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Industry 4.0 Model for circular economy and cleaner production

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ABSTRACT

In today's competitive scenario, the manufacturing industries are lagging behind in implementing the Industry 4.0 concept or in integrating smart, ubiquitous components due to high cost and high energy consumption due to the volatile market. The digital transformation has reshaped the manufacturing industries and has paved the way towards data-driven, intelligent, networked, and resilient manufacturing systems. In this context, Industry 4.0 is progressing exponentially and offers a productive output in terms of circular economy and cleaner production to attain ethical business by achieving accuracy, precision, and efficiency. Hence, there is a strong requirement to revamp the traditional manufacturing set-ups into smart manufacturing to gain self-adaptability, reliability, and flexibility with high quality and low-cost output. The paper proposes a mixed-integer linear programming (MILP) model for Industry 4.0 set-up to achieve circular economy and cleaner production by optimizing products-machine allocation. The proposed MILP model optimizes the trade-off between energy consumption and machine processing cost to gain a circular economy and cleaner production respectively. The proposed model also achieves ethical business by deploying sensors to capture real-time information to establish the Industry 4.0 facility. The paper discusses the product-machine specific analysis to optimize the manufacturing of customized and high-end products at low production cost with minimal energy consumption. The objective of the paper is to minimize the total cost and energy consumption of machines for establishing the Industry 4.0 facility to gain a circular economy and cleaner production. The proposed model is demonstrated and computationally tested on small, moderate, and large data instances and presented with their detailed analysis.

1. Introduction

The manufacturing industries profoundly impact the business and engineering processes that function in an adaptable, sustainable, and efficient way with high quality and low cost (Oztemel and Gursev, 2020). However, these industries have been confronted with the dynamic and volatile market demand for a longer period and end with depleting natural resources. This requires an innovative way to explore the underlying challenges and limitations of the traditional linear economy which can replace the 'end-of-life' concept with the restoration or regeneration leading towards cleaner production and circular economy (CE). The principle of CE has been widely accepted by the organizations to transform their operational practices to ethical and sustainable production and consumption. CE intents to eliminate the use of toxic components and believes in remanufacturing/recycling the used products which are dumped by the end-consumer when no longer required. In the quest for a considerable improvement in resource usages, wastage recovery or to reuse products or components, advanced manufacturing strategies integrated with data acquisition systems have been developed.

With an eye towards an efficient and self-configured manufacturing network, a lot of research efforts have been devoted to achieving CE and cleaner production to improve environmental performance (Lu and Xu, 2019). The manufacturing industries are constantly facing issues in adopting cleaner production and CE strategies due to technology disruption. It has been discussed in previous studies that automation and advanced technological capabilities can develop ethical business practices for achieving CE effectively. Hence, it becomes essential to integrate advanced and ubiquitous technology which can provide real-time information and further can be used for predictive or cognitive analytics. In terms of technology push, Industry 4.0 is a German Federal Government initiative invented in 2011 to enhance the

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competitiveness of the manufacturing industries and supports machine-to-machine and human-to-machine interaction. Industry 4.0 is real-time data-driven which provides alternative approaches to achieve sustainable production and consumption that minimizes the wastages, energy consumption, and environmental deterioration (Yadav et al., 2020). The idea of Industry 4.0 is omnipresent and is one of the main driving strategies to address 3 R's (reduce, reuse, and recycle) to achieve sustainable production and consumption. In essence, Industry 4.0 is considered as a canopy of different high-tech technologies and is characterized by the cyber-physical systems (CPS), Internet of Things (IoT), big data, and cloud computing for cleaner production, reduced lead time and optimized inventory (Manavalan and Jayakrishna, 2019). It has also been argued that Industry 4.0 is a flagstone path towards establishing a proactive, automated, and self-configured manufacturing system to attain ethical business. It aims in the coupling of the cyber and physical world which provides information feed-back, real-time sensing, and dynamic control (Ma et al., 2019).

The existing literature studies have provided evidence that Industry 4.0 technology has a very complex architecture with embedded heterogeneous components, CPS, and cognitive computing in this digital ecosystem. Therefore, integrating Industry 4.0 dynamic facilities for reliable and transparent CE is still an open research gap. There is a plethora of research on the empirical and theoretical aspects of integrated Industry 4.0-CE, proposed frameworks, and maturity models for the implementation of the disruptive technologies to gain CE and cleaner production (Frank et al., 2019). However, there is a still lack of research studies in integrating Industry 4.0 with CE which hinders the reliable operation mechanism and real-time production analysis. In view of the foregoing, the need for the study is to possess the integration of Industry 4.0 with CE to overcome the obstacles of cleaner production and could establish an ethical CE model. It is determined that integrated Industry 4.0-CE has a strong impact on achieving sustainability and aids in improving production efficiency and accuracy which is the basic requirement of the manufacturing industries.

Therefore, the paper proposes a mathematical model of product-machine allocation in Industry 4.0 ecosystem. The proposed model explicitly considers the three machine variants i.e., high precision, medium precision, and low precision machines for multi-product in a multi-time period which is the novelty of the study. The model presents the trade-off between the machine processing costs and energy consumption of the machines through product machine allocation in Industry 4.0 ecosystem. The model includes the machine costs, sensors cost comprising of unit cost, installation cost, calibration, and maintenance cost of sensors, and second is the transportation cost of the multi-products. The parameters of the model are randomly generated and are tested on three data sets i.e., small, moderate, and large. The third data set is relatively bigger with an increased number of variants of machines and products for a multi-time period. This contribution makes the study unique from existing research studies which is relevant from the viewpoint of industry practitioners moving towards achieving CE and cleaner production in Industry 4.0 environment for ethical business.

The rest of the paper is structured as follows: Section 2 describes the literature review. The problem statement, model assumptions, and mathematical formulation of product-machine allocation in Industry 4.0 ecosystem are described in Section 3. Case illustrations of the proposed mathematical model are provided in Section 4. Results and discussions are presented in Section 5 followed by the contribution, implications, and limitations of the study in Section 6. Conclusion and future research directions are presented in Section 7.

2. Literature review

2.1. Literature review of CE and industry 4.0

With an increase in competitiveness among manufacturing industries, there is a requirement of efficient approaches for optimizing manufacturing costs with enhancement in quality and improved lead time. Efficient approaches intend to improve productivity, accuracy, reliability, decision making, monitoring, and flexibility. Besides this, it has also been determined that manufacturing industries are unlocking the closed-loop of resources within supply chains for sustainable operations management decision making. This provides a different perspective of CE to achieve sustainable production and consumption by refurbishing the value of used resources.

The CE was implemented by China in the 1990s to pursue CE aspects of economic and environmental. The CE offers new opportunities to revive the linear economy of take-make-use-dispose to balance supply and demand in managing the resources. However, in adopting CE there have been many hindrances such as inefficient information on used resources, product life cycle, carbon emission, and the shortfall of disruptive technologies for cleaner production. Nevertheless, the emerging and advanced technologies are based on the principles of Industry 4.0 and it may now be possible to overcome the inhibitors of CE and can balance the pillars of CE i.e., environmental, economical, and social. In the context of this, the manufacturing industries are transforming from a linear economy to CE superseded by the progress in advanced technologies. Within this concept, machines and humans are interconnecting at the shop floor to work in a coordinated and efficient way and also automate the data acquisition and transmission between the cyber and physical platforms. This vision has been supported by the Fourth Industrial Revolution i.e., Industry 4.0-German initiative in 2011 (Mohamed et al., 2019).

It has been argued that Industry 4.0 is the building block of CE and can expand the circularity of resources within operational systems of production and consumption. To expedite the understanding of Industry 4.0 concept, prior researchers have focused on the phenomenon of the underlying design principles and technology trends. Since the Industry 4.0 is the recent emergence of the advanced technologies, the knowledge gap between the CE and Industry 4.0 is partially explored. Jabbour et al. (2018) mentioned that Industry 4.0 contributes to sustainability by employing integrated value networks through data capturing and sharing. Rajput and Singh (2019) addressed that integrated Industry 4.0-CE can enhance sustainable production and consumption and can revamp the process of the product life cycle.

Lin (2018) argued that empowering Industry 4.0 in CE explores product decision making in information systems and data-driven innovation. Further, Nascimento et al. (2019) explored that integrating Industry 4.0 with CE establishes business models that remanufactures or recycles waste materials or e-waste. Prior studies have revealed that Industry 4.0 can enable reduced energy consumption, carbon emission, and also provides transparency to the data-driven products which promote ethical practices of producer responsibility and cleaner production. Thus, integrated Industry 4.0-CE facilitates the sustainable innovation model which can enhance end-of-life activities, optimizes wastages, and track the production and consumption operations. For the literature review process, the relevant articles are selected from the Scopus which is a highly peer-reviewed journal database. The research papers which were more aligned towards the Industry 4.0 or CE individually are excluded from the study. Only the recent research studies which were focused on integrated Industry 4.0-CE are included in the study. Depending on these two key research areas, the explored links between Industry 4.0 and CE are reviewed and presented in Table 1. The same literature review process is followed to address the seminal work of the authors relevant to the study are reviewed in the following sub-sections.

2.2. Literature review of sensors/IoT, RFID, and actuators deployed in industry 4.0

The manufacturing industries are currently experiencing a data-driven manufacturing system that brings an efficient and optimized manufacturing network into the picture. These smart technologies are driven through IoT and smart sensors. The concept of IoT was introduced in 1999 by Kevin Ashton in the United States (Mohamed, 2019). In the environment of Industry 4.0, the heterogeneous components, devices, works in a closely interconnected network through identifiable things, i.e., IoT/smart sensors which augment both informed decision making and eliminating inconsistencies. The data capturing and accessibility of production process information imposes a positive impact on decisions about product identification number, its lifecycle, or recovery that is based on the integration of IoT/smart sensors. The manufacturing industries equipped with Industry 4.0 facilities generate voluminous data i.e., big data and it involves data formatting, data reduction, hidden pattern, prediction, etc. (Yan et al., 2017). It is evident that in the manufacturing sector implementing a sensor network is difficult and also incurs a high cost for data monitoring and processing (Yen et al., 2014). Thus, networked sensors infrastructure integrated into Industry 4.0 environment provides automated and highly real-time efficient information, thereby promoting process improvements and high-level analytical decisions, and this data acquired through sensors can be assimilated with external databases or in CPS, a pivotal hub of Industry 4.0 for cognitive analysis. To understand the application of sensors, IoT, and RFID in the context of Industry 4.0, the previous literature studies are reviewed and presented in Table 2.

