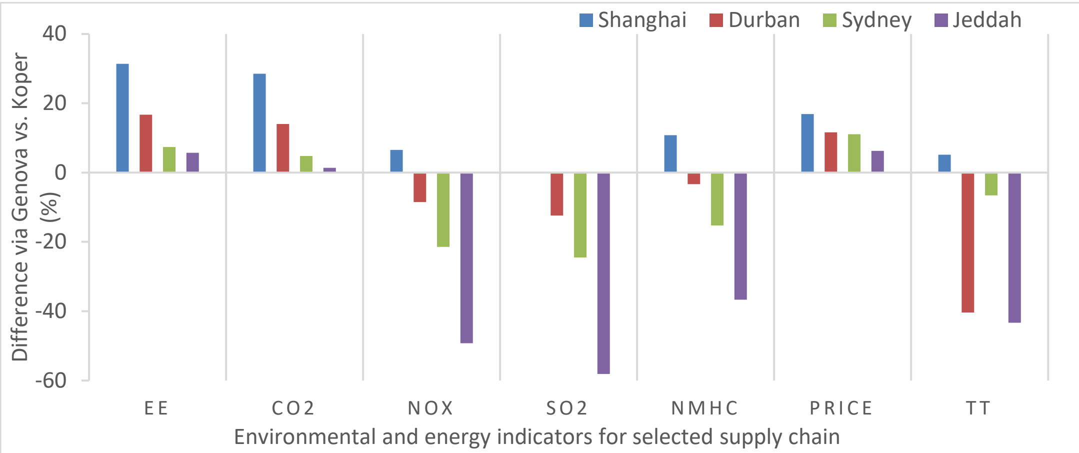


**Fig. 6** Environmental and energy indicators of transport from Belgrade (% of value via Genoa vs. Koper)

**Table 5** Environmental, price, and time values of transport of LCL shipments from Belgrade (in % via Genoa vs Koper)

| | EE | $CO_2$ | $NO_X$ | $SO_2$ | NMHC | Price | TT |
|---|---|---|---|---|---|---|---|
| Shanghai | +31.43 | +28.48 | +6.52 | +0.19 | +10.79 | +16.91 | +5.13 |
| Durban | +16.69 | +14.00 | -8.50 | -12.34 | -3.33 | +11.66 | -40.32 |
| Sydney | +7.36 | +4.79 | -21.45 | -24.45 | -15.29 | +11.05 | -6.56 |
| Jeddah | +5.76 | +1.41 | -49.22 | - 58.12 | -36.64 | +6.30 | -43.33 |

The results of the study demonstrate the importance of comprehensive modelling of general cargo transportation that focuses on sustainable aspects of the intermodal transportation chain opera-tions. It is particularly important to adequately inform freight owners about the GHG emissions that result from transporting a small shipment overseas. Due to the significant difference in total transportation time and lower price differential, they often opt for less environmentally friendly and EE efficient transportation solutions. This raises the issue and the need to externalise the indirect costs of a higher environmental impact with the chosen transportation service, further driving up the cost of transportation to Genoa. This would push shippers who want leaner and more flexible supply chains to contribute more to decarbonizing transportation. It is foolish to expect from NVOCC operators to stop providing diversified transportation services just to reduce the carbon footprint and increase EE of transportation services.

The results can be generally applied to similar geographic areas where LCL shipments are transported to more distant ports in order to fill containers more efficiently and achieve higher shipping frequency and regularity of the LCL service. This, of course, requires an in-depth analysis of the input parameters of LCL services and the characteristics of LCL shipments in order to accurately determine the difference between the GHG emissions generated and the EE achieved. It is also difficult to generalize the approach that a more distant port is not the most appropriate for LCL service from the point of view of a sustainable transportation process. It is necessary to take into account the parameters of maritime services to comparable ports, especially the size and age of the vessels, the maritime route, the type of propulsion, the occupancy of the cargo space in the container and on the vessel, etc. It is expected that through the use of machine learning and artificial intelligence, decision models will be available in the future that will take into account a greater number of input data about LCL services and, based on the elements of price, time and environmental impact, will provide fast and efficient sustainable decisions for cargo owners or contracted logistics companies.

## 6. Conclusion

The environmental aspects of each transport sector are very well developed at the EU level, and strategies are being used to reduce the carbon footprint and improve EE. Building and managing complex intermodal transport chains to support global supply chains brings many other challenges. For example, different modes of transport from different transport sectors, different engines and loading capacities, and different freight space utilisation rates must be used in succession. The latter also applies to the transport of small consignments in cross-border traffic. Global general cargo traffic relies on efficient handling of land and sea transport, with the volume and size of shipments posing an additional challenge, as this is the only way to determine the need for additional handling of shipments and the formation of new consolidated containers along the defined transport chain.

The results of the study confirm research hypothesis H1 that building a supply chain that focuses only on the most direct maritime link may be less environmentally and energy friendly. The $CO_2$ emissions and energy consumption of maritime transport on direct LCL lines via Genoa are more acceptable than on overseas connections via Koper. However, it is necessary to take into account GHG emissions and energy consumption for land transport, the impacts of which are higher than the benefits of direct maritime services.

The study on the operation of supply chains for the introduction of LCL services on the southern part of the Baltic-Adriatic Corridor supports the basic theses on the complexity of the services. The research results underline the importance of considering environmental aspects in LCL services and confirm the H2 hypothesis that in LCL services land transport is an important factor in achieving greener chains, even if it represents only a small share of the total transport distance. The data on LCL services via Genoa for shipments originating in the Western Balkans and Central Europe confirm that the additional land transport from the collection point near Koper has a significant impact on the carbon footprint and EE, even if it represents only 2 % of the total transport route distance.

The results of the study are limited in that they only consider the selected final destination and the vessel characteristics used by CL at a given time, but they provide a measurable framework for current environmental parameters in complex intermodal chains. The information on CL is at the discretion of the NVOCC operator, which does not imply that it has chosen the route with the most environmentally friendly and EE values. The research results serve as a basis for further elaboration to develop an assessment approach useful for supply chain engineering.

## Acknowledgment

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# Design and operations framework for the Twin Transition of manufacturing systems

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**A B S T R A C T**

Manufacturing companies are facing what recently has been called the Twin Transition. They must conduct a digital transition as well as a transition from mere linear toward more circular value creation. The research presents an integrated Design and Operations Framework for digital and circular manufacturing systems. Defined process phases of the framework are described which address: the maturity assessment, Objectives and Key Results, the design (Des) and operations (Ops) of the manufacturing system, and a training concept. The authors follow a qualitative research approach for developing the integrated DesOps Framework for Circular and Digital Manufacturing Systems. The framework is conceptualized by combining state-of-the-art procedures and methods in the field of maturity and readiness assessment, Objectives and Key Results, Systems Engineering, and DesOps. Eventually, a case study is utilized for verifying the principal efficacy of the conceptualized framework. The research intends to scientifically contribute to the field of manufacturing systems design by proposing a novel design framework. From industrial application perspective, the research intends to contribute to improving decision-making in manufacturing companies by providing them with a practical-oriented guideline for transforming their manufacturing systems in the sense of the Twin Transition.

**A R T I C L E   I N F O**

*Keywords:*
Manufacturing systems design;
Circular economy;
Sustainability;
Digital twin;
Twin transition;
Digital transition;
Design and operations (DesOps)

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## 1. Introduction

European Manufacturing companies are constantly facing the challenge to adapt their value creation to novel regulations as well as to relevant technology trends. The EU Commission is pushing forward the implementation of the European Green Deal throughout the EU member states via regulatory activities such as the new circular economy action plan (CEAP), Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) including the introduction of the SCIP database, The Supply Chain act, and the Sustainable Finance taxonomy. Additionally, technology trends, for example in the context of Industry 4.0 sensors, robotics, cloud and edge computing, cyber security, artificial intelligence, and the Industrial Digital Twin are increasingly influencing the design and operation of manufacturing systems. Political stakeholders, industry associations, and manufacturing companies are facing what recently has been called the Twin Transition: a sustainable and digital transition of the industry, which will be of increasing importance as an industrial strategy in the future [1]. For manufacturing companies, the Twin Transition can be translated into two concrete pathways of innovation: (1) transitioning from a mere linear towards a more circular economy, and (2) realizing a digital transition of their value creation, i.e., business models and manufacturing systems.

According to the WEF, "in 2019, over 92 billion tonnes of materials were extracted and processed, contributing to about half of global $CO_2$ emissions" while the resulting waste substantially promotes environmental degradation and human health deterioration [2]. Transitioning from a linear toward a circular economy will serve as a cornerstone for tackling these global challenges [3], can realize up to $4.5 trillion in economic benefits by 2030 [2], and is already determined as the main pillar of Europe's sustainable growth [4]. A key principle of the circular economy is to keep products and materials circulating in closed-loop life cycles [5]. With it, industrial symbiosis, reuse, remanufacture, and recycling moves to the center of interest in industrial value creation [6]. Remanufacturing, for example, enables the circular economy by maintaining the high value of used products, assemblies, components, and parts, so-called cores, throughout multiple life cycles. However, remanufacturing is still a comparably new approach for most companies, since only 8.6 % of the global value networks are circular [2]. It thus poses novel complexity challenges in terms of managing the reverse logistics, reprocessing the used products, assemblies, components, and parts, or in terms of designing products for remanufacturing.

The transition towards circular value networks will be essentially enabled by a digital transition of the manufacturing systems. A digital transition is coined by novel digital and automation technologies fostered by digital ecosystems such as GAIA-X and becomes a more and more important success factor for adaptable and flexible manufacturing systems in an Industry 4.0 context. Manufacturing companies face the challenge of constantly monitoring digitalization trends and evaluating relevant digital technologies to integrate them into their value creation based on their digital maturity level. Given the complexity of these tasks, many manufacturing companies still struggle to create a suitable strategy for their digital transformation.

The presented research aims at supporting the digital and circular transformation of manufacturing companies by addressing the following research question:

*How can manufacturing systems be efficaciously designed and operated to support the Twin Transition of the manufacturing sector?*

The paper intends to scientifically contribute to the field of manufacturing systems design by proposing a novel design framework. From industrial application perspective, the research intends to contribute to improving decision-making in manufacturing companies by providing them with a practical-oriented guideline for transforming their manufacturing systems in the sense of the Twin Transition. The research methodology follows a qualitative approach (Fig. 1). A narrative literature review provides the foundation for positioning the research within the state-of-the-art and for deriving the research gap and contribution. Throughout phases of analyses and syntheses, the novel DesOps Framework was conceptualized based on the expert knowledge and experience of the authors. For this purpose, the idea of the Delphi method was followed until a consensus on the framework concept was reached. A case study in the field of manufacturing engineering served to verify, validate, and evaluate the fundamental efficacy of the DesOps Framework. Feedback from the case study was constantly used for improving the framework.

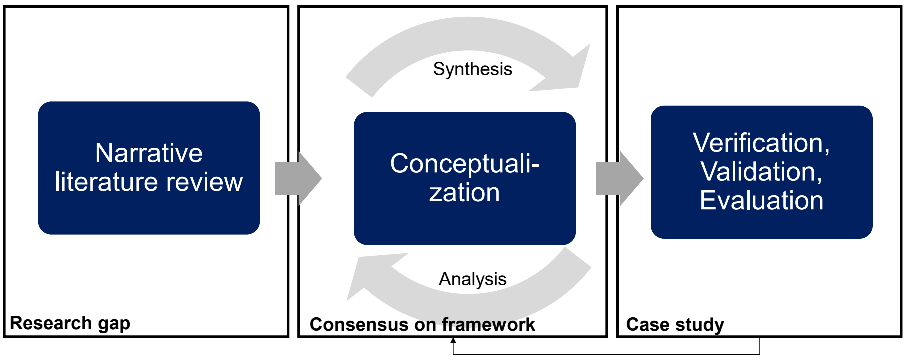


**Fig. 1** Research methodology

The paper is structured as follows. The second section describes the state-of-the-art for design of manufacturing systems in general as well as for circularity and digitalization. The section also includes a description of the scientific contribution. The third section introduces the DesOps framework including a description of the framework's relevant process phases. Section 4 addresses the verification, validation, and evaluation of the proposed framework based on a relevant case study in manufacturing, while Section 5 covers a discussion of results and limitations and gives an outlook on future research activities.

## 2. State-of-the-art

### 2.1 Design of manufacturing systems

Designing manufacturing systems requires the design of relevant manufacturing artifacts while following a certain design process for developing the manufacturing system with its sub-systems. The artifact and design process point of view is broken down into the following.

Manufacturing artifacts can be interpreted from a technology as well as from a management system perspective [7]. From a technology system perspective, the selection of the manufacturing process chain, i.e., concrete fabrication and assembly technologies, processes, and parameters based on product (or product portfolio) characteristics, is at the core of the design task. The management perspective incorporates a broader scope of manufacturing systems addressing the integrated design of the value network (i.e., of technology and equipment, material flow including the logistics and supply chain, ICT infrastructure, digital components), value proposition (i.e., product-related mechanics, electronics/ electrics, software, and services), and value delivery (i.e., customers, communication channels, cost, and revenue structure) [8]. Thus, the design of the management systems can be rather interpreted in the sense of designing a business model for a hardware product which might also include a software or service component [9]. Different levels of system aggregation can be relevant for designing the manufacturing system from a management perspective. For example, Wiendahl *et al*. distinguish between process, station, cell, system, segment, site, and network levels [10].

The actual design process of manufacturing systems is subject to different design procedures: (1) Design procedures with an emphasis on product development, such as Integrated Design Engineering [11], also address elements of designing manufacturing systems from an integrated design perspective. (2) Other design procedures are more linked to the field of Systems Engineering, e.g., [12], and cover the design of the overall manufacturing system with its different domains in a rather generic manner. (3) Further, design procedures are more specifically tailored to the different levels of aggregation or concrete design tasks of manufacturing systems. For example, Factory Planning and Design [13] as a more high-level approach or designing factory layouts [14], process chains [15], adaptive and flexible automation systems [16], and human-robot collaborative workstations [17] are aimed at delimited design tasks of manufacturing systems. (4) In addition, business-model-oriented design procedures for manufacturing systems have attracted some attention lately. For example, the integrated design of the business model including the design of the manufacturing system linked to the design of the hardware product is presented by [9]. (5) Lastly, design procedures emphasizing on the application of determining design principles are available for manufacturing systems. Designing lean manufacturing systems [18], applying axiomatic design principles [19], or designing resilient manufacturing systems [20] are e.g., based on concrete design principles.

### 2.2 Design of circular and digital manufacturing systems

The relevance of sustainability and/or digitalization in the context of manufacturing systems is the subject of ongoing academic discussions in production engineering and management, e.g., as presented by [21, 22]. Design procedures for circular manufacturing systems cover comprehensive development frameworks such as e.g., described in [23]. Other procedures focus more on specific end-of-life phases of products. In this context, procedures are proposed for designing manufacturing systems enabling reuse [24], remanufacturing, and recycling [25] capabilities.

Additionally, design procedures for designing industrial symbiosis ecosystems, business models, and (reverse) supply chains are gaining attention, e.g., described by [26]. Design procedures for digital manufacturing systems cover design frameworks for smart factories in Industry 4.0, e.g., as discussed by [27] as well as for digital manufacturing systems [28] or the digital twin of factories [29]. Other approaches focus on the model-, simulation- and algorithm-based design of manufacturing systems, e.g., as discussed by [14, 30]. From an industry perspective, the integrated design of the Industrial Digital Twin / Asset Administration Shell and the physical system of manufacturing assets is a key building block for realizing manufacturing systems in Industry 4.0 and is the subject of relevant manufacturing industry associations [31]. The target-oriented and integrated design of the standardized Industrial Digital Twin, the so-called Asset Administration Shell, and the physical manufacturing system seems to be insufficiently addressed by current academic research activities. Furthermore, structured design procedures for manufacturing systems supporting the Twin Transition by enabling circular through digital value creation seem to be inadequately discussed so far, even though some researchers started investigating how digital technologies, e.g., the digital twin, can enable specific product end-of-life phases such as recycling and remanufacturing [32].

### 2.3 Scientific contribution

The paper intends to contribute to the scientific field of manufacturing systems design by proposing a framework for the design and operations of digital and circular manufacturing systems which:

- Provides a structured and agile procedure for designing the relevant artifacts of manufacturing systems in the domains: value proposition, value network, and value distribution;
- Incorporate objectives and key results for creating digital and circular manufacturing systems;
- Incorporates the key technology for digitalization, the Asset Administration Shell/Industrial Digital Twin, for enabling circular value creation.

## 3. DesOps framework

### 3.1 Framework elements

The integrated DesOps Framework for Circular and Digital Manufacturing Systems is a further development of [8] and combines state-of-the-art procedures and methods in the field of maturity and readiness assessment of organizations concerning digitalization and circularity [33-35], of Objectives and Key Results (OKRs) [36], and DesOps [37].

The DesOps Framework intends to provide manufacturing companies with a practical-oriented guideline for transforming manufacturing systems towards circular value creation enabled by digitalization. The framework consists of nine process phases (Fig. 2). Phase 0 covers the maturity and readiness assessment for determining the initial status of the company’s manufacturing system in terms of digital and circular value creation. Phase 1 aims at defining the Objectives and Key Results (OKRs) for the manufacturing system development. OKRs determine the target state for a pre-defined development period which then is continuously updated in alignment with the progress of the development progress. OKRs, therefore, serve as management and control measures for the design process. Phases 2 to 7 are the core of the development methodology by describing the relevant process phases for the design (Des) and operations (Ops) of the manufacturing system. Phase 8 comprises the creation of a training concept for developing the competencies for working in a circular and digital manufacturing environment.

Since the proportion of digital components in manufacturing systems is steadily increasing and will become even more important in the future, design frameworks must reflect the challenges coming along with this trend. Thus, agile practices, which originate in software development find their way also in the development methodologies of hardware systems. The proposed DesOps framework follows the philosophy of agile development by combining the concept of OKRs, for controlling the design process progress, with the DesOps approach which allows the integration of agile principles into the actual design and realization process of the manufacturing system.

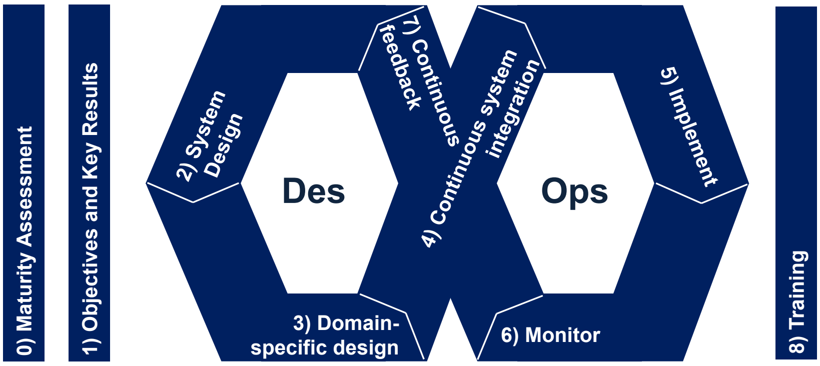


**Fig. 2** DesOps Framework (following the idea from [8])

### 3.2 Phase 0: Maturity assessment

The first framework step aims at assessing the capabilities and maturity of the prevailing company's manufacturing system concerning digitalization and circularity. For that purpose, a range of industry or scientifically-based maturity models can be applied which outline a sequence of either digital and/or circularity capabilities representing a desired evolutionary path for the manufacturing system toward higher levels of maturity and performance. Models typically describe 5 or 6 capability levels and related technology, management, cultural and business practices as well as how they enable higher levels of business and sustainability performance. They are preferably applied to benchmark the current state and develop a future strategic direction for the manufacturing system, including the definition of OKRs and identification of relevant system and domain-specific design components. Table 1 provides examples of recently developed relevant maturity models for this purpose, where two models have an assessment of automation and digitalization maturity in scope, and the third model focuses on the assessment of circularity.

**Table 1** Examples of maturity models for digitalization, automation, and circularity

| **Topic** | **Digitalization** | **Automation** | **Circularity** |
|---|---|---|---|
| Level & Authors | [33] | [34] | [35] |
| Level 0 | Computerization | No Autonomy | - |
| Level 1 | Connectivity | Functional Assistance | Linearity |
| Level 2 | Visibility | Partial Autonomy | Industrial CE Piloting |
| Level 3 | Transparency | Delimited Autonomy | Systemic Materials Management |
| Level 4 | Predictive capacity | Flexible Autonomy | CE Thinking |
| Level 5 | Adaptability | System Autonomy | Full Circularity |

### 3.3 Phase 1: Objectives and Key Results (OKRs)

The OKRs serve as steering, management, and control method for the DesOps phases. The initial ORK work cycle (Fig. 3) for the DesOps process is started based on the results of the maturity assessment (Phase 0).

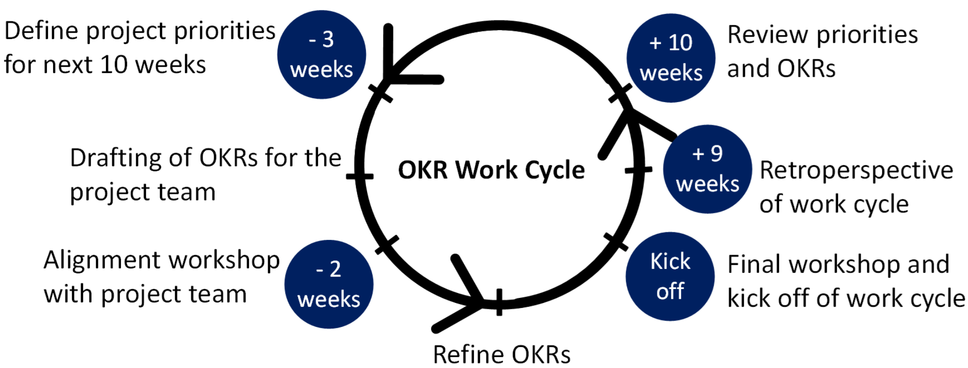


**Fig. 3** ORK Cycle (adapted from [36])

Table 2 highlights some important characteristics of the OKR concept. In other words, the first Objectives and Key Results are defined based on the initial digital and circular maturity levels of the organization. Digital maturity is used here in a broader sense and incorporates automation maturity. If the assessed level of maturity is in the range of 0 and 1, then the OKRs should focus on establishing a maturity level of the manufacturing system in the range of 1 to 2. An example of how the achievement of OKRs linked to digital value creation can enable the definition of OKRs linked to circular value creation for the subsequent OKR cycle is presented in Table 3. The OKRs set concrete and time-dependent objectives and results for the pursuit of engineering tasks for all DesOps phases. For example, an OKR work cycle during the "Implement" phase (Phase 6) of the DesOps process would define objectives and results for implementing the domains of the manufacturing system such as production lines and cells, machine tools and assembly stations, ICT-equipment, software tools, or new product variants.

**Table 2** Characteristics of the OKR concept [36]

| Objectives | Key results | Rules | Roles |
|---|---|---|---|
| … describe an aspirational future state or condition. | … define specific results on how to realize the Objective. | Set an OKR cycle of 4 to 10 weeks and align OKRs accordingly after each cycle. | OKRs are distributed among the available teams, i.e., the OKR owners. |
| … are qualitative. | … are quantitative and measurable. | Set a maximum of three objectives per organizational unit | Objective owners should also be the owner of at least one Key Result linked to the objective. |
| … are developed bottom-up and top town. | … are ambitious but realizable. | Limit the number of Key Results to 2 to 5 per Objective. | OKR coaches facilitate the weekly communication and check in on OKR progress. |
| … should be realizable in one cycle. | … are time-phased and accepted by stakeholders. | Define OKRs for the organizational and team level. | Program leads are responsible for the rollout and development of the OKR process. |

**Table 3** Example of "digital" OKRs enabling "circular" OKRs

| | Digital Value Creation | | Circular Value Creation | |
|---|---|---|---|---|
| **Maturity** | **Objectives** | **Key Results** | | **Objectives** |
| Low (Level 0-1) | Automate simple repetitive manual manufacturing tasks | Robot cell for a certain workplace | Enables | Automate the repairing process for all product lines |
| Medium (Level 2-3) | Use real-time data for identifying anomalies and states of manufacturing equipment | Real-time mapping of energy profiles for two machine tools | Enables | Integrate renewable energy sources into the manufacturing system |
| High (Level 4-5) | Implement a self-optimized manufacturing strategy | Industrial Digital Twin for all instances of a certain product variant | Enables | Use the Industrial Digital Twin for the identification of used products and components, so called cores, inside the EU |

### 3.4 Phases 2 to 7: Design and operations

Table 4 lists the relevant engineering task and exemplary engineering methods for the system levels for the design (phases 2 to 4) and operations phases (phases 5 to 7).

Phases 2 to 4 aim at designing the overall manufacturing system with its relevant domains: value proposition, value network, and value delivery [8]. The value proposition domain incorporates the actual hardware product including its potential services to be processed within the manufacturing system, i.e., the subject of value creation. The design of the value proposition also addresses the design of the whole life cycle of the product with its beginning, middle, and end-of-life phases. From a circular economy perspective, embedding the product in closed-loop lifecycles with distinct consideration of opportunities for reuse, remanufacturing, and recycling. The value network is the object of value creation and covers the connected manufacturing assets, e.g., machine tools and other manufacturing equipment, as well as their digital representations, i.e., the Industrial Digital Twins / Asset Administration Shells, which are required to produce the value proposition. The detailed design of the reuse, remanufacturing, and recycling processes as well as of industrial symbioses networks is coined within the value network domain. The value delivery domain comprises the stakeholders including potential customers, the profit structure, as well as the communication channels with the customers. The value delivery has rather supporting functions for circular value creation. However, the domain depicts if the design solutions for value creation are contributing to the competitiveness of the company by demonstrating their contribution to the company's profit and providing value to the customers and identified customer segments while efficaciously considering other stakeholders such as suppliers. Developed solutions within each domain need to be constantly integrated across the domains to ensure the functional fit between the domains, for example between the product geometry and the required manufacturing process. Integration usually requires the creation of experiments based on digital and/or physical prototypes to test the interfaces and intended interplay between the single-domain solutions. Integration of domains helps to identify potential faults as well as to verify the domain and system functions.

**Table 4** System level, engineering tasks and engineering methods of the DesOps phases [38]

| **System-level** | **Engineering tasks** | **Engineering Methods (Examples for solving the tasks)** |
|---|---|---|
| ***System Design (Phase 2)*** | | |
| System concept | Defining system and domain requirements<br>Determining system and domain functions<br>Selecting basic system and domain solutions | Ideation, conceptual design, creativity methods |
| ***Domain-specific Design (Phase 3)*** | | |
| Domain 1: Value proposition | Designing the mechanics, software, electrics/electronics, services | Integrated design engineering, systems engineering, service design |
| Domain 2: Value network | Designing the manufacturing technology, material flow, information flow and ICT, Industrial digital twin / Asset administration shell | Factory planning and design, supply chain design, design for cybersecurity |
| Domain 3: Value delivery | Designing the stakeholders including the customers, channels, cost and sales structure | Innovation accounting, lean analytics |
| ***Continuous System Integration (Phase 4)*** | | |
| Domain Solutions | Integrating different design solutions across the domains in a pilot manufacturing environment | Experimentation, verification |
| ***Implement (Phase 5)*** | | |
| Domain solutions and overall manufacturing system solutions | Rolling-out and ramping-up of domain and system solutions for the value proposition, value network and value delivery within the real manufacturing environment | Lean manufacturing |
| ***Monitor (Phase 6)*** | | |
| Domain solutions and overall manufacturing system solutions | Monitoring the operations of the implemented domain and system solutions for the value proposition, value network and value delivery | Assessment and evaluation, Key performance indicators, manufacturing metrics, auditing |
| ***Continuous feedback (Phase 7)*** | | |
| Domain solutions and overall manufacturing system solutions | Deriving improvement measures for the next iteration of domain and system solutions based on the outcomes of all phases, but especially the monitoring phase<br>Feeding back the derived measured into the system design (Phase 2) of the next iteration | Quality management, Lean manufacturing, KAIZEN |

Phases 5 to 7 essentially aim at bringing the designed manufacturing system with its different domains into an operational state. For this purpose, iterations of the manufacturing system are implemented and ramped up; and the overall system architecture including the developed domains is tested under real manufacturing conditions. Monitoring serves to qualify but even more important quantify relevant system performance indicators and other parameters which might also be directly linked to the OKRs. Thus, monitoring allows tracking the degree of circular and digital value creation of the designed manufacturing system. The indicators and parameters monitored under real production conditions serve to derive improvement measures for subsequent iterations of the overall system as well as for its domains. The process shall be conducted with the consideration of relevant stakeholders' opinions. For example, suppliers or customers might provide useful inputs for improving the system and its domains based on auditing the operational state of the system or on evaluating the monitored indicators and parameters. Specific improvement measures are constantly fed back to the system design phase to generate new iterations of the system and/or domains. However, continuous feedback is also created based.

### 3.5 Phase 8: Training

Phase 8 aims at skill building for relevant stakeholders and especially for the employees who must operate and maintain the manufacturing system in the future. This phase requires the development of training curricula for the specific target groups. Curricula usually incorporate the teaching objectives and outcomes as well as specific teaching activities to realize the intended outcomes. Teaching objectives are linked to the development of a set of certain skills and competencies. In a manufacturing context, the approach of a learning factory or a Learnstrument can be suitable for conveying the curriculum, especially for teaching aspects of digital and circular value creation.

## 4. Verification, validation, and evaluation

The verification and validation of the DesOps framework are performed based on a case study. In other words, the purpose of the case study is to test the efficacy of the DesOps framework in the context of a real manufacturing challenge. The case study itself is based on a funded project which aims at developing an automated and digitalized Additive Manufacturing (AM) system embedded in an Industry 4.0 manufacturing environment. This includes:

1. The automation of the value creation in the context of an AM system from setting up and equipping the machine tool (3D printer) with materials, up to quality control, and all material handling steps, i.e., removing the printed parts and products from the machine tool.
2. The digitalization of the physical AM system by creating an Industrial Digital Twin for linking the physical system to the virtual system, which enables the exchange of services e.g., transportation, maintenance, and manufacturing tasks, with the internal logistics system as well as the exchange of data with other relevant systems e.g., product design.

The development of the automated and digitalized AM system followed the DesOps framework, was carried out by a group of 7 master's students from the University of Southern Denmark and resulted in a project report [39]. The project kicked off in January 2022.

The group specifically focused on phases 1 "OKRs", 2 "System Design", and 3 "Domain-specific Design" of the DesOps framework over the course of four months.

OKRs were established throughout two cycles, which were updated after the first and second months of the project. Table 5 provides an example of the OKRs for the first months.

During the System Design phase, a conceptual solution for automating and digitalizing the AM system was drafted (Fig. 4). The overall system consists of five relevant sub-systems: 1) Storage, 2) transportation, 3) 3D-Printing, 4) quality control, and 5) communication and infrastructure.