2.3. Literature review of energy consumption in industry 4.0

It is noteworthy that architecture of Industry 4.0 is complex and establishing Industry 4.0 with dynamic facilities, high-end processors, large computing devices and mobile computing devices is a great challenge as well as it is the future scope for manufacturing and services sector. In the context of this, Alqahtani et al. (2019) discussed that Industry 4.0 revolution is a critical challenge and organizations cannot realize the capability and competence value if there is no logical semantic interoperability between the devices. Industry 4.0 is gaining momentum at a rapid pace and changing the landscape of the manufacturing industries. Apart from the technological key elements, energy-aware systems in the factory are emerging as a challenging trend of Industry 4.0. However, Shrouf et al. (2014) addressed that one of the major expenses in enforcing Industry 4.0 in the manufacturing or service industry is energy consumption. Its cost contributes to increasing the total cost of the products and therefore, decreasing the degree of competitiveness of manufacturers. They have also investigated the benefits of Industry 4.0 for enhancing energy efficiency and cost in smart factories. Further, researchers have studied the great advances of Industry 4.0 by proposing the algorithms which can optimize the energy consumption and data transmission for improved real behavior of the manufacturing system (Faheem and Gungor, 2018). Prior research studies addressed the significance of energy efficiency in manufacturing industries in different aspects but not in the context of Industry 4.0. The ubiquitous technologies, smart devices, high end-processors, computing devices are integrated to build Industry 4.0 infrastructure but, the energy consumed by these high computational devices are very high. Therefore, the connecting bridge between the energy consumption and Industry 4.0 is missing and this research area is partially explored. Thus, manufacturing industries are moving towards the competitive edge where energy consumption is less, and efficiency is more. Previous literature studies have addressed the energy consumption minimization in Industry 4.0 depicted in Table 3.

Table 1
Summarized literature review of CE and Industry 4.0

Authors	Models, architecture, frameworks	Approach	Application
Lin (2018)	Defined a user-experienced-based product design approach for smart manufacturing.	Empirical study was conducted	Glass recycling industry
Antikainen et al. (2018)	Product virtualization and utilizing digitalization was adopted for achieving CE-based business models.	Conceptual study	Manufacturing industries
Tseng et al. (2018)	Operation and big data-driven analysis.	Data-driven analysis method	Cross-industry networks
Jabbour et al. (2018)	Proposed pioneering roadmap to enhance the CE principles application through Industry 4.0.	ReSOLVE model	In manufacturing industries for sustainable operations
Rajput and Singh (2019)	Identified the linkage between CE and Industry 4.0.	PCA-DEMATEL	Supply chain networks for sustainable operations
Nascimento et al. (2019)	Proposed a business model from integrating Industry 4.0 and CE.	Qualitative research method	Improves business sustainability by restoring waste into the supply chain
Rosa et al. (2020)	Developed innovative framework mapping Industry 4.0 and CE.	Systematic literature review (SLR)	Implement Industry 4.0 and CE for complex supply chains
Fatimah et al. (2020)	Developed a waste management system using IoT.	SLR	Case of Indonesia
Yadav et al. (2020)	Developed a framework for sustainable supply chain management through Industry 4.0 and CE.	Hybrid Best-Worst Method (BWM)-Elimination and Choice Expressing Reality (ELECTRE)	Automotive
Marchi and Maria (2020)	Discussed the connectivity between knowledge management, CE, and investments in Industry 4.0.	Empirical analysis	Manufacturing firms for sustainability through technology adoption
Piscitelli et al. (2020)	Analyzed and reviewed the scientific literature related to CE and Industry 4.0 and divided the theoretical studies from technical-application case studies.	SLR	Smart manufacturing, Green economy

Table 2
Summarized literature review of Sensors, IoT, and RFID deployed in Industry 4.0

Authors	Technology deployed	Industry 4.0 scenario	Applications
Yen et al. (2014)	Wireless sensor network (WSN)	Real-time data monitoring improves production efficiency and reduced machine failure.	Advanced manufacturing in CPS
Shrouf et al. (2014)	IoT	Flexibility in production volume and customization.	Smart factory
Obitko and Jirkovsky (2015)	Sensors	Decentralization, interoperability, real-time capability, and modularity.	Semantic web technologies for the production process
Bagheri et al. (2015)	Sensors	Self-aware, self-predict, machine health monitoring.	CPS in the manufacturing process
Lu et al. (2016)	Wireless sensor-actuator networks (WSAN)	Supports real-time communication, improved scalability.	Real-time scheduling, cyber-physical co-design of wireless control systems
Lin et al. (2016)	IoT, group-based industrial wireless sensor networks (GIWSNs)	Factory automation and flexibility in a dynamic environment.	Joint deployment and sleep scheduling of sensors along a production/assembly line.
Sipsas et al. (2016)	Sensors	Improves context-aware intelligent service systems.	Smart factory
Yan et al. (2017)	Sensors	Industrial big data processing using a spatio-temporal property.	Predictive Maintenance, Energy saving.
Sha et al. (2017)	WSANs	Process automation on reliable and real-time communication, improves network reliability and energy efficiency.	Transmission failures
Hofmann and Rusch (2017)	IoT	Real-time tracking of material flows and enhanced decentralization, self-regulation, and efficiency.	Logistics management
Zhong et al. (2017)	IoT, RFID	Real-time data capturing and analysis, visibility, and traceability of manufacturing operations.	Semiconductor manufacturing industries, smart grids.
Khan et al. (2017)	IoT, Sensors, Actuators, RFID, WSN	Data integration and modeling, big data analysis, real-time access.	Smart city, production planning, machine health prediction, product quality
Strandhagen et al. (2017)	IoT, Sensors	Seamless information flow improves manufacturing process efficiency.	Manufacturing logistics, 3D printing, Additive Manufacturing
Schutze et al. (2018)	Sensors 4.0	Generate data and allows self-monitoring and self-configuration.	Condition monitoring using data-based modeling
Hidalgo et al. (2018)	IoT, Sensors	Monitor labor activity and reinforce security at work, Sustainable digitalization.	Human-machine interaction towards socially sustainable factories
Xu et al. (2018)	IoT, RFID, WSN,	Enhanced manufacturing efficiency and competency.	Resilient smart factory.
Kumar (2018)	IoT, Sensors	Systems flexibility, monitoring, and self-adaptation.	Robotic manufacturing, smart manufacturing, additive manufacturing.
Lezzi et al. (2018)	IoT, WSN	Controlling and monitoring functionalities of facilities, cyber-security.	Healthcare, discrete manufacturing
Alqahtani et al. (2019)	Sensor	Warranty and maintenance of the remanufactured products.	Smart factory/manufacturing
Ardito et al. (2019)	IoT	Real-time information acquisition and storage.	Supply chain management-marketing (SCM-M) integration.
Manavalan and Jayakrishna (2019)	IoT, Sensors	Improved visibility of the product condition, reduced wastage of the resources and increased productivity as per the customer needs.	Sustainable supply chain, smart manufacturing, smart cities, smart operators, smart factories, logistics, healthcare, and energy management.
Muhuri et al. (2019)	WSN, IoT	Information security, reliability, and integrity.	Healthcare, Semiconductor manufacturing industry
Para et al. (2019)	Sensors	Acquisition of sensing equipment, quantitative assessment of the captured data, and improves the production cycle.	Automotive industry
Hamdi et al. (2019)	IoT	Optimize the available resources and their consumption.	Smart factories
Evtodieva et al., 2019	IoT	Meets consumers' service level and reduced delivery time.	Intelligent supply chain management
Rajput and Singh (2019)	IoT	Interoperability, system robustness.	Logistics, fog computing.
Vidhyotma and Singh (2019)	IoT, RFID	Enhanced interoperability, improved QoS.	Retail supply chain, medical and health, transport, pharmaceutical
Mouapi et al. (2020)	WSN	Ensures reliable measures of physical data.	Mining industry
Khan et al. (2020)	IoT	Sense, collect, process, communicate the real-time events, high operational efficiency, increased productivity, intelligent monitoring, predictive and preventive maintenance.	Smart homes, healthcare, and smart transportation
Olsen and Tomlin (2020)	IoT, RFID	Condition-based maintenance, real-time optimization.	Agriculture 4.0
Kabugo et al. (2020)	Sensors	Leverages industrial big data.	Waste-to-Energy (WTE) plant

Table 3
Summarized literature review of energy consumption optimization in Industry 4.0

Authors	Energy consumption optimization	Industry 4.0 scenario	Applications
Shrouf et al. (2014)	IoT- based energy management approach	Analyzed energy waste at the production level and select the most efficient configuration of the machines.	Production scheduling, maintenance management
Faheem and Gungor (2018)	Bird mating optimization (BMO)- based dynamic clustering algorithm	Balanced data traffic and energy consumption, improved Quality of Service (QoS) performance metrics.	Smart grid
Mohamed et al. (2019)	Enabling architecture and technologies for Industry 4.0 based energy efficiency	Interoperability, decentralization, and service orientation.	Smart factories
Lu et al. (2019)	Cyber-physical production network for energy-efficient manufacturing, Energy-aware data-twin model	Energy-efficient manufacturing models with flexibility and extendibility.	Engineering-to-order production model
Shukla et al. (2020)	Multi-objective energy-efficient task scheduling problem using non-dominated sorting genetic algorithm (NSGA-II)	Task execution with less energy consumption.	Real-time embedded systems (RTES)

2.4. Literature review of architecture/frameworks/conceptual model of industry 4.0

Manufacturing industries are providing the digital sphere at low cost and improved infrastructure to achieve maximum efficiency with the minimum usage of resources. Existing literature studies have addressed that Industry 4.0 combines artificial intelligence (AI), intelligent sensors, big data, cloud computing, and considered as the foundation of intelligent network infrastructure. The manufacturing industries are expecting promising transformational solutions within the intelligent network infrastructure, using resources network in a highly distributed manner. The researchers have attempted to develop future manufacturing systems to make efficient use of real-time data. Theorin et al., 2017 have proposed the Line Information System Architecture (LISA) which is an event-driven, and designed to enable proper data utilization and flexible factory integration.