**Table 5** OKRs for the first month of the project, i.e., the first OKR cycle [39]

| **Key Objective for month 1 (first OKR cycle)** | **Key Results** |
|---|---|
| We have developed a conceptual model for the overall system architecture. | <u>Key result 1:</u> We have held 2 workshops investigating possible solutions based on requirements and functions.<br><u>Key result 2:</u> We have developed a conceptual model showing physical and virtual environments.<br><u>Key result 3:</u> We have developed a conceptual solution for the. The communication system between all assets and systems. |

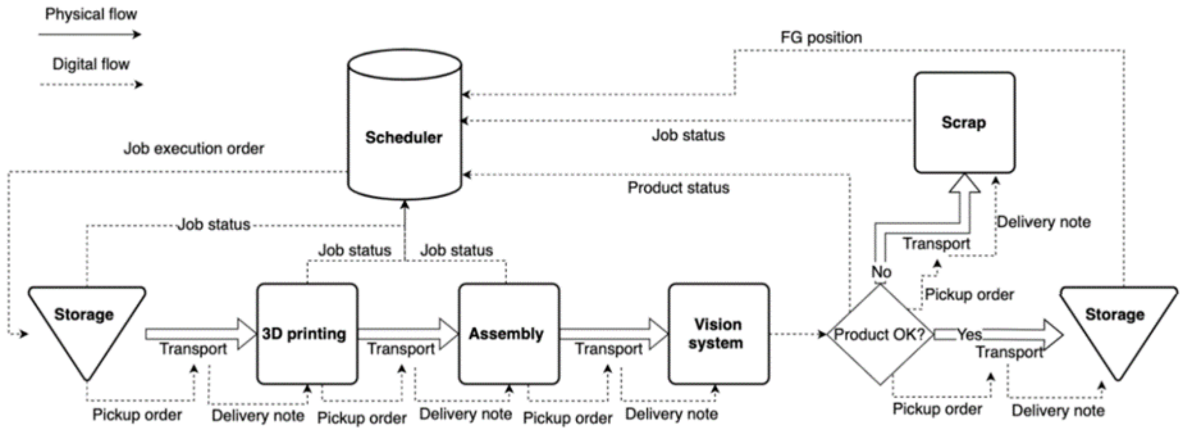


**Fig. 4** Conceptual solution for automating and digitalizing the AM system [39]

The storage sends a "pickup order" to the transport system which will then transport raw materials to the 3D printer. As soon as the 3D printer finished the printing process, it sends a "pickup order" to the transport system to pick up and transport the printed part to the assembly process. When the assembly is completed, another "pickup order" is initiated to transport the assembled product to a vision control process, from where the product is then either transported to the storage or scrap, depending on the result of the quality check. "Delivery notes" ensure the exchange of information between the transport system and the destination, e.g., the 3D printer or the vision system. The job statuses of all processes and the finished good (FG) are reported back to the scheduling system (scheduler) via wireless communication and infrastructure. For each of the sub-systems requirements and functions for both, the physical and virtual systems, are defined.

The functions and requirements create the basis for detailing the five sub-systems. Morphological analysis was used to match functions with concrete equipment. For example, an Autonomous Mobile Robot with an attached articulated robot and gripper, a so-called Enabled Robot, was selected for realizing the transport sub-system, which for example must fulfill the main functions of "pick and place objects" and "drive from requested initial location A to an end location B". The selection was made based on a utility analysis of alternative suitable equipment for fulfilling the functions.

Eventually, an assessment of the concept with the selected equipment was carried out. This assessment included the calculation of the total costs, the calculation of the potential customer lifetime value, and the creation of a Failure Modes and Effects Analysis. The total cost including planning, material, set-up, and installation is in sum of 2.301.000 DKK, while the customer lifetime value is calculated as 777.500 DKK.

## 5. Conclusion

### 5.1 Discussion and limitations

The authors believe that the case study can serve as initial verification and validation of the DesOps framework. The framework complies with its intended purpose of designing manufacturing systems while demonstrating a basic efficacy for designing relevant design artifacts. Especially, the OKRs as the project management layer for facilitating teamwork during the actual DesOps phases seem to be a promising approach for continuously integrating and updating relevant objectives and results according to the project progress and new learnings. OKRs provide a simple yet powerful method to realize efficacious management of the manufacturing systems design through an agile work cycle (Fig. 3) and defined rules and roles. Especially since the project management layer is an often-neglected aspect of design approaches. In the context of the OKRs, the case study is essentially addressing the aspect of integrating digitalization objectives.

However, since circularity was not a key objective for the case study, only limited conclusions can be drawn about the efficacy of designing circular manufacturing systems. The authors believe that circularity objectives can be integrated with similar effectiveness by using the OKR method. Further evaluation is needed for determining how the proposed DesOps framework compares to other manufacturing system design methodologies. Another aspect of the framework that might need a more careful evaluation is the "Ops" cycle since it was not part of the case study. DesOps originates in software development, but the integration (Phase 4) as well as the implementation and testing (Phase 5) of hardware systems is more time-consuming and costly and includes human resources. Thus, hardware and social systems usually cannot be developed in these highly frequent cycles of pivots and iteration compared to software systems. Finding the right moment for starting the implementation process seems to be a crucial aspect of development. Besides, stakeholder management and training, and skill building seem comparably important for the development of hardware systems.

The focus on circular value creation and the end-of-life phase of products as well as on the digitalization of value networks is today often not supported by prevailing business models of manufacturing companies. Thus, the design and operation of digital and circular manufacturing systems might be rather coined by new regulations than by voluntary commitments of companies or pressure from customers. Thus, policy makers will play a crucial role in facilitating this Twin Transition of the economy. Finding competitive business model innovations based on circularity and digitalization within the framework of the new regulations could be the future key to strengthening industrial competitiveness in Europe and companies who struggle in creating these business model innovations might fail on the long run. Business model innovations implemented through digital and circular manufacturing systems will also lead to increasing importance of cybersecurity and reverse supply chains and logistics for managing risks.

### 5.2 Summary and outlook

The research presented a conceptual DesOps framework for supporting the Twin Transition of manufacturing companies, i.e., for improving the level of digital and circular value creation. The procedures and methods underlying the framework were selected based on their proven contribution to operational excellence in companies. The DesOps framework covers nine phases, starting with the assessment of the initial level of digital and circular maturity. Subsequent phases focus on defining Objectives and Key Results (OKRs), on the relevant design (Des) and operation (Ops) phases, as well as on training the required competencies of stakeholders. The verification of the empirical efficacy of the presented framework is ongoing and carried out at SDU's Industry 4.0 laboratory.

Future research will first focus on verifying, validating, and evaluating the efficacy of the framework to support the development of circular and digital manufacturing systems. Secondly, suitable methods for integrating, implementing, and testing iterations of manufacturing systems will be the subject of future investigations.

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# Supply chain game analysis based on mean-variance and price risk aversion under different power structures

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**A B S T R A C T**

In view of the random retail price and retailer's preference for retail price risk aversion, we used mean-variance to describe the uncertainty risk of retail price. To study the impacts of both the retail price uncertainty risk and retail price risk aversion preference on supply chain (SC) decision-making, we constructed a SC game model based on three different power structures, including Manufacturer Stackelberg (MS) game, Retailer Stackelberg (RS) game, and Vertical Nash (VN) game. The results showed that the retail price uncertainty risk and the retailer's retail price risk aversion preference weakened the manufacturer's production effort input, decreased the retailer's enthusiasm for ordering, and damaged the interests of manufacturer and retailer. Under the three different power structures, the production effort input of the manufacturer depended on the production effort affecting wholesale price efficiency and retail price efficiency. The retailer's expected utility was largest under the MS game model and smallest under the VN game model. The manufacturer's profits were closely related to each parameter under the three respective power structures. This study provides theoretical guidance for the decision-making of SC enterprises with retail price risk and retailer with retail price risk aversion preference under different power structure situations.

**A R T I C L E  I N F O**

*Keywords:*
Supply chain game;
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## 1. Introduction

Product market prices are often affected by various factors, which means they are uncertain [1-2]. For example, the Russian-Ukrainian conflict has influenced higher prices for food, oil, and gas across the globe. Additionally, the US trade war has prompted price increases for domestic electronic products, clothing, and furniture. In 2013, the avian influenza A(H7N9) emerged in China, thus decreasing the price of poultry meat [3]. Given the continuous potential for life events such as these, we cannot accurately predict market prices. This seriously impacts decision makers when dealing with issues such as ordering, pricing, and production input. Faced with market price uncertainty risk, different decision makers may also exhibit different behavioral preference; for example, some will adopt risk neutral positions because they are not sensitive to market price uncertainty risk, while others will adopt risk averse positions for the opposite reason. In this context, it is of great practical and theoretical significance to study the SC decision-making problem based on market price uncertainty and market price risk aversion preference among decision makers.

At present, most studies on risk aversion preference have focused on solving decision-making and coordination problems in the SC, as follows:

(1) Decision-making problems under risk aversion preference. Liu *et al*. [4] analyzed how risk aversion affects pricing decisions in the context of competition and information asymmetry. Zhou *et al*. [5] considered optimal advertising investments and ordering decisions when the bilateral parties have risk aversion preference. Targeting cases of demand risk caused by uncertainty in customer valuation, Li and Qi [6] discussed optimal product pricing and quality decisions among risk-averse enterprises. Other scholars have focused on issues such as pricing decisions with consumers' channel preference [7], pricing decisions amid fairness concerns [8], the demand information sharing strategy [9], and retailer procurement and promotion strategies [10].

(2) Coordination problems under risk aversion preference. Adhikari *et al*. [11] studied the design of a five-level textile SC coordination mechanism when there are uncertain risks of supply and demand. Liu *et al*. [12] solved the coordination problem based on option contracts and different power structures. Fan *et al*. [13] analyzed the effectiveness of the option contract coordination between bilateral participants with risk-averse. Niu *et al*. [14] discussed the SC coordination of risk-averse consumers both with and without blockchain quality information. Other studies have examined issues such as the inherent law of the buyback contract coordinate SC in the context of asymmetric production cost information and a risk-averse retailer [15], and the SC channel coordination strategy when consumers have low carbon preference and retailer have risk aversion preference [16].

Most previous studies have analyzed the impact of risk aversion preference on decision-making and coordination in SC based on the risk aversion preference of either demand uncertainty, capacity uncertainty, or quality uncertainty [17]. However, none of these investigations examined situations involving participants with risk aversion preference for random market prices, nor did they consider the existence of different power structures between the SC participants. With reference to the existing literature and real life cases, we addressed this gap by further considering uncertainty risk pertaining to product retail prices, wherein the retailer adopts a risk aversion preference for random retail prices. Meanwhile, referring to literature [18], we used mean-variance to characterize the retail price uncertainty risk. To study how both the retail price uncertainty risk and retailer's retail price risk aversion preference impacted decision-making among SC participants, we considered three different power structures in our SC game model, including MS, RS, and VN. We also compared and analyzed the equilibrium decision, profit, and utility under these power structure models.

## 2. Problem description and assumptions

### 2.1 Problem description

We considered a two-echelon SC system consisting of a risk-neutral manufacturer $M$ and retailer $R$ with a retail price risk aversion preference. The manufacturer first organize production according to the retailer's order quantity $q$ and determine the input level of its production efforts $e$ (e.g., technological innovation [19], equipment upgrading and labor input). Based on the above, we analyzed both the manufacturer's production effort input and retailer's order quantity decision under three different power structures, including a VN game, RS game, and MS game. Given the results, we discuss how retail price uncertainty risk and the retailer's retail price risk aversion impact SC participants' decision-making and profit (utility), with a comparison of Nash equilibrium results under all three power structures.

### 2.2 Model assumptions

Assumption 1: The additional input of production efforts $e$ (e.g., technological innovation, equipment upgrading, and labor) will improve the quality of manufacturer' products to a certain extent, thus increasing the wholesale price $w$ of products. Therefore, the manufacturer's wholesale price

$w$ is positively correlated with the input level of production efforts $e$. The wholesale price function of the product is as follows:

$$w = w_0 + \lambda e \quad (1)$$

Here, $w_0$ is the wholesale price of the product without additional production efforts ($e = 0$) and $\lambda$ is the production effort efficiency that affects the wholesale price. The larger the value of $\lambda$, the more obvious the effect of unit additional production efforts on the increase of the wholesale price.

Assumption 2: The input of additional production efforts $e$ improves product quality, which will also increase the retail price $p$ of products to a certain extent. In reference to previous research [20-22], the retail price function is as follows:

$$p = 1 - q + \beta e + \xi \quad (2)$$

Here, $q$ is the retailer's order quantity, $\beta$ is the production effort efficiency that affects the retail price, $\xi$ is the random variable factor, $E(\xi) = 0$, and $Var(\xi) = \delta^2$ [22-23]. The larger the $\delta$, the greater the volatility of the retail price or greater the risk of uncertainty. The production effort cost is $C(e) = e^2$ [21].

Assumption 3: Because the uncertainty of product retail prices will induce uncertainty risk in retailer, they will adopt a risk aversion preference for random retail prices (retail price risk aversion preference).

Assumption 4: To simplify the model without affecting the conclusion, the manufacturer's unit product production cost is $c = 0$.

## 3. SC models under different power structures

### 3.1 VN game model

In the VN game model, manufacturer and retailer have equivalent power. All carry out non-cooperative games with the goal of maximizing their expected profit (utility). At this point, the profits of the risk-neutral manufacturer $\Pi_M^V(e)$ and retailer $\Pi_R^V(q)$ are respectively as follows:

$$\Pi_M^V(e) = (w_0 + \lambda e)q - e^2 \quad (3)$$

$$\Pi_R^V(q) = (1 - q + \beta e + \xi - w_0 - \lambda e)q \quad (4)$$

Referring to both Xie *et al.* and Chiu and Choi's construction method for expected utility function in the case of SC participants with demand risk aversion preference [24-25], we constructed the expected utility function of retailer with retail price risk aversion preference, expressed as follows:

$$U_R^V(q) = E[\Pi_R^V(q)] - \frac{1}{2}\eta Var[\Pi_R^V(q)] = (1 - q + \beta e + \xi - w_0 - \lambda e)q - \frac{1}{2}\eta q^2\delta^2 \quad (5)$$

Here, η is the retailer's retail price risk aversion coefficient. The larger the value of $\eta$, the greater the retailer's risk aversion to random retail prices.

The first-order partial derivatives of $\Pi_M^V$ and $U_R^V$ with respect to $e$ and $q$ are as follows:

$$\begin{cases} \dfrac{\partial \Pi_M^V}{\partial e} = \lambda q - 2e = 0 \\ \dfrac{\partial U_R^V}{\partial q} = 1 + \beta e - \lambda e - w_0 - 2q - \eta\delta^2 q = 0 \end{cases} \quad (6)$$

Because $\frac{\partial^2 \Pi_M^V}{\partial e^2} = -2 < 0$ and $\frac{\partial^2 U_R^V}{\partial q^2} = -2 - \eta\delta^2 < 0$, the simultaneous solution (6) can obtain the manufacturer's unique optimal production effort input level $e^{V*}$ and retailer's unique optimal order quantity $q^{V*}$, as follows:

$$\begin{cases} e^{V*} = \dfrac{\lambda(1-w_0)}{4+2\eta\delta^2-\lambda\beta+\lambda^2} \\ q^{V*} = \dfrac{2(1-w_0)}{4+2\eta\delta^2-\lambda\beta+\lambda^2} \end{cases} \tag{7}$$

Bringing $e^{V*}$ and $q^{V*}$ into Eqs. 3 and 5, respectively, the optimal profit of the manufacturer $\Pi_M^{V*}$ and optimal expected utility of the retailer $U_R^{V*}$ can be obtained as follows:

$$\begin{cases} \Pi_M^{V*} = \dfrac{(1-w_0)[\lambda^2+w_0(8+4\eta\delta^2-2\lambda\beta+\lambda^2)]}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} \\ U_R^{V*} = \dfrac{2(1-w_0)^2(2+\eta\delta^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} \end{cases} \tag{8}$$

The first-order partial derivatives of the optimal decision and profit (utility) of the manufacturer and retailer with respect to $\eta$ and $\delta$ are as follows:

$$\begin{cases} \dfrac{\partial e^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{V*}}{\partial \delta} = \dfrac{-2\lambda\delta^2(1-w_0)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} < 0 \\ \dfrac{\partial q^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial q^{V*}}{\partial \delta} = \dfrac{-4\delta^2(1-w_0)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} < 0 \\ \dfrac{\partial \Pi_M^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial \Pi_M^{V*}}{\partial \delta} = \dfrac{-4\delta^2(1-w_0)[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} \\ \qquad < \dfrac{-4w_0\delta^2(1-w_0)(4+2\eta\delta^2-\lambda\beta+\lambda^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} < 0 \\ \dfrac{\partial U_R^{V*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial U_R^{V*}}{\partial \delta} = \dfrac{-2\delta^2(1-w_0)^2(4+2\eta\delta^2+\lambda\beta-\lambda^2)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^3} < 0 \end{cases} \tag{9}$$

Proposition 1: $e^{V*}$, $q^{V*}$, $\Pi_M^{V*}$, and $U_R^{V*}$ are decreasing functions of $\eta$ and $\delta$.