Further, Para et al., 2019 have proposed the edge-based architecture to support time-dependent applications in Industry 4.0 context. Likewise, many authors have demonstrated their research in the developing Industry 4.0 architecture to leverage the opportunities of manufacturing industries. For example, Santos et al. (2017) have proposed Big Data Analytics architecture, Lee et al. (2018) have addressed the AI-driven industrial ecosystem; Schlechtendahl et al., 2014 have addressed an approach in reshaping the existing production system to Industry 4.0 centric; Dutra and Silva (2016) have proposed product-service architecture (PSA) in Industry 4.0 perspective. Similarly, other authors have also focused on developing architectures, conceptual frameworks, or models which is summarized in Table 4.

2.5. Literature review of the proposed mathematical model of industry 4.0

Industry 4.0 concept was developed for digitizing the manufacturing companies with a high configuration where real-time information flows within the controlled manufacturing environment. It aims to revolutionize the vertical and horizontal integration of the industry, facilitates the communication on innovation, and also provides high-tech developments whose implications are still undeveloped in the field of manufacturing and service industries. Existing literature argues that Industry 4.0 adopts industrial automation systems that assist in managing manufacturing, logistics, and value chains of the business operations. This automation provides the semantic interoperability between the production processes which interconnects the heterogeneous components communicating under an automated manufacturing ecosystem (Buchi et al., 2020).

Presently, authors are moving towards exploring the mathematical side of Industry 4.0 which is undercover and is considered as a research gap for future studies. Yang et al. (2015) have presented the RFID-enabled manufacturing execution system (MES) with real-time and wireless information capability. Sokolov and Ivanov (2015) proposed a model for dynamic and real-time scheduling of services for Industry 4.0 supply networks. Prior research studies state that the digital transformation is working on the assumptions of Industry 4.0 which can provide flexible production with customized products and real-time data exchange (Kerin and Pham, 2019). On the other side, researchers are also focusing on the large networked system i.e. CPS which is considered as the hub of Industry 4.0. The authors have highlighted the underpinning mathematical foundation by coupling the cyber-physical space of CPS. For example, Shen et al. (2016) have proposed a non-cooperative game with scheduling algorithm to provide real-time and an anticipated communication, Ivanov et al. (2016); Li and Tang (2018) have focused on the short term supply chain and on maintaining the data integrity in false data injection attack environment. A limited literature study explored in the area of mathematical modeling of Industry 4.0/CPS is presented in Table 5.

The literature review provides work on the integration of Industry 4.0 and CE, the energy consumed through data transmission in Industry 4.0 to attain CE and cleaner production. It also provides seminal work on IoT/sensors/RFID/WSN deployed in Industry 4.0 environment for the ease of security, reliability, and enhanced interoperability. Industry 4.0 architectures/frameworks/conceptual models proposed for dynamic production system and optimized decision making and mathematical model of Industry 4.0 is proposed to improve accuracy in real-time is addressed in this section. The literature survey reveals that a rich body of literature is available linked to Industry 4.0. However, in the extant literature, very limited work is done considering Industry 4.0, CE, cleaner production, and ethical business. Therefore, the paper provides a mathematical model of Industry 4.0 focusing on cleaner production, ethical business, and CE by reducing energy consumption which is the array of data transmission energy, and high-end systems/machines energy which is reduced ethically. The production is cleaner and the overall cost may be increased but it provides optimal output to make informed decisions to integrate Industry 4.0 and CE. The proposed mathematical work may not minimize the economy in a shorter run but in real industrial cases, it minimizes energy consumption and allocates products to machines effectively for cleaner production in the integrated Industry 4.0-CE environment. The next sub-section describes identified research gaps and research objectives of the study based on the summarized literature review depicted in Tables 1–5

2.6. Research gaps and research objectives

From the extant literature review, the following research gaps have been identified. The paper attempts to focus on the following issues by developing the mathematical model:

Table 4
Summarized literature review of architectures, frameworks or models in Industry 4.0

Authors	Models, architecture, frameworks	Industry 4.0 scenario	Applications
Shrouf et al. (2014)	Reference architecture for IoT- based Industry 4.0	Proactive maintenance, visibility, optimized decision making.	Smart manufacturing
Schlechtendahl et al., 2014	Cyber-physical production system (CPPS)	Detects available production system and their communication interfaces.	Intelligent production systems
Bagheri et al. (2015)	CPS architecture	Self-aware, self-predict, machine health monitoring.	CPS in manufacturing
Dutra and Silva (2016)	Product-service architecture (PSA)	Dynamic production process.	IT infrastructure, Hardware and human agents
Zhong et al. (2017)	Intelligent Manufacturing System (IMS) framework	Improves manufacturing efficiency, agility, and self-adaptive decisions.	Semiconductor manufacturing industries, Smart grid
Li et al. (2017)	System framework based on Industry 4.0	Fault analysis, predictive maintenance.	Green monitoring
Theorin et al., 2017	LISA	Flexible factory integration and data utilization.	Automotive industry
Santos et al. (2017)	Big data analytics architecture	Data analysis and prediction for sustainable innovation.	Smart manufacturing
Ghobakhloo (2018)	Industry 4.0 architecture	Connectivity, integration, transparency, data consistency, and interoperability.	Smart logistics, smart manufacturing
Lee et al. (2018)	AI-driven ecosystem	Improved system performance over time.	Intelligent spindle system
Alcacer and Machado (2019)	Reference Architecture Model Industrie 4.0 (RAMI4.0)	Distributed computing systems, interoperability, cost reduction.	Fashion manufacturing
Vidhyotma and Singh (2019)	Layered architecture	Enhanced interoperability, and improved QoS.	Retail supply chain, medical and health, transport, pharmaceutical
Para et al., 2019	Edge-based architecture, BodyEdge	High flexibility, robustness, and adaptive service level.	Healthcare industry
Lu et al. (2020)	Digital Twin reference model	Operation monitoring and optimization.	Smart manufacturing
Cimini et al. (2020)	Human-in-the-loop CPPS architecture	Hierarchical and heterarchical data-driven decision-making processes in manufacturing.	Smart factories, social supply chain
Liu et al. (2020)	Block chain-based product lifecycle management (PLM) framework	Openness, interoperability, and decentralization.	Smart factory

Table 5
Summarized literature review of mathematical modeling of Industry 4.0/CPS.

Authors	Objective	Industry 4.0 scenario	Solution methodology
Yang et al. (2015)	Minimize cost	Improves the accuracy of the monitoring information in a real shop-floor environment.	Lagrangian approach
Sokolov and Ivanov (2015)	Minimize the idle time of services and total service costs; maximizing service level by the volume of completed jobs	Optimal schedule of a manufacturing process in real-time.	Krylov-Chernousko
Shen et al. (2016)	Resource allocation	Real-time performance, scalability.	Simulation
Ivanov et al. (2016)	Optimal scheduling with control functions	Short term supply chain scheduling.	Dynamic decomposition
Li and Tang (2018)	Maximize the trace of the remote estimation error covariance	Maintains the integrity of the data in a false data injection attack.	Convex optimization

- Limited mathematical model is developed for implementing Industry 4.0 facility that considers product and machine parameters.
- Integration of multi-product and multi-machine i.e., high precision, medium precision, and low precision machines allocation for Industry 4.0 specific mathematical modeling is not available.
- Limited mathematical model is developed with sensor parameters and its associated costs viz. unit cost, installation, calibration, and maintenance costs used in the Industry 4.0 environment.
- The mathematical model of energy consumption and processing time of multi-machines in product-machine allocation is limited.

Based on the research gaps, the following are the research objectives for the proposed model:

- To develop a mathematical model for actualizing Industry 4.0 facility in the manufacturing industry considering multi-product and multi-time period with connected facilities.
- To propose a mathematical model for multi-products and multi-machine i.e., high precision, medium precision, and low precision machines allocation for Industry 4.0.
- To develop a mathematical model for sensor deployment capturing the production real-time data processed through multi-machines.
- To propose an energy consumption and processing a time-driven mathematical model through product-machine allocation.

The paper addresses the above mentioned research gaps through mathematical modeling. The novelty of the proposed model is that it has considered three machine variants: high precision, medium precision, and low precision machine, balanced the trade-off between the energy consumption and costs of machine variants and IoT sensors. The model has considered multi-products which are produced and sequentially allocated on machine variants and further shipped from plant to warehouse to market. The research framework of the proposed mathematical model is provided in the next sub-section.

2.7. Research framework

This sub-section provides the research framework of the proposed mathematical model. The framework provided in Fig. 1 depicts the flow of the study to address the research gaps in Industry 4.0.

3. Problem statement and mathematical model formulation

This section describes the problem statement of Industry 4.0 and the mathematical model formulation of the stated problem.

3.1. Problem statement

The problem considered here is of implementing Industry 4.0 considering CE and cleaner production with a mathematical model. There is a plethora of literature in qualitative studies related to Industry 4.0, smart manufacturing, Industrial Internet of Things (IIoT), real-time scheduling jobs but its integration with the optimization models focusing on CE and cleaner production is attempted by only a few researchers and most of the studies are focused on the real-time data availability, big data, cloud computing, and cyber-attacks. In the viewpoint of this, there is a need to integrate different types of precision machines with embedded sensors and high-end processors in the Industry 4.0 ecosystem. The sensors deployed in the Industry 4.0 manufacturing environment provide real-time data of the production which is further used for predictive or cognitive analytics. Industry 4.0 is also interlinked with other facilities such as warehouses and markets to fulfill the demand arising from different market locations. Based on the arising demands of different customized products, the firm has come up with multi product-multi machine allocation in Industry 4.0 ecosystem at different plant locations. The warehouses are considered to store the products being shipped to the required markets. The production under Industry 4.0 network is dynamic and flexible as multi-machines i.e., high precision, medium precision, and low precision machines are allocated in plants that manufacture multi-products in the multi-time period. Further, these products are delivered to the market from different warehouse locations.