In the VN game model, Proposition 1 shows that the manufacturer's profit and retailer's expected utility decrease with increases in the retail price uncertainty risk degree $\delta$ and retailer's retail price risk aversion degree $\eta$, thus reducing the manufacturer's production effort input and retailer's enthusiasm for ordering.

### 3.2 RS game model

In the RS game SC, the retailer is the leader and therefore has the priority to determine its order quantity $q$. The manufacturer then determines the input level of its production effort $e$ based on $q$.

Similar to the conditions described in Section 3.1, the expected utility function of risk-neutral manufacturer's profit $\Pi_M^R(e)$ and retail price risk-aversion preference retailer $U_R^R(q)$ can be expressed as follows:

$$\begin{cases} \Pi_M^R(e) = (w_0+\lambda e)q - e^2 \\ U_R^R(q) = (1-q+\beta e-w_0-\lambda e)q - \dfrac{1}{2}\eta q^2\delta^2 \end{cases} \tag{10}$$

From Eq. 6, the manufacturer's optimal production effort $e^{R*}$ satisfies $e^{R*} = \frac{\lambda q}{2}$. Substitute $e^{R*}$ into Eq. 10, as follows:

$$U_R^R(q) = \frac{q[2(1-w_0)-q(2+\eta\delta^2-\lambda\beta+\lambda^2)]}{2} \tag{11}$$

The first and second partial derivatives of $U_R^R$ with respect to $q$ are as follows:

$$\begin{cases} \dfrac{\partial U_R^R}{\partial q} = 1 - w_0 - q(2 + \eta\delta^2 - \lambda\beta + \lambda^2) = 0 \\ \dfrac{\partial^2 U_R^R}{\partial q^2} = -(2 + \eta\delta^2 - \lambda\beta + \lambda^2) \end{cases} \tag{12}$$

When $2 + \eta\delta^2 - \lambda\beta + \lambda^2 > 0$, then $\frac{\partial^2 U_R^R}{\partial q^2} < 0$. The solution to (12) can reveal the only optimal order quantity $q^{R*} = \frac{1-w_0}{2+\eta\delta^2-\lambda\beta+\lambda^2}$.

Substituting $q^{R*}$ into the above equation, we can obtain the retailer's optimal expected utility $U_R^{R*}$, manufacturer's optimal profit $\Pi_M^{R*}$, and production effort input $e^{R*}$, as follows:

$$\begin{cases} U_R^{R*} = \dfrac{(1 - w_0)^2}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)} \\ \Pi_M^{R*} = \dfrac{\left[(1 - w_0)[\lambda^2 + w_0(8 + 4\eta\delta^2 - 4\lambda\beta + 3\lambda^2)]\right]}{4(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^2} \\ e^{R*} = \dfrac{\lambda(1 - w_0)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)} \end{cases} \tag{13}$$

The first-order partial derivatives of $e^{R*}$, $q^{R*}$, $U_R^{R*}$, and $\Pi_M^{R*}$ with respect to $\eta$ and $\delta$ are as follows:

$$\begin{cases} \dfrac{\partial e^{R*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{R*}}{\partial \delta} = \dfrac{-\lambda\delta^2(1 - w_0)}{2(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial q^{R*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial q^{R*}}{\partial \delta} = \dfrac{-\delta^2(1 - w_0)}{(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial U_R^{R*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial U_R^{R*}}{\partial \delta} = \dfrac{-\delta^2(1 - w_0)^2}{2(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial \Pi_M^{R*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial \Pi_M^{R*}}{\partial \delta} = \dfrac{-\delta^2(1 - w_0)[\lambda^2 + w_0(4 + 2\eta\delta^2 - 2\lambda\beta + \lambda^2)]}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^3} \\ \qquad < \dfrac{-2w_0\delta^2(1 - w_0)(2 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^3} < 0 \end{cases} \tag{14}$$

Proposition 2: $e^{R*}$, $q^{R*}$, $U_R^{R*}$, and $\Pi_M^{R*}$ are all decreasing functions for $\eta$ and $\delta$.

In the RS game model, Proposition 2 shows that the degree of uncertainty risk of the retail price and the degree of risk aversion of the retailer's retail price will not only weaken the manufacturer's production effort input, but will also weaken the enthusiasm retailer has for placing orders. This arrangement simultaneously harms the interests of manufacturer and retailer.

### 3.3 MS game model

If the manufacturer is the Stackelberg game leader of the SC, then the order of the SC is: the manufacturer first determines the input level of its production efforts $e$, then the retailer determines its order quantity $q$ according to the manufacturer's decision. Similar to the conditions described in Section 3.1, the expected utility function of risk-neutral manufacturer's profit $\Pi_M^M(e)$ and retail price risk-aversion preference retailer $U_R^M(q)$ is expressed as follows:

$$\begin{cases} \Pi_M^M(e) = (w_0 + \lambda e)q - e^2 \\ U_R^M(q) = (1 - q + \beta e - w_0 - \lambda e)q - \dfrac{1}{2}\eta q^2\delta^2 \end{cases} \tag{15}$$

Because $\frac{\partial^2 U_R^M}{\partial q^2} = -2 - \eta\delta^2 < 0$, the solution to $\frac{\partial U_R^M}{\partial q} = 0$ can reveal the retailer's only optimal order quantity $q^{M*} = \frac{1-w_0+\beta e-\lambda e}{2+\eta\delta^2}$.

Substitute $q^{M*}$ into Eq. 15, as follows:

$$\Pi_M^M(e) = \frac{(w_0 + \lambda e)[1 - w_0 + e(\beta - \lambda)]}{2 + \eta\delta^2} - e^2 \tag{16}$$

The first and second partial derivatives of $\Pi_M^M$ with respect to $e$ are as follows:

$$\begin{cases} \dfrac{\partial \Pi_M^M}{\partial e} = \dfrac{w_0(\beta - 2\lambda) + \lambda - 2e(2 + \eta\delta^2 - \lambda\beta + \lambda^2)}{2 + \eta\delta^2} \\ \dfrac{\partial^2 \Pi_M^M}{\partial e^2} = \dfrac{-2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)}{2 + \eta\delta^2} \end{cases} \tag{17}$$

From Eq. 17, when $2 + \eta\delta^2 - \lambda\beta + \lambda^2 > 0$, we have $\frac{\partial^2 \Pi_M^M}{\partial e^2} < 0$. We then let $\frac{\partial \Pi_M^M}{\partial e} = 0$, such that the optimal production effort input of the manufacturer is $e^{M*} = \frac{w_0\beta + \lambda - 2\lambda w_0}{4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2}$.

Therefore, we can obtain the optimal profit of the manufacturer $\Pi_M^{M*}$, the optimal expected utility of the retailer $U_R^{M*}$, and the order quantity $q^{M*}$ as follows:

$$\begin{cases} \Pi_M^{M*} = \dfrac{\lambda^2 + w_0(8 + 4\eta\delta^2 - 2\lambda\beta) - {w_0}^2(8 + 4\eta\delta^2 - \beta^2)}{2(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)} \\ U_R^{M*} = \dfrac{[4 + 2\eta\delta^2 - \lambda\beta + \lambda^2 - w_0(4 + 2\eta\delta^2 - \beta^2 + \lambda\beta)]^2}{2(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)^2} \\ q^{M*} = \dfrac{4 + 2\eta\delta^2 - w_0(4 + 2\eta\delta^2 - \beta^2) - \beta\lambda(1 + w_0) + \lambda^2}{(2 + \eta\delta^2)(4 + 2\eta\delta^2 - 2\lambda\beta + 2\lambda^2)} \end{cases} \tag{18}$$

The first-order partial derivatives of $e^{M*}$, $q^{M*}$, $U_R^{M*}$, and $\Pi_M^{M*}$ with respect to $\eta$ and $\delta$ are as follows:

$$\begin{cases} \dfrac{\partial e^{M*}}{\partial \eta} = \dfrac{\delta}{2\eta}\dfrac{\partial e^{M*}}{\partial \delta} = \dfrac{-\delta^2(w_0\beta + \lambda - 2\lambda w_0)}{2(2 + \eta\delta^2 - \lambda\beta + \lambda^2)^2} < 0 \\ \dfrac{\partial q^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial q^{M*}}{\partial \delta} = \dfrac{\delta^2[2(1 - w_0)(2A_3 - \eta^2\delta^4) - A_1(2 + A_3 + 2\eta\delta^2)]}{2(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} \\ \quad < -\dfrac{\delta^2(\lambda - \beta)^2(4 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{2(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} < 0 \\ \dfrac{\partial U_R^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial U_R^{M*}}{\partial \delta} \\ = \dfrac{\delta^2[2\eta\delta^2(1 - w_0) - A_1]\{A_1(4 + A_3 + 3\eta\delta^2) + 2(1 - w_0)[A_3(4 + \eta\delta^2) - \eta^2\delta^4]\}}{8(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^3} \\ \quad < -\dfrac{\delta^2(\lambda - \beta)^4(6 + 3\eta\delta^2 - \lambda\beta + \lambda^2)}{8(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^3} < 0 \\ \dfrac{\partial \Pi_M^{M*}}{\partial \eta} = \dfrac{\delta}{\eta}\dfrac{\partial \Pi_M^{M*}}{\partial \delta} = \dfrac{\delta^2[4w_0(1 - w_0)(2A_3 - \eta^2\delta^4) - A_2(2 + A_3 + 2\eta\delta^2)]}{4(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} \\ \quad < -\dfrac{\delta^2(\lambda - \beta)^2(4 + 2\eta\delta^2 - \lambda\beta + \lambda^2)}{4(2 + \eta\delta^2)^2(A_3 + \eta\delta^2)^2} < 0 \end{cases} \tag{19}$$

Here, $A_1 = 4 - \lambda\beta(1 + w_0) + \lambda^2 - w_0(4 - \beta^2)$, $A_2 = \lambda^2 + w_0(8 - 2\beta\lambda) - {w_0}^2(8 - \beta^2)$, and $A_3 = 2 - \lambda\beta + \lambda^2$.

Proposition 3: $e^{M*}$, $q^{M*}$, $U_R^{M*}$, and $\Pi_M^{M*}$ are all decreasing functions pertaining to $\eta$ and $\delta$.

From Proposition 3, it can be concluded that both the degree of uncertainty risk of retail price $\delta$ and degree of risk aversion of the retailer's retail price $\eta$ will negatively impact the income of manufacturer and retailer in the MS game model. In turn, this will promote the manufacturer's production effort input and the retailer's order quantity reduction.

**Table 1** The effects of $\eta$ and $\delta$ on the manufacturer's production effort input and retailer's order quantity

| $\delta$ | $\eta$ | $e^{V*}$ | $e^{R*}$ | $e^{M*}$ | $q^{V*}$ | $q^{R*}$ | $q^{M*}$ |
|---|---|---|---|---|---|---|---|
| 0.2 | 0.2 | 0.232 | 0.347 | 0.496 | 0.464 | 0.694 | 0.596 |
| | 0.4 | 0.231 | 0.344 | 0.492 | 0.462 | 0.689 | 0.591 |
| | 0.8 | 0.228 | 0.339 | 0.484 | 0.457 | 0.678 | 0.583 |
| 0.4 | 0.2 | 0.228 | 0.339 | 0.484 | 0.457 | 0.678 | 0.583 |
| | 0.4 | 0.224 | 0.329 | 0.470 | 0.448 | 0.658 | 0.567 |
| | 0.8 | 0.215 | 0.310 | 0.443 | 0.430 | 0.621 | 0.537 |
| 0.8 | 0.2 | 0.215 | 0.310 | 0.443 | 0.430 | 0.621 | 0.537 |
| | 0.4 | 0.199 | 0.279 | 0.399 | 0.399 | 0.557 | 0.487 |
| | 0.8 | 0.174 | 0.231 | 0.331 | 0.348 | 0.463 | 0.410 |

**Table 2** The effects of $\eta$ and $\delta$ on the manufacturer's profit and retailer's expected utility

| $\delta$ | $\eta$ | $U_R^{V*}$ | $U_R^{R*}$ | $U_R^{M*}$ | $\Pi_M^{V*}$ | $\Pi_M^{R*}$ | $\Pi_M^{M*}$ |
|---|---|---|---|---|---|---|---|
| 0.2 | 0.2 | 0.216 | 0.243 | 0.356 | 0.193 | 0.329 | 0.228 |
| | 0.4 | 0.215 | 0.241 | 0.352 | 0.192 | 0.325 | 0.226 |
| | 0.8 | 0.212 | 0.237 | 0.345 | 0.189 | 0.319 | 0.223 |
| 0.4 | 0.2 | 0.212 | 0.237 | 0.345 | 0.189 | 0.319 | 0.223 |
| | 0.4 | 0.207 | 0.230 | 0.332 | 0.184 | 0.306 | 0.216 |
| | 0.8 | 0.197 | 0.217 | 0.307 | 0.175 | 0.282 | 0.203 |
| 0.8 | 0.2 | 0.197 | 0.217 | 0.307 | 0.175 | 0.282 | 0.203 |
| | 0.4 | 0.179 | 0.195 | 0.267 | 0.159 | 0.245 | 0.181 |
| | 0.8 | 0.152 | 0.162 | 0.211 | 0.135 | 0.192 | 0.149 |

To further validate our conclusions, we conducted an analysis using numerical examples. Without loss of generality, take the parameters $w_0 = 0.3$, $\lambda = 1.0$ and $\beta = 2.0$, which result in the arrangements shown in Tables 1 and 2.

## 4. Comparing the models

In the previous section, we explained how we solved the optimal decision, profit, and utility of SC participants under different power structure models. As described in this section, we then compared and analyzed the Nash equilibrium results in three cases.

$$\begin{cases} e^{R*} - e^{V*} = \dfrac{\lambda^2(1-w_0)(\beta-\lambda)}{2(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ e^{M*} - e^{R*} = \dfrac{w_0(\beta-\lambda)}{4+2\eta\delta^2-2\lambda\beta+2\lambda^2} \end{cases} \tag{20}$$

Proposition 4:

- If $\beta < \lambda$, then $e^{R*} < e^{V*} < e^{M*}$
- If $\beta > \lambda$, then $e^{V*} < e^{R*} < e^{M*}$

From Proposition 4, we can make two conclusions. If the efficiency of the production effort affecting wholesale price $\lambda$ is greater than that affecting retail price $\beta$, then the manufacturer's production effort input level is the largest under the VN game model, followed by the RS game model and MS game model. To the contrary, if $\lambda$ is less than $\beta$, then the manufacturer's production effort input level is the largest under the MS game model, followed by the RS game model and VN game model (Fig. 1).

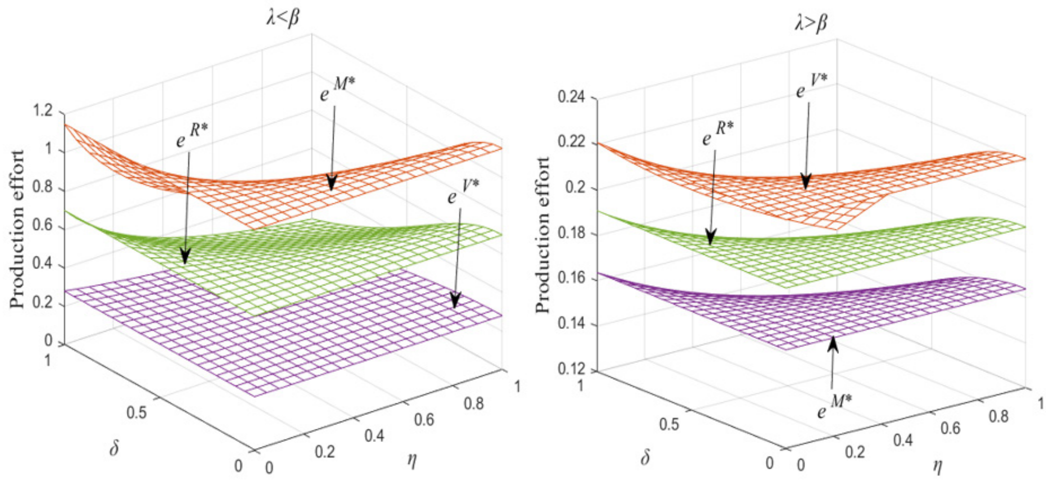


**Fig. 1** The effects of $\delta$ and $\eta$ on the manufacturer's production effort

$$\begin{cases} q^{R*} - q^{V*} = \dfrac{\lambda(1-w_0)(\beta-\lambda)}{(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ q^{M*} - q^{R*} = \dfrac{(w_0\beta-\lambda)(\beta-\lambda)}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)} \\ q^{M*} - q^{V*} = \dfrac{(\beta-\lambda)^2[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]}{2(2+\eta\delta^2)(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)} \\ \qquad > \dfrac{w_0(\beta-\lambda)^2}{2(2+\eta\delta^2)(2+\eta\delta^2-\lambda\beta+\lambda^2)} > 0 \end{cases} \tag{21}$$

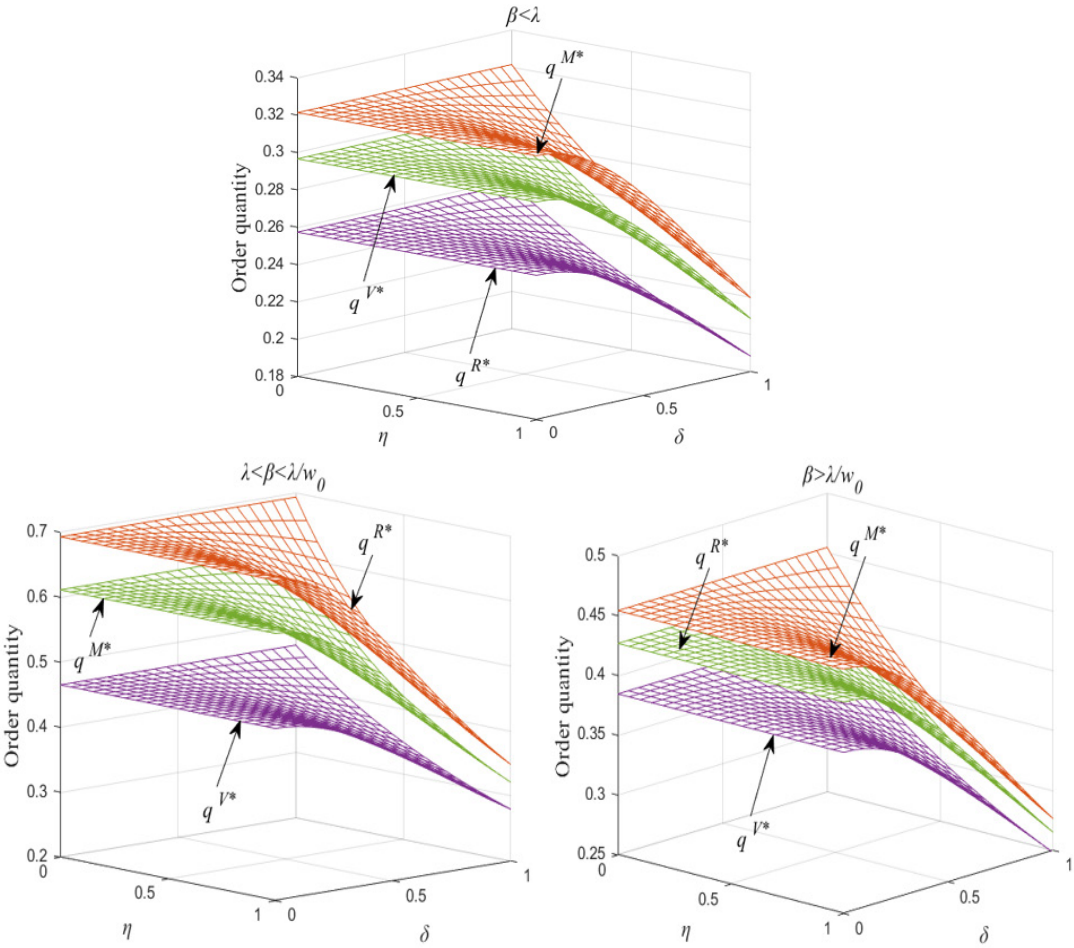


**Fig. 2** The effects of $\delta$ and $\eta$ on the retailer's order quantity

Proposition 5 is obtained through Eq. 21.

Proposition 5:

- If $\beta < \lambda$, then $q^{R*} < q^{V*} < q^{M*}$
- If $\lambda < \beta < \lambda/w_0$, then $q^{V*} < q^{M*} < q^{R*}$
- If $\beta > \lambda/w_0$, then $q^{V*} < q^{R*} < q^{M*}$

From Proposition 5, we can make three conclusions. If the efficiency of the production effort affecting retail price $\beta$ is small, then the retailer's order quantity is largest under the MS game model, followed by the VN game model and RS game model. If $\beta$ is medium, then the retailer's order quantity is largest under the RS game model, followed by the MS game model and VN game model. If $\beta$ is relatively large, then the retailer's order quantity is largest under the MS game model, followed by the RS game model and VN game model (Fig. 2).

$$\begin{cases} U_R^{R*} - U_R^{V*} = \dfrac{\lambda^2(1-w_0)^2(\beta-\lambda)^2}{2(2+\eta\delta^2-\lambda\beta+\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} > 0 \\ U_R^{M*} - U_R^{R*} = \dfrac{[\lambda^2+w_0(8+4\eta\delta^2-2\lambda\beta)] - {w_0}^2(8+4\eta\delta^2-\beta^2)(\beta-\lambda)^2}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)^2} > 0 \end{cases} \tag{22}$$

Proposition 6: $U_R^{M*} > U_R^{R*} > U_R^{V*}$.

According to Proposition 6, the retailer always obtains the maximum expected utility under the MS game model, but obtains the minimum expected utility under the VN game model (Fig. 3).

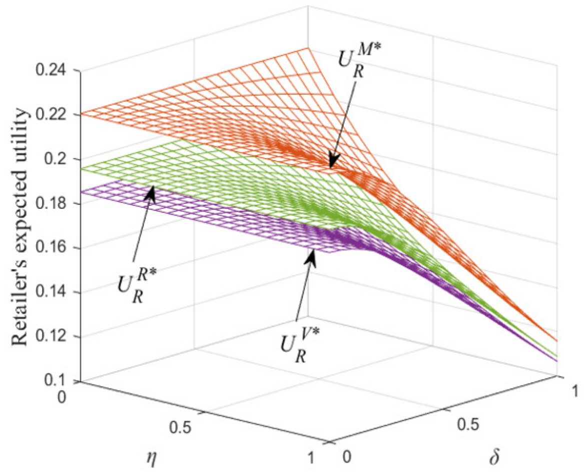


**Fig. 3** The effects of $\delta$ and $\eta$ on the retailer's expected utility

$$\begin{cases} \Pi_M^{M*} - \Pi_M^{V*} = \dfrac{(\beta-\lambda)^2[\lambda^2+w_0(4+2\eta\delta^2-\lambda\beta)]^2}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2} > 0 \\ \Pi_M^{M*} - \Pi_M^{R*} = \dfrac{H_1(\beta,\lambda,w_0,\eta,\delta)}{2(2+\eta\delta^2)(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)} \\ \Pi_M^{R*} - \Pi_M^{V*} = \dfrac{\lambda(1-w_0)H_2(\beta,\lambda,w_0,\eta,\delta)}{(4+2\eta\delta^2-\lambda\beta+\lambda^2)^2(4+2\eta\delta^2-2\lambda\beta+2\lambda^2)^2} \end{cases} \tag{23}$$

$$\begin{cases} H_1(\beta,\lambda,w_0,\eta,\delta) = (\beta-\lambda)\{\beta {w_0}^2(2+\eta\delta^2) - \lambda w_0[4-2w_0 \\ +w_0\beta^2+\eta\delta^2(2-w_0)] + 2\beta\lambda^2 w_0 - \lambda^3\} \\ H_2(\beta,\lambda,w_0,\eta,\delta) = (\beta-\lambda)\{8w_0(2+\eta\delta^2)^2 - 12\beta\lambda w_0(2+\eta\delta^2) \\ +4\lambda^2[2+\eta\delta^2+w_0(4+2\eta\delta^2+\beta^2)] - \beta\lambda^3(3+5w_0) + \lambda^4(3+w_0)\} \end{cases} \tag{24}$$

Proposition 7:

- If $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then $\Pi_M^{M*} > \Pi_M^{V*} > \Pi_M^{R*}$

- If $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then $\Pi_M^{M*} > \Pi_M^{R*} > \Pi_M^{V*}$
- If $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then $\Pi_M^{R*} > \Pi_M^{M*} > \Pi_M^{V*}$
- If $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then there is no solution

Proposition 7 shows a complex situation for manufacturer's profit under the three power structures, depending on parameters $(\beta,\lambda,w_0,\eta,\delta)$. If the parameters satisfy $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$, then the manufacturer obtains maximum profit under the MS game model, followed by the VN game model and RS game model. If the parameters satisfy $H_1(\beta,\lambda,w_0,\eta,\delta) > 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then the manufacturer also obtains maximum profit under the MS game model, this time followed by the RS game model and VN game model. If each parameter satisfies $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) > 0$, then the manufacturer obtains maximum profit under the RS game model, followed by the MS game model and VN game model. However, the case of $H_1(\beta,\lambda,w_0,\eta,\delta) < 0$ and $H_2(\beta,\lambda,w_0,\eta,\delta) < 0$ does not exist. Fig. 4 illustrates these arrangements.

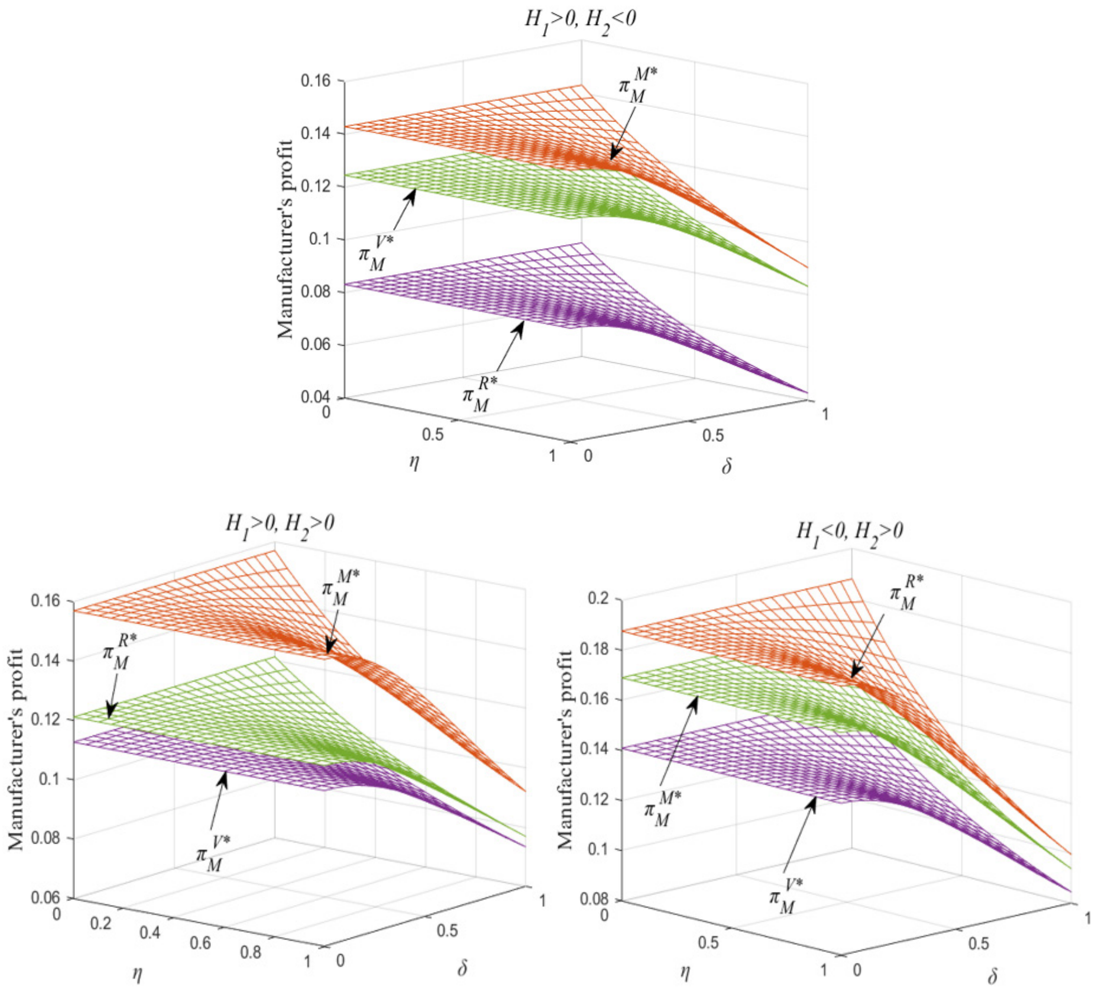


**Fig. 4** The effects of $\delta$ and $\eta$ on the manufacturer's profit

## 5. Conclusion

In a two-level SC consisting of a single manufacturer and single retailer, the product retail price is considered uncertain and affected by the manufacturer's production efforts. In this study, we used the mean-variance method to describe the uncertainty of retail prices, with a consideration of retail price risk aversion preference. Based on three different power structures, including a MS game, RS game, and VN game, we examined how the degree of both retail price uncertainty risk and retail price risk aversion impacted decision-making, profit, and utility among SC participants.

We then compared and analyzed optimal decisions, profits, and utility between these power structure models. In sum, we draw the following five conclusions:

- The uncertainty risk $\delta$ of the retail price and the retailer's retail price risk aversion $\eta$ will not only reduce the manufacturer's production effort input and retailer's enthusiasm for ordering, but will also adversely affect the manufacturer's profit and retailer's expected utility.
- If the efficiency of the production effort affecting the wholesale price $\lambda$ is less than the efficiency of the production effort affecting the retail price $\beta$(that is, $\lambda < \beta$), then the manufacturer's production effort input $e^{M*}$ is largest under the MS game model, while the production effort input is smallest under the VN game model(that is, $e^{V*} < e^{R*} < e^{M*}$) . In the reverse arrangement $\lambda > \beta$, the conclusion is completely opposite, (that is, $e^{M*} < e^{R*} < e^{V*}$).
- If the efficiency $\beta$ of the production effort affecting the retail price is small (that is $\lambda > \beta$), then the retailer's order quantity is largest under the MS game model and smallest under the RS game model (that is, $q^{R*} < q^{V*} < q^{M*}$). If the $\beta$ in general (that is, $\lambda < \beta < \lambda/w_0$), then the retailer's order quantity is largest under the MS game model and smallest under the VN game model (that is, $q^{V*} < q^{M*} < q^{R*}$). If the $\beta$ is large (that is, $\beta > \lambda/w_0$), then the retailer's order quantity is largest under the MS game model and smallest under the VN game model (that is, $q^{V*} < q^{R*} < q^{M*}$).
- The retailer always obtains the maximum expected utility under the MS game model, but obtains the minimum expected utility under the VN game model (that is, $U_R^{M*} > U_R^{R*} > U_R^{V*}$).
- Under the three power structure models, optimal manufacturer profits depend on the parameter $(\beta, \lambda, w_0, \eta, \delta)$.