The main aim of the paper is to optimize the energy consumption ethically through product-machine allocation in Industry 4.0 environment to achieve CE and cleaner production at different plant locations. It optimizes the overall cost considering the cost of high precision, medium precision and low precision machines, cost of sensors deployed over the entire planning horizon, and the transportation cost of multi-products from the warehouses to different markets. The proposed stated problem is solved by developing the mathematical model of Industry 4.0 focusing on cleaner production, CE, and ethical business. The paper provides a novel attempt considering multi-machines, plants, warehouses, multi-products, markets, and multi-time periods to reduce data transmission energy ethically. The planning horizon in the proposed mathematical model is divided into t = 1, 2, 3 …. T time periods. The proposed model is tested on three data instances viz., small data (3i-3r-5t-2j-3k-3h-5m-6l), moderate data (3i-5r-7t-2j-5k-3h-5m-6l) and large data (5i-10r-10t-3j-7k-5h-7m-8l). These three data instances are considered to test the real industrial problems of different sizes and analyze the energy consumption of machines in terms of data transmission over a period of time. This attempts to model MILP and gains practical insights into CE and cleaner production using three data instances.

3.2. Mathematical model formulation

This section presents the model assumptions, indices, parameters, and variables to formulate the MILP model for multi-product and multi-machine allocation at a varying time in Industry 4.0.

3.2.1. Model assumptions

Implementing Industry 4.0 facility in manufacturing or service

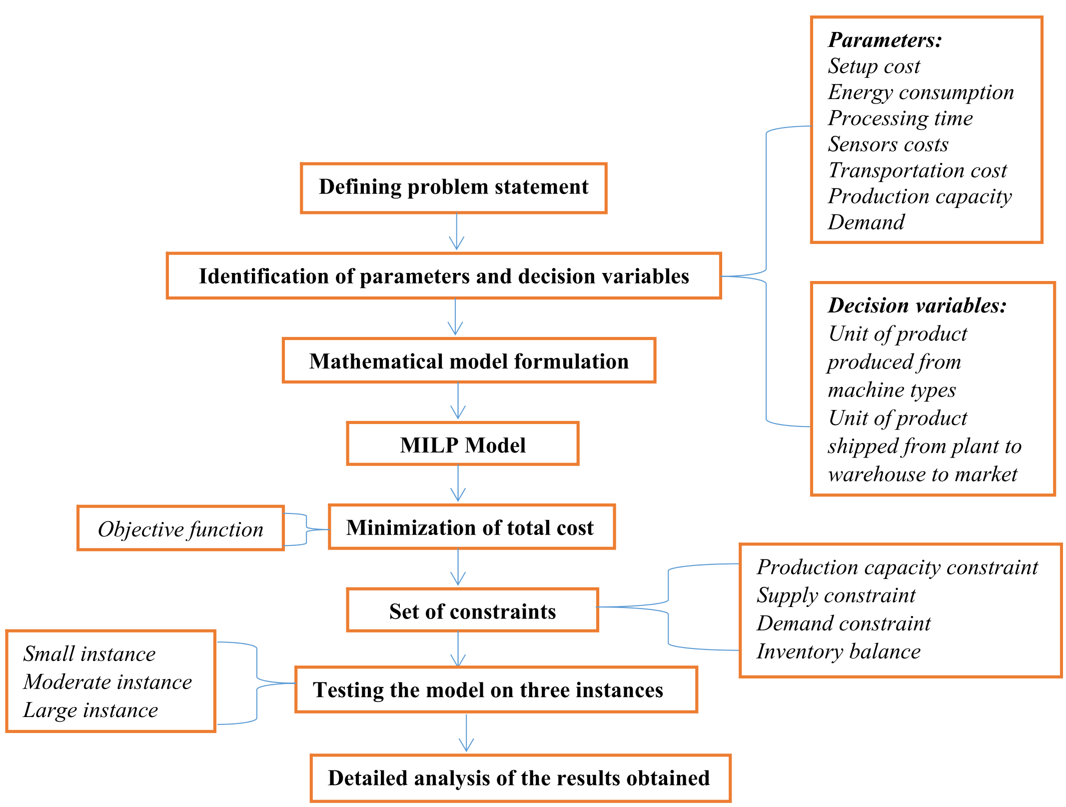

Fig. 1. Research Framework of the proposed model.

industry has the following assumptions:

- Sensors deployed in Industry 4.0 incurs high costs which comprise of the unit cost of sensors, installation, calibration, and maintenance costs and are calculated on per unit production.
- Maintenance and calibration of sensors are done annually.
- Multi-machines viz., high precision, medium precision, and low precision machines are considered for integration in Industry 4.0 facility.
- Each multi-machine in each plant is capable to produce multi-products at different time periods with no production capacity constraint.
- The energy consumption considered here is the array of data transmission energy, high-end systems/machines energy, and processors' energy.
- Energy consumption and processing time of each machine are calculated at per unit production.
- Plants and warehouse locations are selected at the prominent location.
- The warehouse has no storage capacity constraint.
- Market locations are fixed with known demand.

3.2.2. List of indices

i = index for plant
j = index for warehouse
k = index for market
r = index for product
t = index for time period
h = index for high precision machine
m = index for medium precision machine
l = index for low precision machine

3.2.3. List of parameters

MC_{irht} = Fixed setup cost in ith plant for product 'r' for hth high precision machine for tth time period.
$\mathrm{EC}_{\mathrm{irht}}$ = Energy consumption in ith plant for product 'r' for hth high precision machine for tth time period.
PTH_{irht} = Processing time in ith plant for product 'r' for hth high precision machine for tth time period.
$\mathrm{UPH}_{\mathrm{irht}}$ = Unit cost of sensors in ith plant for product 'r' for hth high precision machine for tth time period.
$\mathrm{INH}_{\mathrm{irht}}$ = Installation cost of sensors in ith plant for product 'r' for hth high precision machine for tth time period.
$\mathrm{CAH}_{\mathrm{irht}}$ = Calibration cost of sensors in ith plant for product 'r' for hth high precision machine for tth time period.
$\mathrm{MAH}_{\mathrm{irht}}$ = Maintenance cost of sensors in ith plant for product 'r' for hth high precision machine for tth time period.
MM_{irmt} = Fixed setup cost in ith plant for product 'r' for mth medium precision machine for tth time period.
$\mathrm{ECM}_{\mathrm{irmt}}$ = Energy consumption in ith plant for product 'r' for mth medium precision machine for tth time period.
PTM_{irmt} = Processing time in ith plant for product 'r' for mth medium precision machine for tth time period.
$\mathrm{UPM}_{\mathrm{irmt}}$ = Unit cost of sensors in ith plant for product 'r' for mth medium precision machine for tth time period.
$\mathrm{INM}_{\mathrm{irmt}}$ = Installation cost of sensors in ith plant for product 'r' for mth medium precision machine for tth time period.
$\mathrm{CAM}_{\mathrm{irmt}}$ = Calibration cost of sensors in ith plant for product 'r' for mth medium precision machine for tth time period.
$\mathrm{MAM}_{\mathrm{irmt}}$ = Maintenance cost of sensors in ith plant for product 'r' for mth medium precision machine for tth time period.
LM_{irmt} = Fixed setup cost in ith plant for product 'r' for lth low precision machine for tth time period.
$\mathrm{ECL}_{\mathrm{irlt}}$ = Energy consumption in ith plant for product 'r' for lth low precision machine for tth time period.
PTL_{irlt} = Processing time in ith plant for product 'r' for lth low precision machine for tth time period.
$\mathrm{UPL}_{\mathrm{irlt}}$ = Unit cost of sensors in ith plant for product 'r' for lth low precision machine for tth time period.
$\mathrm{INL}_{\mathrm{irlt}}$ = Installation cost of sensors in ith plant for product 'r' for lth low precision machine for tth time period.
$\mathrm{CAL}_{\mathrm{irlt}}$ = Calibration cost of sensors in ith plant for product 'r' for lth low precision machine for tth time period.
$\mathrm{MAL}_{\mathrm{irlt}}$ = Maintenance cost of sensors in ith plant for product 'r' for lth low precision machine for tth time period.
$TC1_{\mathrm{irjt}}$ = Transportation cost for shipping a unit of product 'r' from ith plant to jth warehouse for tth time period.
$TC2_{\mathrm{jrkt}}$ = Transportation cost for shipping a unit of product 'r' from jth warehouse to kth market for tth time period.
PQ_{irt} = Maximum production capacity in ith plant for rth product for tth time period.
D_{rkt} = Demand for rth product at kth market for tth time period.
3.2.4 List of decision variables
$P1_{\mathrm{irht}}$ = Unit of rth product produced in ith plant from hth high precision machine for tth time period.
$P2_{\mathrm{irmt}}$ = Unit of rth product produced in ith plant from mth medium precision machine for tth time period.
$P3_{\mathrm{irlt}}$ = Unit of rth product produced in ith plant from lth low precision machine for tth time period.
Q_{irjt} = Unit of rth product shipped from ith plant to jth warehouse for tth time period.
W_{jrkt} = Unit of rth product shipped from jth warehouse to kth market for tth time period.

3.2.4. Model formulation

1. Objective function

$$Z1 = \sum_i\sum_r\sum_h\sum_t P1_{irht}*MC_{irht} + \sum_i\sum_r\sum_m\sum_t P2_{irmt}*MM_{irmt} + \sum_i\sum_r\sum_l\sum_t P2_{irlt}*LM_{irlt} \quad (1)$$

$$Z2 = \sum_i\sum_r\sum_h\sum_t (P1_{irht}*(EC_{irht}+PTH_{irht})) + \sum_i\sum_r\sum_m\sum_t (P2_{irmt}*(ECM_{irmt}+PTM_{irmt})) + \sum_i\sum_r\sum_l\sum_t (P3_{irlt}*(ECL_{irlt}+PTL_{irlt})) \quad (2)$$

$$Z3 = \sum_i\sum_r\sum_h\sum_t (P1_{irht}*(UPH_{irht}+INH_{irht}+CAH_{irht}+MAH_{irht})) + \sum_i\sum_r\sum_m\sum_t (P2_{irmt}*(UPM_{irmt}+INM_{irmt}+CAM_{irmt}+MAM_{irmt})) + \sum_i\sum_r\sum_l\sum_t (P3_{irlt}*(UPL_{irlt}+INL_{irlt}+CAL_{irlt}+MAL_{irlt})) \quad (3)$$

$$Z4 = \sum_i \sum_r \sum_j \sum_t Q_{irjt} * TC1_{irjt} + \sum_j \sum_r \sum_k \sum_t Q_{jrkt} * TC2_{jrkt} \tag{4}$$

$$\text{Min } Z = Z1+Z2+Z3+Z4 \tag{5}$$

2. Set of Constraints

$$\sum_h P1_{irht} + \sum_m \sum_r P2_{irmt} + \sum_l \sum_r P3_{irlt} + PQ_{irt} \quad \forall\, i, r, t \tag{6}$$

$$\sum_j Q_{irjt} = \sum_h \sum_r P1_{irht} + \sum_m \sum_r P2_{irmt} + \sum_l \sum_r P3_{irlt} \forall\, i, r, t \tag{7}$$

$$\sum_i Q_{irjt} = \sum_k W_{jrkt} \forall\, j, r, t \tag{8}$$

$$\sum_j W_{jrkt} > \; = D_{rkt} \forall\, k, r, t \tag{9}$$

$$P1_{\mathrm{irht}},\ P2_{\mathrm{irmt}},\ P3_{\mathrm{irlt}},\ Q_{\mathrm{irjt}},\ W_{\mathrm{jrkt}} \text{ are integers} \tag{10}$$

Eq. (1) corresponds to the high precision, medium precision, and low precision machine costs for production in Industry 4.0 ecosystem. Eq. (2) corresponds to energy consumption and processing time of production. Eq. (2) will balance the trade-off between the energy consumption and machine costs as P1, P2 and P3 will be produced on those machines whose energy consumption and machine cost are low. Eq. (3) provides the total sensors cost (unit cost, installation, calibration, and maintenance cost of sensors) deployed in the manufacturing firm which will capture the real-time production information from different machines (hth, mth and lth) and other smart components connected through IoT network. Eq. (4) provides the transportation cost of rth product shipped from ith plant to jth warehouse and from jth warehouse to kth market. Eq. (5) depicts the objective function which is to minimize the total cost of Industry 4.0.

Eqs. (6–10) represent the set of constraints. Constraint (6) corresponds to the production capacity constraint in which the rth product is produced from hth, mth, lth precision machine allocated in ith plant for tth time period. Constraint (7) corresponds to the supply constraint. Constraint (8) presents the inventory balance equation at the warehouse for all products and time periods. Constraint (9) corresponds to the demand of the markets for all products and time periods. Constraint (10) corresponds to the integer restrictions for all product quantities. The proposed Industry 4.0 mathematical model is solved using LINGO 10 optimization software and its code is provided in Appendix A.

4

4 Case illustrationsThis section describes the case illustration of the proposed MILP model with the aid of small, moderate, and large data instances. The large data instance has an increased number of hth, mth and lth precision machines to gain impactful insights on product-machine allocation in dynamic Industry 4.0 facility. The data of all instances for various costs such as setup costs, energy consumption, sensor costs, and transportation costs, production quantity, and market demand is provided in the supplementary data file.

4.1

4.1 Illustration for 3i-3r-5t-2j-3k-3h-5m-6lThe mathematical modeling for Industry 4.0 is developed in the preceding section will now be illustrated by three instances. Data for three instances have been generated randomly and are provided in the supplementary data file. In an illustrative instance, the case is of manufacturing firm having three plants (3i), produce three products (3r), and having two warehouses (2j) at prominent locations. To meet the demand generated from three markets (3 k), three high precision machines (3 h), five medium precision machines (5 m), and six low precision machines (6 l) are allocated in three plants to produce three products for all five time periods (5t). These precision machines are considered for Industry 4.0 based manufacturing processes to produce functional and customized products in most efficiently and accurately, and quality assurance checks are also integrated throughout the process to meet the end-customer needs. The firm intends to implement Industry 4.0 in a manufacturing firm to capture and access the real-time production information for effective and informed decisions. The overall objective is to minimize the total cost by sequence allocation of multi-product on multi-machine in three plant locations over the planning horizon. Simultaneously, the energy consumption incurred from production is also optimized for better cleaner production.

4.2

4.2 Illustration for 3i-5r-7t-2j-5k-3h-5m-6lIn this case, a moderate data set provided in the supplementary data file. which is randomly generated is considered to solve the proposed MILP model. The case considers three plants (3i), producing five products (5r), and having two warehouses (2j). To meet the demands from five markets (5 k), three high precision machines (3 h), five medium precision machines (5 m) and six low precision machines (6 l) are allocated in three plants in the planning horizon of seven time periods (7t). Similarly, the objective is to minimize the total cost by sequence allocation of multi-product on multi-machines over the planning horizon.

4.3

4.3 Illustration for 5i-10r-10t-3j-7k-5h-7m-8lIn this case, a large data set provided in the supplementary data file is considered to solve the proposed MILP model. The case considers five plants (5i), producing ten products (10r), and having three warehouses (3j). To meet the demands from seven markets (7 k), five high precision machines (5 h), seven medium precision machines (7 m) and eight low precision machines (8 l) are allocated in five plants in the planning horizon of seven time periods (7t). Likewise, the objective is to minimize the total cost by sequence allocation of multi-product on multi-machines over the planning horizon.

5

5 Results and discussion

5.1

5.1 Results

5.1.1

5.1.1 Illustration for 3i-3r-5t-2j-3k-3h-5m-6l (small problem size)This section provides a detailed analysis of the results obtained for the *small dataset. The model provides the objective function value 2.13655e+006 which implies the total cost. This case of the proposed mathematical model of multi-product and multi-machine allocation in Industry 4.0 consists of total 814 variables (integer) and 170 constraints. The solution obtained for the allocation of rth products and the units of product produced shown in parentheses from the hth, mth and lth machine from the proposed mathematical model is depicted in Table 6. The unit of products produced in all time periods is shown in Fig. 2.*

For the ease of understanding, the following nomenclature is adopted to represent the results depicted in Table 6. The proposed mathematical model states the sequence of allocation of rth product on machine type (hth, mth, lth) and units produced at ith plant in tth time period.

$\{ [(\_^{i}, \_^{i}, \_^{i}) (\_^{i}, \_^{i}, \_^{i}) (\_^{i}, \_^{i}, \_^{i})] \}$

where, { } represents machine type viz., high precision (hth), medium precision (mth), and low precision (lth).

[ ] represents time period i.e., t1, t2 …. T
( ) represents products i.e., r1, r2 …. R
$\_^{i}$ represents the unit of product produced in *i*th plant

The following nomenclature illustrates that hth machine type depicted as { } for t = 4 depicted as [ ], r1 product depicted as ( ) allocated on hth machine type and 280 units produced in plant i2. The 0^{i1} illustrates that r1 product is not allocated on hth machine and no unit is produced in i1 in t1 time period.

$\{ [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 300^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2})], [(280^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2})], [(410^{i2}, 0^{i3}) (0^{i2}) (0^{i2}, 0^{i3})] \}$

Likewise, the following two nomenclatures represent the sequence of allocation of rth product on mth and lth machine types respectively and rth units produced at ith plant in tth time period.

$\{ [(225^{i1}, 125^{i2}, 290^{i3}) (0^{i1}, 290^{i2}, 350^{i3}) (300^{i1}, 300^{i2}, 35^{i3})], [(335^{i1}, 45^{i2}, 335^{i3}) (85^{i1}, 300^{i2}, 360^{i3}) (150^{i1}, 400^{i2}, 250^{i3})], [(5^{i1}, 0^{i2}, 445^{i3}) (385^{i2}, 345^{i3}) (180^{i1}, 345^{i2})], [(0^{i2}, 335^{i3}) (445^{i2}, 170^{i3}) (220^{i1}, 335^{i2})], [(0^{i2}, 390^{i3}) (540^{i2}) (445^{i2}, 125^{i3})] \}$

$\{ [(0^{i1}, 0^{i2}, 0^{i3}) (30^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2})], [(0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2})], [(0^{i2}, 0^{i3}) (0^{i2}) (0^{i2}, 0^{i3})] \}$

The representative case has considered three products viz., r1, r2 and r3 produced on hth, mth and lth machines in plant *i* across all five time periods. *i*1, *i*2 and *i*3 are the three plants, j1 and j2 are the warehouses and k1, k2 and k3 are the markets located in prominent locations considered in this case. The firm has established a plant equipped with smart and advanced technologies, sensors are installed through which real-time information could be retrieved. The solution corresponding to the unit of products shipped from plant to warehouse and from warehouse to market is represented in Table 7 and Table 8 respectively. For better understanding, the nomenclature is adopted to represent the results obtained.

$[(Q^{ij}, W_{jk}) (Q^{ij}, W_{jk}) (Q^{ij}, W_{jk})]$

where, [ ] represents time period i.e., t1, t2 …. T.

( ) represents products i.e., r1, r2 …. R
Q^{ij} represents the amount of product shipped from ith plant to jth warehouse
W_{jk} represents the amount of product shipped from jth warehouse to kth market

The nomenclature is used for representing the results obtained in Tables 7 and 8 and in this representative case, it illustrates that for t = 1 depicted as [ ], for r = 1 depicted as ( ) the plant *i*1 shipped 225 unit of r1 to warehouse j1 represented as 225^{11}. Similarly, the warehouse j1 shipped 115 unit of r1 to market k1 represented as 115_{11} as per the market demand. Likewise, for all time periods Q^{ij} and W_{jk} is represented in the following manner.