This paper solves how the SC enterprises should make the most favorable decisions for themselves when there are retail price risk and the retailer has retail price risk aversion preference under different power structure situations, so as to provide theoretical guidance for enterprises to make decisions. In the future, we can continue to consider the presence of multiple manufacturers, multiple retailers and multi-supply chains.

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# A NSGA-II based approach for multi-objective optimization of a reconfigurable manufacturing transfer line supported by Digital Twin: A case study

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**ABSTRACT**

In response to the wide range of customer demands, the concept of reconfigurable manufacturing systems (RMS) was introduced in the industrial sector. RMS enables producers to meet varying volumes of demand over varying time periods by swiftly adjusting its production capacity and functionality within a part family in response to abrupt market changes. In these circumstances, RMS are made to swiftly reconfigure their Reconfigurable Machine Tools (RMTs). RMTs are designed to have a variety of configurations that may be conditionally chosen and reconfigured in accordance with specific performance goals. However, the reconfiguration process is not an easy process, which entails optimization of several objectives and many of which are inherently conflictual. As a result, it necessitates real-time monitoring of the RMS's condition, which may be achieved by digital twinning, or the real-time capture of system data. The concept of using a digital replica of a physical system to provide real-time optimization is known as digital twin. This work considered a case study of discrete parts manufacturing on a reconfigurable single manufacturing transfer line (SMTL). Six manufacturing operations are required to be performed on the parts at six production stages. This work uses the Digital Twin (DT) based approach to assist a discrete multi-objective optimization problem for a reconfigurable manufacturing transfer line. This multi-objective optimization problem consists of four objective functions which is illustrated by using DT-based Non-dominated Sorting Genetic Algorithm-II (NSGA-II). The innovative aspect of the current study is the use of a DT-based framework for RMS reconfiguration to produce the best optimum solutions. The produced real-time solutions will be of great assistance to the decision maker in selecting the appropriate real-time optimal solutions for reconfigurable manufacturing transfer lines.

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## 1. Introduction

Manufacturing has ushered in the digital era thanks to developments in data-acquisition systems, information technology (IT), and network technologies. With the fast progress of digital technology, the industrial sector is confronting global issues against a backdrop of digitalization. In the present-day production environment, sophisticated manufacturing initiatives have been launched, including Industry 4.0, Industrial Internet of Things (IIoT), etc. Achieving smart manufacturing, usually referred to as intelligent manufacturing, which is the unifying goal of these initiatives [1]. Since the 1980s, intelligent manufacturing has been used to describe the nexus of manufacturing and artificial intelligence (AI) [2] . Nowadays, knowledge-based intelligent manufacturing is being replaced by data-driven and knowledge-enabled smart manufacturing, where "smart" refers to the collection and usage of data [2]. Moreover, with the evolution of AI, Internet of Things (IoT), the Digital twins (DTs) and Reconfigurable manufacturing systems (RMS) are considered among the smart technologies that are adopting a vital role in the new generation manufacturing [2], [3].

### 1.1 Reconfigurable manufacturing systems

An emerging area in the era of Industry 4.0 is Reconfigurable Manufacturing Systems (RMS). Past two decade ago, this new paradigm of manufacturing systems has emerged in order to cope with circumstances where the capacity and productivity of the system must respond to fluctuation [4]. RMS offer customized flexibility through scalability and reconfiguration as needed in order to meet customer demand [5]. An RMS is built from the ground up to accommodate quick structural, software, and hardware changes in order to quickly adjust production capacity and functionality [4].

An RMS is designed around a part family and manufactures all the variants of the part family. The system require reconfiguration when switching from one part family to another, which is a labour and financially-intensive operation. The difficulty and expense of changing configurations relies on the original configuration already in place and the new configuration needed to produce orders in the future that belong to a different part family [6]. Hence, RMS is a component of industry 4.0 which is based upon digitization [7] where all parts of an industry are connected and have real-time communication capabilities. Digital Twin (DT) is one such technology that emerged as a tool for achieving intelligent production through RMS [8].

### 1.2 Digital Twin

Digital Twin (DT) is considered as a new data-driven vision that brings together real-time data analytics, optimization, and simulation. DT is composed of two major components (physical and virtual), with real-time data transfer between them, i.e., each system consists of two parts, a physical part and a virtual one that contains all of the information about the physical part [8]. DT analyzes, and evaluates the massive quantity of data gathered (in real-time/offline mode), resulting in improved system transparency [18]. As a result, a wide range of information may be gathered and used for a variety of purposes, including tracking system condition, generating predictions, diagnosing, simulating, and optimizing the system [9].

### 1.3 Digital twinning of RMS

Reconfigurable machine tools (RMTs) are an integral part of RMS. These RMTs are required to be reconfigured from time to time as per the system requirements. The reconfiguration of RMTs can be done by keeping the basic modules of RMTs as it is and adding/replacing/rearranging the auxiliary modules according to the system needs. However, the reconfiguration of RMTs is a complex process which requires a lot of technical support from the technology like Digital Twin (DT). By simulating the reconfiguration on a virtual environment, DT enables the solution of the challenging RMT reconfiguration issues [20]. As a result, this work suggests the idea of the DT-based selection of RMTs and its respective configurations for RMS.

A digital twin of an RMT consists of both its physical and virtual counterparts as well as continuous data transfer between them. The virtual RMT is updated with the most recent states of the physical RMT thanks to the data flow from the physical RMT to the virtual RMT, which keeps the virtual RMT in a high-fidelity condition. Hence, the virtual RMT may be used to check on the functionality of the actual RMT [10].

Moreover, a DT is composed up of four layers, which correspond to data collecting, data transmission, data aggregation, and decision-making. This is based on the DT's anticipated functionality. The third and fourth layers of a DT focuses areas pertaining to reconfiguration process in RMS. The DT models must be changing in real-time while executing concurrently with the reconfiguration process.

Since, Digital Twinning of RMS involve gathering a range of information and using it for a variety of purposes like for simulating and optimizing the system [11]. This work presented a framework that addresses the fourth layer of DT that involve simulation of a multi-objective optimal configuration selection problem for a Single Manufacturing Transfer Line (SMTL). The problem has been illustrated by using non-dominated sorting Genetic algorithm (NSGA-II). In a SMTL, a family of raw materials enters the production line at one end, it undergoes various number of operations which are generally being performed at various stages and finally leaves the production line at the other end after finished product. At each stage, a reconfigurable manufacturing tool with different changeable RMT configurations having capability to perform variety of operations has been switched over. When one product family type gets finished, the RMT configurations at the stages are changed (if needed) for processing/manufacturing another product family [12]. A Multi-objective optimization problem (MOOP) based on best optimal configuration selection of machines in a SMTL is considered which comprises four conflicting parameters, i.e., one parameter (cost) that should be minimised and three other parameters (reconfiguration factor, process feasibility, and reliability) which should be maximised simultaneously till optimized level.

## 2. Literature review

### 2.1 Beginning and advacements in Digital Twins

As defined in [13], "A Digital twin can be defined as a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making". In 2003 lecture, Michael Grieves coined the word "Digital Twin" for the first time [14]. Due to the constraints and initial stages of the technology at the time, there was essentially no pertinent research or applications [14]. The development of DTs is currently made possible by new IT advancements. Product design [15], manufacturing [16], manufacturing line design [17], prognosis [18], health management, retail and water supply [16] are just a few of the recent uses of DTs in a variety of sectors. Several significant companies, including General Electric, Siemens, etc. adopt DT industrial methods to boost their product performance. This viewpoint reveals how widespread DT's technical uses are. DT is hence comparable to an engineering category as compared to CPS. In this context, Tao *et al*. [19] suggested a method for product design and manufacturing driven by DT, the application methods and frameworks were investigated and case studies were illustrated for future applications of DT. Qi *et al*. [20] found that through integration of the physical and digital worlds in production, DT offers a potential chance to adopt smart manufacturing and industrial 4.0. A DT of a cutting tool was provided by Botkina *et al*. [21], they discussed the data format and structure, information flows, and data management of the digital version of a physical tool as well as potential future applications and productivity analyses. A decision support system for the order management process in manufacturing systems was studied by Kunath & Winkler [22] based on the DT-based conceptual framework and prospective applications. Durão *et al.* [23] conducted a study aiming to address two research inquiries, i.e., what are the main criteria involved in creating a DT, and how does the industry comprehend the concept of DT? Their work provided an explanation and evaluation of the requirements for DT. Luo *et al*. [24] described a modelling method of DT for CNC machine tools and provided a demonstration of DT application scenarios in CNC machine tool era. Another similar work presented types of data and technology required to build the DT of each stage for an injection moulding industry and how to integrate these DT models [25]. Twin [26] discussed a DT demonstrator method involving the design and implementation for privacy enhancement mechanisms in the automotive industry.

### 2.2 Integration of Digital Twin with RMS

In this context, a method for designing and simulating an RMS by employing the DT technique was proposed [27]. Another RMS-DT based modular structure [9] was reported to predict the condition of a system at any given time while enabling comprehensive system visibility to enhance performance and allowing flexible decision-making. Tang *et al*. [28] introduced the DT-RMS idea, which allowed for high levels of transparency about data, performance, and pertinent reconfiguration decisions by creating a dynamic cyber-replica of the physical production environment. A DT based analytical model for performance evaluation of manufacturing system integrating evaluation of joint parameter fluctuations was introduced that focused in particular on the advantages of an integrated system model that may provide tactical decision makers [29]. The functionality of a simulation program with a DT simulation program was compared by some academicians [30] for incorporation of DT into RMS. Two simulation models were compared by using the Plant simulation 11 for a normal simulation model and Visual components for a DT model. The idea of a creating DT of an RMT was presented to carry out reconfiguration experiments on a high-fidelity virtual RMT in order to tackle complicated reconfiguration challenges. Three components for the RMT-DT were explored, considering the design processes of RMT during reconfiguration. Another idea [10] of Digital twinning of an RMT was presented for carrying out reconfiguration experiments on a high-fidelity virtual RMT in order to address complicated reconfiguration challenges.

### 2.3 Optimal configuration selection in RMS

One of the emerging area in the era of Industry 4.0 is RMS which offers customized flexibility through reconfiguration and scalability as needed in order to meet consumer needs [5]. When switching from one part family to another, the system may need to be reconfigured, which is a labour and money-intensive procedure. The difficulty and expense of changing configurations relies on the original configuration already in place and the new configuration needed to produce orders in the future that belong to a different part family [6]. For producing multiple part families, RMS optimal configurations at production stages must be identified. In relation to that Hasan *et al.* [6] determined the best optimal configuration of an RMS required by multiple part family orders.

### 2.4 Multi-objective optimization

In the present days, several kinds of Multi-objective optimization problems (MOOP) are correlated with manufacturing systems [31]. These problems are often solved by using a range of evolutionary algorithms. In this relation, Yu *et al.* developed a tailored instruction method in combination with the notion of non-dominated sorting [32]. In a discrete MOOP, Ashraf *et al.* considered the multiple conflicting objectives for RMT configuration rearrangement [12]. Dou *et al.* [33] suggested the multi-objective particle swarm optimization (MoPSO) technique for RMS's integrated configuration design and scheduling. Liu *et al.* [34] investigated a multi-module RMS for multi-product manufacturing. A mixed-integer programming model was presented in order to minimise the total cost and minimise the cycle time simultaneously. This work compared the efficiency of the proposed algorithm with a classic NSGA. Xu *et al.* [35] developed NSGA-III algorithm to address the multi-objective model and reported that the designed multi-objective model successfully decreases system downtime. Another work [36] optimized multiple objectives in the estimation of heat transfer coefficients while numerically simulating the quenching process of cylindrical steel samples. The proposed approach reported that it outperformed the results of existing works in terms of faster convergence time. Umer *et al.* [37] investigated four parameters with three levels of machining performance variables while machining Aluminium based composites, the utilization of the NSGA-II enabled the achievement of multi-response optimization objectives. Amjad *et al.* [38] proposed a four-layered genetic algorithm (GA) for a flexible job shop scheduling problem, while Xu *et al.* [39] investigated a scheduling problem in manufacturing by applying standard GA.

From the above literature review, it can be concluded that several continuous MOOPs has been solved by using NSGA-II. However, no research addressed the DT-based application of NSGA-II for a discrete kind of optimal configuration selection problem for RMS.

## 3. Problem formulation

### 3.1 Evolutionary multi-objective optimization

Many real-life problems comprise multiple performance parameters, or objectives, which should be optimized simultaneously. These performance parameters are termed as objective functions. Such kind of optimization problems which consist of multiple objective functions are called as Multi-Objective Optimization Problems (MOOPs). A MOOP comprises simultaneous optimization of certain objective functions which have to be maximized or minimized. It may enclose several constraints which any viable solution (i.e., all optimal solutions) need to satisfy. Since all the objectives can either be maximized or minimized, thus, the MOOP can be represented in its generalised form as defined in Eqs. 7 and 8. The MOOPs become more challenging when the objectives are conflicting in nature [40], i.e., the objectives are generally contradictory in nature, preventing optimization of each objective concurrently and most of the real engineering problems actually do have conflicting multiple-objectives which are unified into one objective [41].

### 3.2 Revised Non-Dominanted Sorting Genetic Algorithm

Revised Non-dominated Sorting Genetic Algorithm (NSGA-II) is found an effective tool for solving MOOPs. It is reported that when compared to other evolution techniques, NSGA-II is found to have significantly greater distribution of solutions and superior convergence near Pareto-optimal front [4]. A key aspect of NSGA-II is that the best members are chosen from a pool of parent and offspring solutions (produced by parent crossover and mutation) and are further used as the parents of the subsequent generation. It maintains elitism, which limits the variety of the solutions and retain the ones having greater fitness over the generations together with the other solutions, while the solutions with lower fitness are swept away with the passing of generations. The best solutions are produced in the first pareto-front, that is how NSGA-II implements the idea of choosing non-dominated solutions.

### 3.3 DT-based MOOP in RMS

This work considered a case study of discrete parts (see Fig. 1 in Section 6) manufacturing on a reconfigurable single manufacturing transfer line (SMTL). Six manufacturing operations, i.e., Milling, Grinding, Drilling, Boring, Surface finishing, and Assembly are required to be performed on the parts at six production stages, S-I, S-II,….,S-VI.

It involves four performance parameters, i.e., operating cost, reconfiguration factor, process feasibility factor and reliability factor in a SMTL that involve discrete MOOP for developing a decisive criterion in selecting machine tool and its corresponding configuration. For a SMTL, the assignment of machine and its configuration on the stages is carried out based on the four aforementioned objectives by applying NSGA II, the notations used in the problem definition are presented in Tables 1-4.