$[(225^{11}, 125^{21}, 290^{31}, 115_{11}, 225_{12}, 300_{13}) (30^{11}, 215^{21}, 75^{22}, 350^{32}, 245_{11}, 200_{22}, 225_{23}) (300^{12}, 300^{22}, 35^{32}, 155_{21}, 330_{22}, 150_{23})]$ $[(335^{11}, 45^{21}, 335^{31}, 200_{11}, 115_{12}, 400_{13}) (85^{11}, 215^{31}, 300^{22}, 145^{32}, 300_{11}, 145_{22}, 300_{23}) (150^{12}, 400^{22}, 250^{32}, 250_{21}, 350_{22}, 200_{23})]$ $[(5^{11}, 445^{31}, 300^{22}, 300_{12}, 150_{13}, 225_{21}, 75_{23}) (385^{21}, 175^{31}, 170^{32}, 225_{11}, 335_{13}, 170_{22}) (180^{11}, 45^{21}, 300^{22}, 225_{13}, 200_{21}, 100_{22})]$ $[(335^{31}, 280^{22}, 300_{11}, 35_{13}, 200_{22}, 80_{23}) (55^{21}, 170^{31}, 390^{22}, 225_{13}, 200_{21}, 190_{22}) (200^{11}, 20^{12}, 335^{22}, 200_{13}, 155_{21}, 200_{22})]$ $[(410^{21}, 90^{31}, 300^{32}, 400_{11}, 100_{13}, 300_{22}) (540^{22}, 190_{21}, 200_{22}, 150_{23}) (175^{21}, 125^{31}, 270^{22}, 300_{13}, 100_{21}, 170_{22})]$.

5.1.2

5.1.2 Illustration for 3i-5r-7t-2j-5k-3h-5m-6l (moderate problem size)

This section describes the results of the slightly bigger dataset. The objective function value for this case is 7.39469e+006 and consists of total 2030 variables (integer) and 460 constraints. The following nomenclature described in the preceding illustration represents the solution corresponding to the sequence of allocation of rth product on hth, mth and lth machine. The unit of products produced in all time periods is shown in Fig. 3.

$\{ [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (270^{i1}, 0^{i2})], [(0^{i1}, 345^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 335^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})], [(0^{i1}, 445^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3})], [(0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 155^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i3})], [(0^{i1}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (290^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3})] \}$

$\{ [(225^{i1}, 85^{i2}, 550^{i3}) (0^{i1}, 290^{i2}, 600^{i3}) (300^{i1}, 350^{i2}, 305^{i3}) (0^{i1}, 395^{i2}, 400^{i3}) (170^{i1}, 345^{i2}, 0^{i3})], [(335^{i1}, 125^{i2}, 575^{i3}) (200^{i2}, 620^{i3}) (295^{i1}, 360^{i2}, 300^{i3}) (0^{i1}, 250^{i2}, 125^{i3}) (0^{i1}, 570^{i2})], [(310^{i1}, 0^{i2}, 425^{i3}) (135^{i1}, 445^{i2}, 475^{i3}) (365^{i1}, 345^{i2}, 145^{i3}) (440^{i2}, 300^{i3}) (390^{i1}, 250^{i2}, 335^{i3})], [(140^{i1}, 0^{i2}, 390^{i3}) (240^{i1}, 335^{i2}, 520^{i3}) (255^{i1}, 340^{i2}, 410^{i3}) (300^{i1}, 250^{i2}, 410^{i3}) (445^{i1}, 400^{i2}, 255^{i3})], [(305^{i1}, 0^{i2}, 450^{i3}) (150^{i1}, 390^{i2}, 500^{i3}) (120^{i1}, 300^{i2}, 350^{i3}) (0^{i1}, 200^{i2}, 400^{i3}) (0^{i2}, 0^{i3})], [(280^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (400^{i1}, 0^{i2}, 350^{i3}) (440^{i2}, 330^{i3}) (0^{i1}, 390^{i3})], [(430^{i1}, 560^{i3}) (445^{i1}, 300^{i2}, 0^{i3}) (25^{i1}, 0^{i2}, 430^{i3}) (0^{i1}, 210^{i2}, 550^{i3}) (55^{i1}, 375^{i2}, 575^{i3})] \}$

Table 6
Solution corresponding to sequence of allocation of rth product on hth, mth and l^{th}machine.

	t1			t2			t3			t4			t5		
	i1	i2	i3	i1	i2	i3	i1	i2	i3	i1	i2	i3	i1	i2	i3
r1	m4 (225)	m1 (125)	m3 (290)	m4 (335)	m3 (45)	m3 (335)	m4 (5)	h2 (300)	m3 (445)	–	h2 (280)	m1 (335)	–	h2 (410)	m2 (390)
r2	l1 (30)	m3 (290)	m3 (350)	m1 (85)	m3 (300)	m3 (360)	–	m3 (385)	m2 (345)	–	m2 (445)	m2 (170)	–	m2 (540)	–
r3	m1 (300)	m4 (300)	m2 (35)	m3 (150)	m2 (400)	m2 (250)	m3 (180)	m4 (345)	–	m3 (220)	m2 (335)	–	–	m2 (445)	m3 (125)

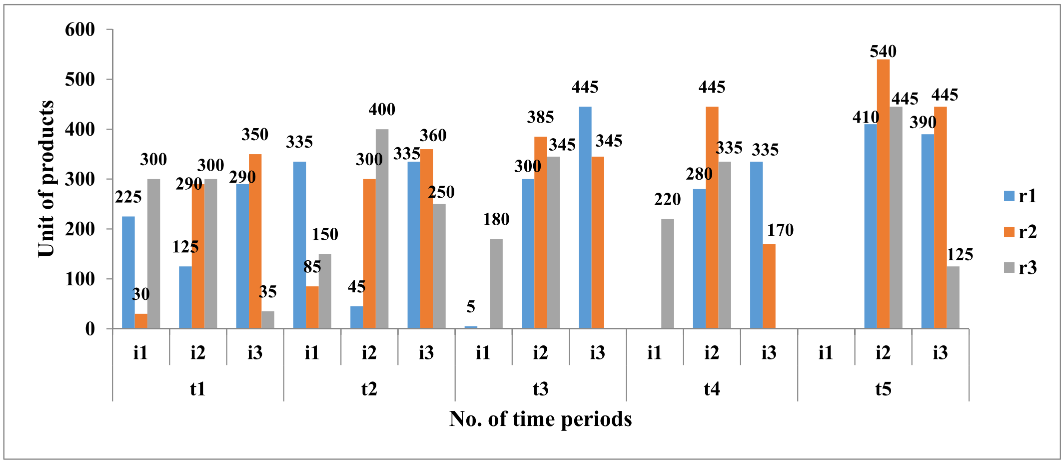

Fig. 2. Unit of products produced in ith plants in all time periods.

Table 7
Solution corresponding to unit shipped from plant to warehouse.

		t1		t2		t3		t4		t5	
		j1	j2	j1	j2	j1	j2	j1	j2	j1	j2
r1	i1	225	–	335	–	5	–	–	–	–	–
	i2	125	–	45	–	–	300	–	280	410	–
	i3	290	–	335	–	445	–	335	–	90	300
r2	i1	30	–	85	–	–	–	–	–	–	–
	i2	215	75	–	300	385	–	55	390	–	540
	i3	–	350	215	145	175	170	170	–	–	–
r3	i1	–	300	–	150	180	–	200	20	–	–
	i2	–	300	–	400	45	300	–	335	175	270
	i3	–	35	–	250	–	–	–	–	125	–

Table 8
Solution corresponding to unit shipped from warehouse to market.

		t1		t2		t3		t4		t5	
		j1	j2	j1	j2	j1	j2	j1	j2	j1	j2
r1	k1	115	–	200	–	–	225	300	–	400	–
	k2	225	–	115	–	300	–	–	200	–	300
	k3	300	–	400	–	150	75	35	80	100	–
r2	k1	245	–	300	–	225	–	–	200	–	190
	k2	–	200	–	145	–	170	–	190	–	200
	k3	–	225	–	300	335	–	225	–	–	150
r3	k1	–	155	–	250	–	200	–	155	–	100
	k2	–	330	–	350	–	100	–	200	–	170
	k3	–	150	–	200	225	–	200	–	300	–

$\{ [(0^{i1}, 0^{i2}, 0^{i3}) (205^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3}) (100^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 395^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (245^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3})], [(0^{i1}, 0^{i2}, 0^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3}) (300^{i1}, 0^{i2}, 0^{i3}) (300^{i2}, 490^{i3})], [(0^{i2}, 650^{i3}) (350^{i1}, 275^{i2}, 295^{i3}) (0^{i1}, 0^{i2}, 0^{i3}) (0^{i2}, 0^{i3}) (320^{i1}, 0^{i3})], [(0^{i1}, 0^{i3}) (0^{i1}, 0^{i2}, 185^{i3}) (0^{i1}, 345^{i2}, 0^{i3}) (0^{i1}, 210^{i2}, 0^{i3}) (0^{i1},0^{i2}, 0^{i3})] \}$

Similarly, the following nomenclature represents the result corresponding to the unit shipped from ith plant to jth warehouse to kth market.