**Table 1** General notations for SMTL modelling

| | |
|---|---|
| $M_t$ | Cluster of all machine tools engaged in a SMTL. |
| $M_c$ | Cluster of all machine tool configurations engaged in a SMTL $\|\forall M_c \in M_t$. |
| $P_c$ | Cluster of processes required to be performed on the parts. |
| $MC_p$ | Cluster of feasible alternative RMT configurations essential to execute $p_{th}$ operation $\|\forall p \in P_c$. |
| $MC_m^c$ | A specific machine tool $m$ in its $c^{th}$configuration $\| \; \forall \; m \in M_t$ and $\forall \; c \in M_c$ |
| $MC_i^j$ | A possible alternative configuration of an $i^{th}$ machine in its $j^{th}$ configuration |
| $J_i$ | Maximum possible number of configurations of a machine tool $MC_i \mid \forall MC_i \in M_t$. |
| $D_r$ | Demand rate (parts/hr) |
| $s$ | Production stage of a reconfigurable Serial product transfer line $\|1 \leq s \leq S$. |
| $\psi$ | Power index for Process feasibility |
| $N_i^j$ | Number of machine tools required to meet the demand when a specific machine tool in its configuration $MC_i^j$is selected $\| \; \forall \; i \in M_t$ and $\forall j \in M_c$. |
| $CM_i^j$ | Cost of a specific machine tool in its configuration $MC_i^j \| \; \forall \; i \in M_t \; and \; \forall j \in M_c$ |
| $P_i^{j_o}$ | Capacity (parts/hour) of $i^{th}$machine with its $j^{th}$configuration for performing the $o^{th}$operation $\| \; \forall \; o \in O, \; \forall \; i \in M_t \; and \; \forall \; j \in M_c$ |

**Table 2** Decision variables for SMTL modelling

| | |
|---|---|
| $CO_i^j$ | Cost of operating machine tool configuration $MC_i^j$ from the alternative feasible machine tools and its respective feasible configurations for the execution of a process at demand rate $D_r|\ \forall i \in M_t$ and $j \in M_c$ |
| $MR_i^j$ | Machine reconfiguration factor for allocating $MC_i^j$ from the alternative feasible machines with its respective feasible configurations for the execution of a process at a demand rate $D_r|\ \forall i \in M_t$ and $j \in M_c$. |
| $PF_i^j$ | Process feasibility of a RMT configuration for allocating $MC_i^j$ on SMTL from the alternative feasible machines with its configuration for the execution of a process at the demand rate $D_r|\ \forall i \in M_t$ and $j \in M_c$ |
| $RL$ | Reliability of the SMTL |
| $R_{i_s}^{j_s}$ | Reliability of allocating $MC_i^j$ on the $s^{th}$ stage from the alternative feasible machine tools with its respective feasible configurations for executing a process at a demand rate $D_r|\ \forall i \in M_t$ and $j \in M_c$. |

**Table 3** Notations for machine reconfiguration factor (MRF)

| | |
|---|---|
| $\gamma$ | Machine reconfiguration index |
| $\lambda$ | Weightage for the number of modules that need to be added while changing RMT configurations. |
| $\mu$ | Weightage for the number of modules that need to be eliminated while changing RMT configurations. |
| $\delta$ | Weightage for the number of modules that need to be readjusted while changing RMT configurations. |
| $A_i^j$ | Set of auxiliary modules needed in $i^{th}$ machine with its $j^{th}$ configuration $|\ \forall\ i \in M_t\ and\ \forall j \in M_c$. |
| $\Phi_{i,o}^j$ | $\begin{cases} 1, \text{if } o^{th} \text{operation can be performed selecting } i^{th} \text{ machine with its } j^{th} \text{ configuration} \mid \forall\ i \in M_t\ and\ \forall j \in M_c \\ 0, \text{otherwise} \end{cases}$ |
| $Y$ | Secondary modules set up in the $i^{th}$ existing feasible machine with its $j^{th}$ configuration |
| $Z$ | Secondary modules set up in the $i^{th}$ configured feasible machine with its $k^{th}$ configuration |

**Table 4** Optimization and ranking parameters

| | |
|---|---|
| $\mathrm{F}_1, \mathrm{F}_2, \mathrm{F}_3, \mathrm{F}_4$ | Objective functions |
| $f_i$ | The $i^{th}$ objective function which is to be minimized $|1 \leq i \leq I$. |
| $I$ | Maximum number of objective functions. |
| $g_j(x) \geq 0$ | Inequality constraint. |
| $x$ | Decision variable vector representing a feasible solution, i.e., satisfying the $J$ inequality constraints and $K$ equality constraints. |

## 4. Performance parameters

The allocation of a feasible machine and its optimal configuration on the production stages of SMTL for execution of a process is based upon four performance factors: (1) Operating cost, (2) Machine Reconfiguration factor (MRF) (3) Process feasibility of a RMT configuration, and (4) Reliability of the system. Here, the operating cost refers to operating cost of the RMT configuration which is an attribute that is to be minimised. The other three attributes, i.e., Process feasibility, Reconfiguration factor and Reliability are beneficial attributes which have to be maximised. The Process feasibility is the ability of a RMT configuration to perform certain number of processes, MRF represent the responsiveness of a machine and Reliability refers to the reliability of the SMTL.

In the previous works, no such all-inclusive work has been done considering these four performance parameters for searching an all-inclusive suitability of a possible alternative RMT configuration in a SMTL. In the succeeding section, four performance factors [4]are discussed for determining a comprehensive fitness of a possible alternative RMT configuration.

### 4.1 Operating cost

The operating cost of a feasible alternative RMT configuration for performing the $o^{th}$ process at a certain demand rate $D_r$ is evaluated from Eqs. 1 and 2:

$$CO_i^j = N_i^j \times CM_i^j \tag{1}$$

$$N_i^j = ceil(D_r/P_i^{jo}) \cdot \left[D_r/P_i^{jo}\right] \tag{2}$$

### 4.2 Machine reconfiguration factor

Machine Reconfiguration factor (MRF) indicates the feasibility of Reconfiguration of machine, that can be accomplished by adding, deleting, or readjusting the auxiliary modules in addition to maintaining the primary modules in the current configuration. In the present work, the number of modules to be included/discarded/rearranged are evaluated along with the total modules while changing machine from one of its configuration to other configuration say from $c_1$ to $c_2$. It also shows the auxiliary module set-Y which involve the secondary modules of machine $m$ in its $c_1$ configuration, i.e., $MC_m^{c_1}$ and auxiliary module set-Z consist of the auxiliary modules of machine $m$ in its $c_2$ configuration, i.e., $MC_m^{c_2}$. The machine $MC_m^{c_1}$ is reconfigured by eliminating unnecessary secondary modules from set-Y, adding modules from set-Z, and changing or keeping the shared auxiliary modules between set-Y and set-Z. Thus, the reconfiguration of RMTs is evaluated by using Eq. 3.

$$MR_i^j = \frac{[J_i - 1]^\gamma}{\left\{N_i^j \times \sum_{k=1,k\neq j}^{J_i} \left[\lambda \times \frac{\left|A_i^k - A_i^j\right|}{\left|A_i^j \cup A_i^k\right|} + \mu \times \frac{\left|A_i^j - A_i^k\right|}{\left|A_i^j \cup A_i^k\right|} + \delta \times \frac{\left|A_i^j \cap A_i^k\right|}{\left|A_i^j \cup A_i^k\right|}\right]\right\}} \tag{3}$$

### 4.3. Process feasibility

An $o^{th}$process is performed such that $\forall\ o \in O$, the Process feasibility of a viable alternative RMT configuration is formulated on the basis of variety of processes that can be executed by the machine in its existing configuration. Increase in number of processes performed by a machine, increases the process feasibility. Hence, the aim of this research is to maximise the process feasibility of an RMT. The process feasibility of a viable alternative RMT configuration to accomplish certain process with $\psi$ as power index, is determined by using Eq. 4.

$$PF_i^j = \left[\left(\sum_{o=1}^{O} \Phi_{i,o}^j\right) - 1\right]^\psi \tag{4}$$

### 4.4 Reliability

In a SMTL, at each stage a machine performs certain process which indicates, all the machines are linked in series. For the series linking of machines, reliability of the whole SMTL can be calculated by using Eq. 5.

$$RL = \prod_{s=1}^{S} R_{i_s}^{j_s} \tag{5}$$

## 5. Multi-objective optimization function

The multiple objective functions comprising four objective function for the present problem are defined in Eq. 6. The overall optimization problem is transformed into a minimization problem by multiplying the beneficial objective functions $F_2$, $F_3$, and $F_4$ with a negative sign.

$$\left.\begin{aligned}
&\text{Minimize, } F_1 = \sum_{s=I}^{S} CO_{i_s}^{j_s} \\
&\text{Maximize, } F_2 = \sum_{s=I}^{S} MR_{i_s}^{j_s} \Leftrightarrow \text{Minimize, } F_2 = -\sum_{s=I}^{S} MR_{i_s}^{j_s} \\
&\text{Maximize, } F_3 = \sum_{s=I}^{S} PF_{i_s}^{j_s} \Leftrightarrow \text{Minimize, } F_3 = -\sum_{s=I}^{S} PF_{i_s}^{j_s} \\
&\text{Maximize, } F_4 = \prod_{s=I}^{S} R_{i_s}^{j_s} \Leftrightarrow \text{Minimize, } F_4 = -\prod_{s=I}^{S} R_{i_s}^{j_s}
\end{aligned}\right\} \tag{6}$$

Since, the present work has considered the performance and optimization of four objectives as mentioned in Eq. 6 hence, the formulated problem is a multi-objective optimization problem (MOOP) with conflicting objectives, where Operating cost has to be minimized and other three objectives have to be maximized. For a MOOP, it is impossible to have a single particular solution which concurrently optimizes all objectives. Therefore, NSGA-II is used for finding the non-dominated solutions. Most of the MOOPs use concept of domination where two solutions are selected for comparison on the basis of whether one solution dominates other solution or not [12]. The common representation of a MOOP consists of a certain objectives and several equality and inequality constraints which are defined in Eqs. 7 and 8:

$$min( f_i(x)) = [f_1(x), f_2(x), \dots, f_n(x)], \tag{7}$$

$$\text{Subjected to:} \begin{Bmatrix} g_j(x) \geq 0 & , j = 1,2,\dots,m \\ h_k(x) = 0 & , k = 1,2,\dots,n \end{Bmatrix} \tag{8}$$

$x$ is the decision variable vector that satisfy $m$ inequality constraints and $h$ equality constraints representing a feasible solution, $f_i$ is the $i^{th}$ objective function to be minimized, and $n$ is the number of objective functions.

## 6. Selection of optimal RMT configurations in SMTL

A Serial Manufacturing Transfer Line (SMTL) following an operation sequence 2 → 5 → 7 → 15 → 8 → 16 is considered (Fig. 2). Raw materials are processed at various stages from one stage to the next stage performing variety of operations at the stages. A SMTL permits paralleling of identical machines where each process is consigned to a stage as per the precedence constraint of an operation sequence. After assigning an operation to each stage, a suitable machine type and its configuration to each stage is designated for performing that operation. Various sets of viable alternative RMT configurations $MC_p$ are logged at each stage, performing $o^{th}$operation at the corresponding stages. Each feasible alternative $MC_i^j$ has two characteristic parameters, i.e., machine number '$i$' and its configuration number '$j$' from the respective set of its RMT configurations $M_c$. Each configuration is built with some primary modules as well as secondary auxiliary modules. Generally, the basic modules within a machine remains same while the auxiliary modules are changed while switching from one RMT configuration to the other as presented in the Table 5. Each configuration has its configuration cost and its own capacity to perform variety of operations at prescribed capacity which is termed as the Process feasibility of a RMT configuration as well as Reliability that is being mentioned in Table 6 and Table 7, respectively.

Eq. 6 represents four performance parameters, taken into consideration for present work applied to a SMTL. The optimal RMT configuration assignment is tackled by NSGA-II, taking cost, reconfigurability, process feasibility and reliability as the objective functions of the MOOP.

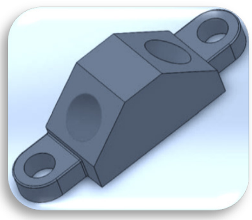

**Fig. 1** Finished product

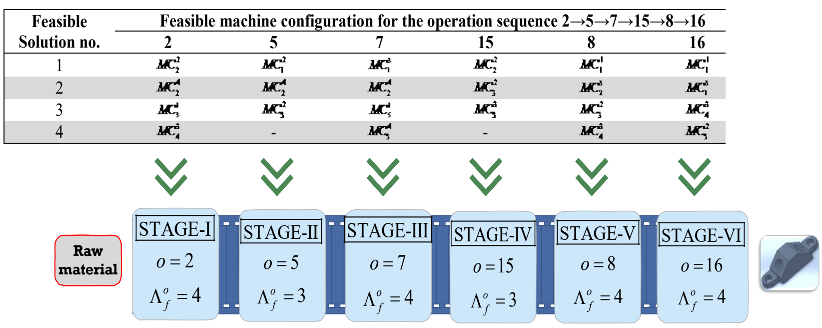


**Fig. 2** RMT configuration assignment to the stages in a SMTL

**Table 5** RMT configurations, process feasibility and cost of RMT configuration

| RMT | RMT configurations | Operations performed | Operation cost (in SAR (x103)) |
|---|---|---|---|
| M1 | $MC_1^1$ | {4,8,12,16} | 85 |
| | $MC_1^2$ | {5,18,9} | 132 |
| | $MC_1^3$ | {7,3,16} | 89 |
| | $MC_1^4$ | {19,10} | 145 |
| M2 | $MC_2^1$ | {12,1,6,20} | 133 |
| | $MC_2^2$ | {15,2,13} | 121 |
| | $MC_2^3$ | {3,17,8,11} | 200 |
| | $MC_2^4$ | {2,7,5,14} | 158 |
| | $MC_2^5$ | {4,18,13,20} | 175 |
| M3 | $MC_3^1$ | {2,12,9,17} | 140 |
| | $MC_3^2$ | {8,1,4,15,11,19,17} | 252 |
| M4 | $MC_4^1$ | {10,6,18} | 192 |
| | $MC_4^2$ | {17,1,20,12} | 202 |
| | $MC_4^3$ | {13,2,8,4,19,16} | 188 |
| M5 | $MC_5^1$ | {14,1,11,7,18} | 173 |
| | $MC_5^2$ | {5,3,17,20,10} | 153 |
| | $MC_5^3$ | {9,4,15} | 216 |
| | $MC_5^4$ | {14,1,7,6,19,16} | 180 |

**Table 6** Capacity (parts/h) RMT configurations for performing operations

| o | Capacity (in parts/h) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $MC_1^1$ | $MC_1^2$ | $MC_1^3$ | $MC_1^4$ | $MC_2^1$ | $MC_2^2$ | $MC_2^3$ | $MC_2^4$ | $MC_2^5$ | $MC_3^1$ | $MC_3^2$ | $MC_4^1$ | $MC_4^2$ | $MC_4^3$ | $MC_5^1$ | $MC_5^2$ | $MC_5^3$ | $MC_5^4$ |
| 1 | - | - | - | - | 20 | - | - | - | | - | 12 | - | 22 | - | 25 | - | - | 13 |
| 2 | - | - | - | - | - | 24 | - | 25 | - | 15 | - | - | - | 17 | - | - | - | - |
| 3 | | | 24 | | - | - | 17 | - | - | - | - | - | - | - | - | 14 | - | - |
| 4 | 18 | - | - | - | - | - | - | - | 16 | - | 19 | - | - | 21 | - | - | 17 | - |
| 5 | - | 20 | - | - | - | - | - | 19 | - | - | - | - | - | - | - | 25 | - | - |
| 6 | | | | | 16 | - | - | - | - | - | - | 16 | - | - | - | - | - | 27 |
| 7 | - | - | 18 | - | - | - | - | 20 | - | - | - | - | - | - | 18 | - | - | 12 |
| 8 | 16 | - | - | - | - | - | 28 | - | - | - | 29 | - | - | 24 | - | - | - | - |
| 9 | - | 12 | - | - | - | - | - | - | - | 23 | - | - | - | - | - | - | 10 | - |
| 10 | - | - | - | 18 | - | - | - | - | - | - | - | 18 | - | - | - | 22 | - | - |
| 11 | - | - | - | - | - | - | 21 | - | - | - | 22 | - | - | - | 16 | - | - | - |
| 12 | 10 | - | - | - | 22 | - | - | - | - | 18 | - | - | 24 | - | - | - | - | - |
| 13 | - | - | - | - | - | 19 | - | - | - | - | - | - | - | 16 | - | - | - | - |
| 14 | - | - | - | - | - | - | - | 16 | - | - | - | - | - | - | 10 | - | - | 18 |
| 15 | - | - | - | - | - | 20 | - | - | - | - | 17 | - | - | - | - | - | 14 | - |
| 16 | 15 | - | 22 | - | - | - | - | - | - | - | - | - | - | 26 | - | - | - | 21 |
| 17 | - | - | - | - | - | - | 30 | - | - | 20 | 24 | - | 19 | - | - | 19 | - | - |
| 18 | - | 20 | - | - | - | - | - | - | 14 | - | - | 22 | - | - | 28 | - | - | - |
| 19 | - | - | - | 23 | - | - | - | 23 | | - | 24 | 23 | - | - | - | - | - | 15 |
| 20 | - | - | - | - | 26 | - | - | - | 23 | - | - | - | 15 | - | - | 30 | - | - |