$[(550^{31}, 225^{12}, 85^{21}, 115_{11}, 225_{12},110_{13}, 100_{14}, 190_{23}, 120_{25}) (205^{12}, 290^{22}, 600^{32}, 245_{11}, 200_{22}, 225_{23}, 200_{24}, 225_{25}) (200^{11}, 100^{12}, 350^{22}, 305^{32}, 200_{14}, 155_{21}, 200_{22}, 150_{23}, 250_{25}) (100^{12}, 395^{22}, 400^{32}, 180_{21}, 150_{22}, 200_{23}, 175_{24}, 190_{25}) (170^{11}, 345^{22}, 395^{32}, 170_{14}, 200_{21}, 190_{22}, 200_{23}, 150_{25})]$ $[(45^{11}, 575^{31}, 290^{12}, 125^{22}, 200_{11}, 200_{13}, 220_{14}, 115_{22}, 300_{25}) (150^{31}, 200^{22}, 470^{32}, 150_{11}, 145_{22}, 175_{23}, 200_{24}, 150_{25}) (295^{12}, 360^{22}, 300^{32}, 250_{21}, 150_{22}, 200_{23}, 175_{24}, 180_{25}) (245^{11}, 125^{22}, 125^{22}, 125^{32}, 110_{11}, 160_{12}, 100_{13}, 100_{24}, 150_{25}) (200^{21}, 270^{12}, 370^{22}, 200_{12}, 150_{21}, 300_{23}, 100_{24}, 90_{25})]$ $[(425^{31}, 310^{12}, 345^{22}, 60_{12}, 225_{13}, 140_{15}, 225_{21}, 240_{22}, 190_{24}) (475^{31}, 135^{12}, 445^{22}, 225_{11}, 10_{12}, 240_{15}, 160_{22}, 150_{23}, 270_{24}) (365^{11}, 345^{22}, 145^{32}, 225_{13}, 140_{15}, 200_{21}, 100_{22}, 180_{24}, 10_{25}) (440^{21}, 300^{32}, 100_{11}, 150_{12}, 190_{15}, 100_{23}, 200_{24}) (335^{31}, 390^{12}, 250^{22}, 10_{11}, 150_{14}, 175_{15}, 440_{21}, 100_{22}, 100_{23})]$ $[(140^{11}, 335^{21}, 390^{32}, 300_{11}, 115_{13}, 60_{15}, 200_{12}, 150_{14}, 40_{15}) (240^{12}, 335^{22}, 520^{32}, 200_{21}, 275_{22}, 150_{23}, 120_{24}, 350_{25}) (200^{11}, 55^{12}, 340^{22}, 410^{32}, 200_{13}, 155_{21}, 200_{22}, 220_{24}, 230_{25}) (250^{21}, 300^{12}, 410^{32}, 150_{12}, 100_{14}, 250_{21}, 130_{22}, 210_{23}, 120_{25}) (445^{12}, 400^{22}, 255^{32}, 300_{21}, 300_{22}, 100_{23}, 230_{24}, 170_{25})]$ $[(300^{21}, 450^{31}, 305^{12}, 145^{22}, 400_{11}, 100_{13}, 250_{15}, 300_{22}, 150_{24}) (150^{12}, 390^{22}, 500^{32}, 190_{21}, 200_{22}, 150_{23}, 200_{24}, 300_{25}) (120^{11}, 350^{31}, 300^{22}, 170_{12}, 150_{13}, 150_{15}, 100_{21}, 160_{24}, 40_{25}) (200^{21}, 220^{31}, 300^{12}, 180^{32}, 300_{12}, 120_{13}, 250_{21}, 100_{24}, 130_{25}) (490^{31}, 300^{22}, 50_{12}, 100_{13}, 220_{14}, 120_{15}, 200_{21}, 100_{22})]$ $[(280^{21}, 650^{31}, 150_{11}, 200_{12}, 220_{13}, 110_{14}, 250_{15}) (275^{21}, 350^{12}, 295^{32}, 25_{11}, 250_{15}, 150_{21}, 150_{22}, 145_{23}, 200_{24}) (400^{12}, 155^{22}, 350^{32}, 175_{21}, 220_{22}, 250_{23}, 160_{24}, 100_{25}) (130^{21}, 310^{22}, 330^{32}, 130_{14}, 230_{21}, 160_{22}, 140_{23}, 110_{25}) (340^{31}, 320^{12}, 50^{32}, 130_{12}, 210_{15}, 120_{21}, 100_{23},$

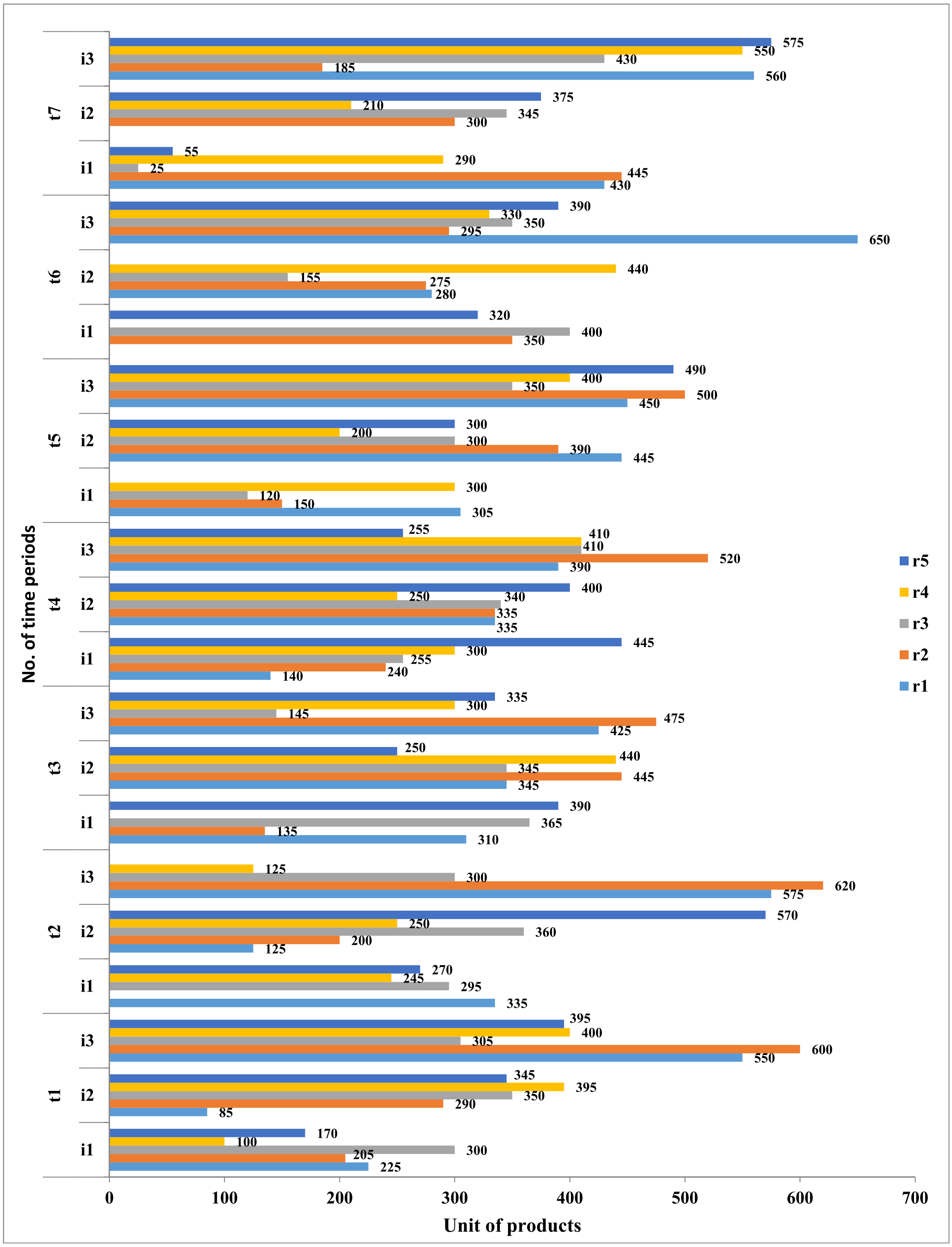

Fig. 3. Unit of products produced in ith plants in all time periods.

150_{24})] [(430^{11}, 245^{31}, 315^{32}, 220_{11}, 225_{12}, 250_{13}, 150_{24}, 165_{25}) (185^{31}, 445^{12}, 300^{22}, 185_{14}, 200_{21}, 160_{22}, 140_{23}, 35_{24}, 210_{25}) (345^{21}, 25^{12}, 430^{32}, 180_{11}, 165_{13}, 175_{22}, 150_{24}, 130_{25}) (290^{11}, 210^{21}, 550^{32}, 10_{11}, 310_{12}, 180_{15}, 230_{21}, 150_{23}, 170_{24}) (55^{12}, 375^{22}, 575^{32}, 250_{21}, 150_{22}, 175_{23}, 180_{24}, 250_{25})].

5.1.3

5.1.3 Illustration for 5i-10r-10t-3j-7k-5h-7m-8l (large problem size)

This section describes the results of the larger dataset. The objective function value for this case is 3.09302e+007 and consists of total 13,600 variables (integer) and 2005 constraints. The representative case considers five hth, seven mth, and eight lth machines. The unit of products produced in ith plants in all time periods is shown in Fig. 4a and Fig. 4b. Likewise, the nomenclature depicts the solution corresponding to the sequence of allocation of rth product on hth, mth, and lth machines as well as the result corresponding to the unit shipped from ith plant to jth warehouse to kth market is given in Appendix B.

The proposed MILP model developed in the previous section is tested on three instances of varying datasets i.e., small, moderate, and large instances and its comparative analysis is shown in the following Table 9. The variation in datasets is kept to check the accuracy and robustness of the proposed model. The model