**Table 7** Reliability of RMT configuration for performing operations

| o | Reliability (× $10^{-2}$) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $MC_1^1$ | $MC_1^2$ | $MC_1^3$ | $MC_1^4$ | $MC_2^1$ | $MC_2^2$ | $MC_2^3$ | $MC_2^4$ | $MC_2^5$ | $MC_3^1$ | $MC_3^2$ | $MC_4^1$ | $MC_4^2$ | $MC_4^3$ | $MC_5^1$ | $MC_5^2$ | $MC_5^3$ | $MC_5^4$ |
| 1 | - | - | - | - | 97 | - | - | - | - | - | 91 | - | 94 | - | - | 94 | - | 95 |
| 2 | - | - | - | - | - | 95 | - | 75 | - | 98 | - | - | - | 97 | - | - | - | - |
| 3 | | | 80 | | - | - | 93 | - | - | - | - | - | - | - | - | 96 | - | - |
| 4 | 88 | - | - | - | - | - | - | - | 96 | - | 87 | - | - | 94 | - | - | 97 | - |
| 5 | - | 80 | - | - | - | - | - | 98 | - | - | - | - | - | - | - | 85 | - | - |
| 6 | - | - | - | - | 84 | - | - | - | - | - | - | 93 | - | - | - | - | - | 96 |
| 7 | - | - | 98 | - | - | - | - | 72 | - | - | - | - | - | - | 88 | - | - | 82 |
| 8 | 76 | - | - | - | - | - | 98 | - | - | - | 79 | - | - | 84 | - | - | - | - |
| 9 | - | 88 | - | - | - | - | - | - | - | 92 | - | - | - | - | - | - | 94 | - |
| 10 | - | - | - | 97 | - | - | - | - | - | - | - | 88 | - | - | - | 96 | - | - |
| 11 | - | - | - | - | - | - | 95 | - | - | - | 97 | - | - | - | 96 | - | - | - |
| 12 | 95 | - | - | - | 96 | - | - | - | - | 94 | - | - | 96 | - | - | - | - | - |
| 13 | - | - | - | - | - | 88 | - | - | - | - | - | - | - | 93 | - | - | - | - |
| 14 | - | - | - | - | - | - | - | 88 | - | - | - | - | - | - | 86 | - | - | 97 |
| 15 | - | - | - | - | - | 72 | - | - | - | - | 87 | - | - | - | - | - | 84 | - |
| 16 | 95 | - | 92 | - | - | - | - | - | - | - | - | - | - | 86 | - | - | - | 75 |
| 17 | - | - | - | - | - | - | 95 | - | - | 96 | 87 | - | 95 | - | - | 95 | - | - |
| 18 | 93 | - | - | - | - | - | - | - | 86 | - | - | 94 | - | - | 86 | - | - | - |
| 19 | - | - | - | 91 | - | - | - | 91 | - | - | 81 | 97 | - | - | - | - | - | 94 |
| 20 | - | - | - | - | 97 | - | - | - | 95 | - | - | - | 89 | - | - | 93 | - | - |

### 6.1 Machine feasibility

The Fig. 2 shows a SMTL where allocation of RMT configurations ($MC_i^j$) is to be done at several stages by chromosome encoding and decoding technique. A random gene value in the range [0.01 1.00] is assigned to each stage forming a set of gene values called as chromosome. Since, it has already been established that Real Encoded chromosome (REC) are superior to Binary Encoded chromosome (BEC) for optimization problems as established in previous works [42], therefore, REC along with NSGA II has been implemented in the present research for finding the non-dominated solutions of the proposed optimal machine allocation problem. The length of the chromosome is equal to the number production stages, and on each stage an $o^{th}$ operation has been performed following an operation precedence constraint. At each stage, the gene values are multiplied to the number of respective alternative feasible RMT configurations ($\Lambda_f^o$) and the rational number is rounded off to the higher digit because the RMT configuration can't be rational and thus it gives the suitable RMT configuration number from the set of alternative feasible RMT configurations ($\Lambda_f^o$) which can be traced from Fig. 2. Thus how, a chromosome representing various stages in a SMTL can be decoded into a solution vector of the assigned RMT configuration at various stages of the SMTL.

### 6.2 Problem illustration

In this case study, a reconfigurable SMTL having six manufacturing stages with six different variety of operations are performed at each stage thereby, requiring allocation of the suitable RMT configuration at each stage. Chromosomes having six random gene values in the range [0.01 1.00] is generated for each stage. Each gene value corresponds to a stage performing a specific operation. Based upon this procedure the feasible RMT configurations are allocated at each stage for performing the desired operation on the respective stages. In order to allocate feasible and best optimal RMT configuration for each stage, number of alternative RMT configurations are evaluated for each stage, following the defined operation sequence by fetching the necessary data from Fig. 2. Further, the gene values of respective stages are multiplied with their counterpart number of feasible alternative RMT configurations, the obtained value are rounded off to the higher digit which gives the feasible RMT configuration number at various stages in a SMTL. Then, the corresponding feasible RMT configurations are allocated for each stage.

The objective function values of operating cost ($CO_i^j$), MRF ($MR_i^j$), process feasibility ($PF_i^j$) and reliability (RL) are evaluated at each stage for the corresponding allocated RMT configurations by using Eqs. 1 to 5. Further, the obtained objective function values for all stages for a SMTL from S-I to S-VI are summed up and the MOOP criterion formulation is considered using Eq. 6.

## 7. Results and discussion

Following the process outlined in the previous sections, the DT-based MATLAB program using NSGA-II algorithm is run for 200 population size and 100 generation runs. The objective functions are sorted in a non-dominated manner to provide optimal solutions using the MOOP criteria specified in Eq. 6. Out of the large number of non-dominated solutions presented in Fig. 3(a)-(f), only few alternative solutions have been presented in Table 8 for different manufacturing scenarios. These solutions may aid production planners in crucial decision-making tasks by assisting in RMT configuration selection strategy through selecting the best suitable optimal solutions. However, the selection of only one optimal solution out of the 12 alternative solutions for each production stage can be made by the enterprise management as per the facility requirements and the constraints. The results presented in Table 8 depicts 12 alternative non-dominated solutions which represents the viable RMT configurations allocated to RMS manufacturing stages from stage S-I to S-VI. Moreover, the corresponding objective functions values are evaluated based on the MOOP criterion using the DT-based NSGA-II algorithm.

The Viable RMT configurations required to be allocated to manufacturing stages can be understood in this way, i.e., the first digit signifies the RMT number and another digit represent its respective feasible RMT configuration. Furthermore, the best optimal objective function values that have been evaluated reveals that Machine 5 in its 2nd configuration, i.e., $MC_5^2$ and Machine 2 in its 4th configuration, i.e., $MC_2^4$ are the only two feasible optimal RMT configurations that are allocated to production stage S-II. Likewise, Machine 2 in its 2nd configuration, i.e., $MC_2^2$ and Machine 3 in its 2nd configuration, i.e., $MC_3^2$ are the two most likely feasible optimal RMT configurations that are allocated to production stage S-IV. As for the production stage S-V, $MC_2^3$ and $MC_4^3$ are the most likely allocated best suitable optimal RMT configurations on the SMTL.

**Table 8** Optimal configuration solutions obtained after 100 simulation runs

| | Produc-tion | Alternative solutions 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feasible RMT configu-ration allocated to production stages | S-I | 24 | 24 | 24 | 43 | 43 | 22 | 22 | 43 | 24 | 24 | 22 | 22 |
| | S-II | 52 | 52 | 24 | 52 | 24 | 52 | 24 | 52 | 52 | 24 | 24 | 24 |
| | S-III | 13 | 24 | 24 | 13 | 51 | 24 | 51 | 51 | 51 | 24 | 13 | 13 |
| | S-IV | 22 | 32 | 53 | 32 | 32 | 22 | 32 | 32 | 22 | 22 | 22 | 22 |
| | S-V | 23 | 32 | 23 | 43 | 32 | 23 | 23 | 43 | 43 | 23 | 11 | 23 |
| | S-VI | 11 | 54 | 43 | 11 | 11 | 13 | 43 | 13 | 13 | 54 | 13 | 11 |
| Corresponding objective func-tion values | $CO_i^j$ | 38.24 | 34.79 | 41.8 | 25.26 | 38.59 | 37.42 | 28.19 | 31.55 | 23.21 | 26.54 | 34.93 | 33.82 |
| | $MR_i^j$ | 59.52 | 47.68 | 59.69 | 39.40 | 39.65 | 61.41 | 49.24 | 39.51 | 53.46 | 64.02 | 57.17 | 59.78 |
| | $PF_i^j$ | 23 | 33 | 25 | 31 | 33 | 22 | 29 | 32 | 26 | 25 | 20 | 21 |
| | RL (%) | 41.88 | 23.66 | 37.46 | 56.1 | 54.62 | 37.74 | 60.07 | 48.78 | 31.21 | 28.01 | 45.93 | 61.16 |

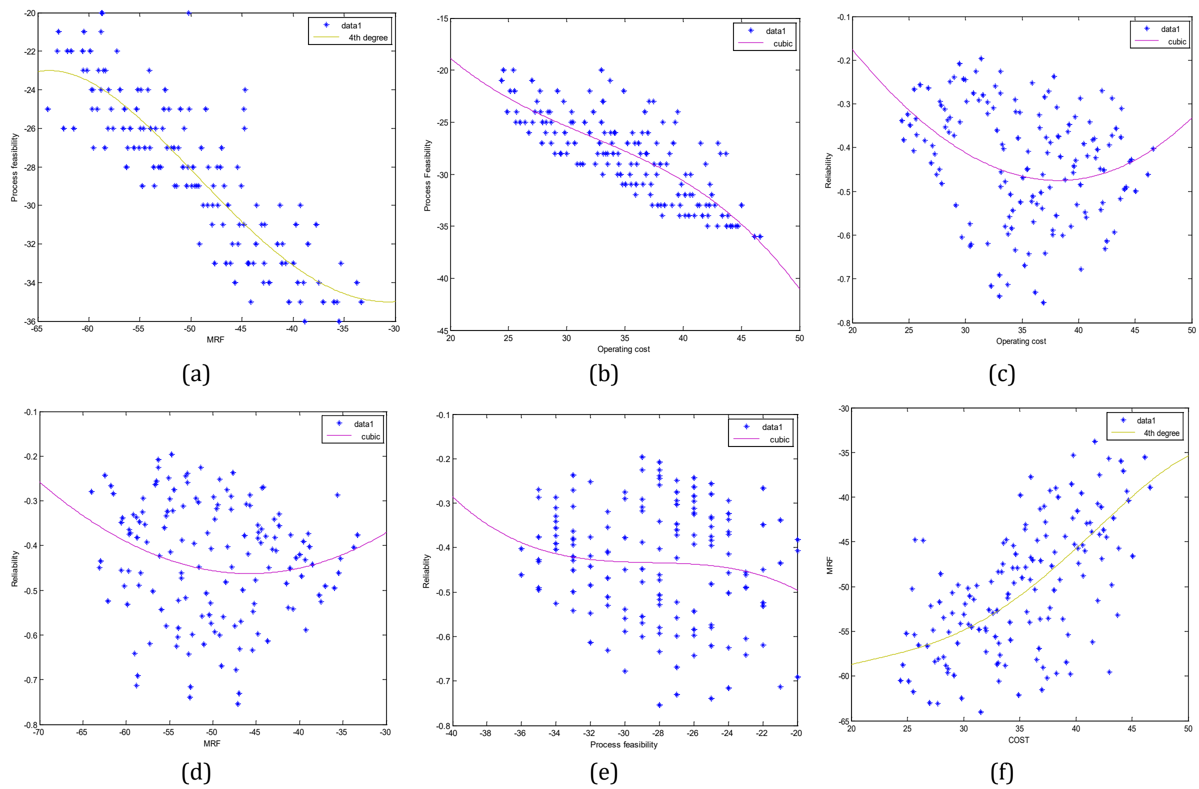


**Fig. 3** (a) Process feasibility vs MRF; (b) Process feasibility vs operating cost; (c) Reliability vs operating cost; (d) Reliability vs MRF; (e) Reliability vs process feasibility; (f) MRF vs operating cost

Moreover, the relationship variation between objective function values are presented in Fig. 3(a)-(f). The process feasibility found to have inverse proportional relationship with rest of all the parameters, i.e., the process feasibility drops with the rise of another parameter or vice-versa as shown in Fig. 3(a)-(b) and Fig. 3(e). The objectives MRF and Operating cost have direct propor-tional relationship, Fig. 3(f), and thus both parameters increase or decrease altogether. Reliability have Bath-tub curve relationship with operating cost and Machine Reconfiguration factor, Fig. 3(c)-(d).

In relation to the present work, another study [43] presented a simulation-based MOOP tech-nique for optimizing the configuration of a Multi-Part Production Flow Line by applying NSGA-II algorithm for only two factors, i.e., (1) assigning tasks to workstations and (2) allocating buffers to achieve maximum throughput (THP) while minimizing the total buffer capacity required. Non-dominated solutions so obtained with a THP higher/lower than 60 in numbers were presented by different colours. Further, a bi-objective minimization problem in RMS [44] obtained the pareto front using the proposed multi-objective simulated annealing algorithm. The effectiveness of the proposed algorithm was compared with NSGA-II that was reported outperformed in several aspects. However, this work considered a bi-objective optimization problem with no conflicting objectives and moreover, the results revealed lowly crowded solutions. Kurniadi *et al*. [30] considered an RMS problem and compared a conventional simulation program with a DT-based simulation program, results showed that total Reconfiguration Planning cost of RMS using Visual Components was found lower while using Plant Simulation software. Xu *et al*. [35] developed a selective maintenance model. In order to assess the efficacy of the devised strategy, the NSGA-II and NSGA-III algorithms were employed to address two maintenance decision-making models. The first model aimed to minimize maintenance and maximize the probability of the system completing the next task, while the second model included an objective of minimizing system downtime. The findings affirmed that the three-objective decision-making model, which considered minimizing downtime, effectively reduced system downtime. From the past studies, it can be concluded that NSGA-II is an effective algorithm that can be used in solving the MOOP related to DT-based works in RMS.

## 8. Conclusion and future work

This case study addressed a DT-based reconfiguration planning problem for RMS, particularly with regards to configuration selection of machines needed to meet future demands. The research demonstrated how DTs may be used in the configuration planning of RMTs used in RMS. RMT configuration selection is among the most crucial factors required for the successful and efficient planning of RMS. Every time new demands are raised to the system, machine reconfigurations are quite likely to occur. Thus, one of the most crucial factors in achieving a successful and efficient RMS is the RMT configuration selection. The integration of DT technology into RMS make real-world applications conceivable, and by integrating all the operators, physical equipment, and data, the system will be able to function more efficiently and logically. A novel DT-based MOOP technique is proposed for RMS which is based on four objective functions—Operation cost, MRF, process feasibility, and machine reliability. The best optimum configuration for the six-stage reconfigurable SPFL has been evaluated. To create a virtual environment, a DT-based optimization cum simulation model is developed in order to evaluate the non-dominated solutions for the optimal RMT configuration selection problem for RMS. The authors developed a MATLAB simulation program using NSGA-II algorithm. This research will aid production planners in crucial decision-making tasks for DT-based RMS production planning by assisting in RMT configuration selection strategy through evaluating the best suitable optimal solutions. As for limitations of the study, this work is only limited for the case of single reconfigurable manufacturing transfer line. The complexity of the problem may increase with the increase in (1) The number of parallel reconfigurable manufacturing transfer lines and (2) Number of conflicting objectives considered in the Multi-objective optimization problem. Hence, this work can be extended for the DT-based integrated production planning of (1) multiple reconfigurable flow lines (2) considering more multiple conflicting objectives and (3) solving the MOOP with the help of more powerful optimization algorithms.

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## Conflicts of interest

The authors declare no conflict of interest.

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