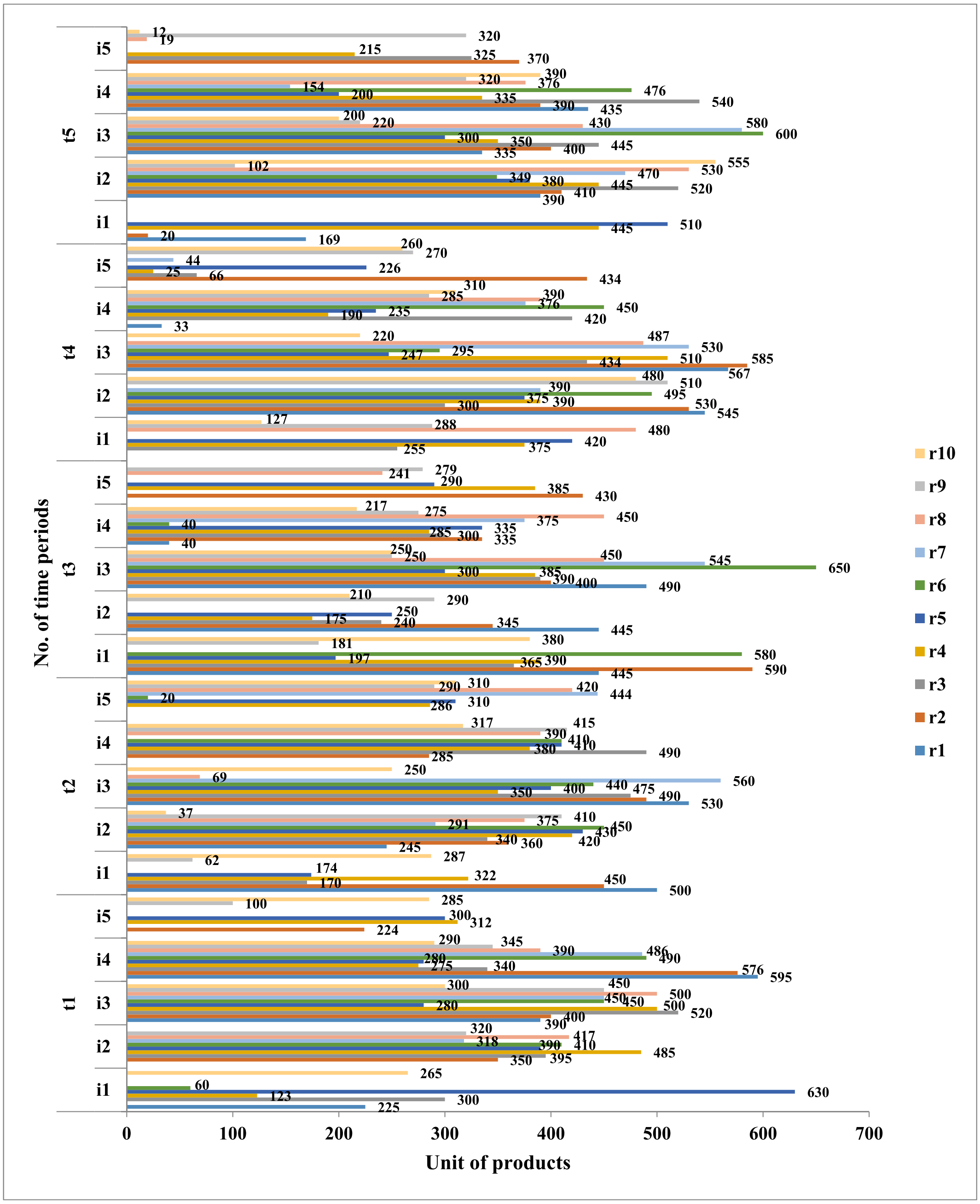

Fig. 4a. Unit of products produced in ith plants in t1-t5 time periods.

provided an optimal solution for all three instances in polynomial time. This justifies the potential of the proposed MILP model to solve the real industrial problems of a reasonable size. The results are summarized and discussed in the following subsection.

5.2

5.2 DiscussionPrevious studies are more aligned towards the conceptual models or frameworks of CE integrated with Industry 4.0 to achieve the triple bottom line of sustainability. However, the adoption of sustainability has always been an extremely essential aspect of manufacturing industries. Fatimah et al., 2019 have focused on developing a sustainable and smart waste management system using Industry 4.0 computational abilities. This leads towards gaining the three pillars of sustainability i.e., economic, social, and environmental. In support of this, Yadav et al. (2020) have developed the framework to overcome the hurdles of the sustainable supply chain through Industry 4.0 and CE based solution measures. To deal with the issues of cleaner production and CE, Moktadir et al. (2020) have proposed the decision support framework for analyzing the issues to CE practices for sustainable development.

The transition from a linear economy to CE is a major organizational change process as well as ethical business agenda to improve cleaner production and environmental performance. Particularly, in the era of advanced computational devices, existing research studies have addressed the complexity and value of Industry 4.0 which is formed on the building blocks of IoT, real-time data capabilities, and big data analytics. This research delves deeper to

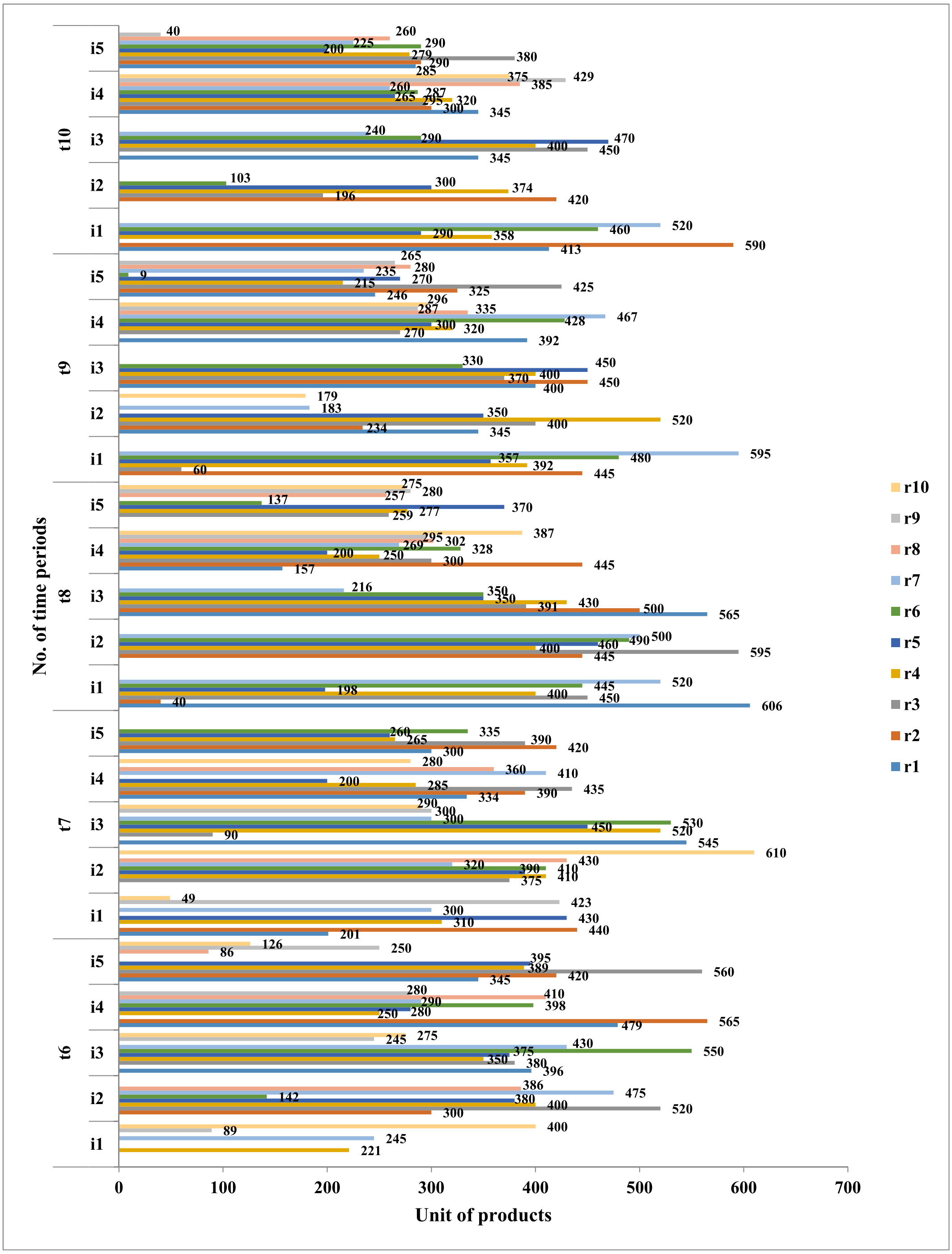

Fig. 4b. Unit of products produced in ith plants in t6-t7 time periods.

evolve a novel and innovative research challenges on the contribution of Industry 4.0 to CE and cleaner production. The integrated Industry 4.0-CE in manufacturing industries is unexplored and this is the future research opportunity to embrace the CE practices and cleaner production. It has been argued that Industry 4.0 is considered as an enabler for CE and cleaner production which can minimize the wastages and have significant economic and environmental impacts. Mastos et al. (2020) have provided evidence of the influence of IoT solutions on CE performance to improve sustainability both at the firm and supply chain levels. Existing literature contributes to linking the gap between the theoretical developments and real-world cases in the fields of Industry 4.0 and CE but lacks in providing the practical implications which could be beneficial to industry practitioners.

Several authors inspired by the frameworks and theoretical concepts developed are reviewing the emerging technologies of Industry 4.0 in CE. Their findings suggested that the connection of CPS to IoT needs to be explored to support CE. In the context of this, Ghobakhloo (2020) reviewed the fundamental design principles and technology trends of Industry 4.0 and identified its sustainability functions. It has been determined that improved production efficiency and innovative business model is the potential outcome of Industry 4.0 which paves the way for energy consumption reduction, improved precision, accuracy, and cleaner production. The

Table 9
Comparative analysis of three different instances.

	3i-3r-5t-2j-3k-3h-5m-6l (Small instance)	*3i-5r-7t-2j-5k-3h-5m-6l* (Moderate instance)	*5i-10r-10t-3j-7k-5h-7m-8l* (Large instance)
Time (t)	5	7	10
Plant (i)	3	3	5
Product (r)	3	5	10
Warehouse (j)	2	2	3
Market (k)	3	5	7
High precision machine (h)	3	3	5
Medium precision machine (m)	5	5	7
Low precision machine (l)	6	6	8
Total variables (Integers)	814	2030	13,600
Total constraints	170	460	2005
CPU time	00:00:00	00:00:01	00:00:04
Objective value	2.13655e+006	7.39469e+006	3.09302e+007

existing literature studies are deprived of the mathematical model of Industry 4.0 which can provide information on products manufactured on the allocated machines with high productivity and at low cost. The minimum energy consumption by machines for sustainability and cleaner production is partially explored in contrast with the machine cost in Industry 4.0.

The proposed MILP model is a generic formulation that can be applied to multi-product and multi-machine allocation under the Industry 4.0 ecosystem in any manufacturing firm. The study considers the cost associated with each product and each machine required to deploy in Industry 4.0 and also considers the trade-off between the energy consumption of machines and machine costs which is the novelty of the proposed mathematical model. The model has considered three types of machines viz., high precision, medium precision, and low precision machines to produce different innovative and customized multi-products. These multi-machines are considered to implement a cost-effective Industry 4.0 facility where the sequence of allocation of products on multi-machines is based on the energy consumed by machines and machines cost. Further, the model also considers the associated sensors costs for multi-machines deployed in integrated Industry 4.0 manufacturing firms to capture the real-time information of not only the unit of multi-products produced but also captures the resource usage, energy consumption and processing time of machines.

The proposed work provides flexibility to the firm to allocate the multi-products to multi-machines as per the cost and energy consumption to incur the minimum cost and high productivity with accuracy and efficiency. The proposed model plays a consequential role in achieving CE and cleaner production and ethically optimizes the energy consumption by effective product-machine allocation. It provides new perspectives on the production and consumption systems, also aims to capture real-time information on production and machines to make informed decisions, monitor the products produced. It provides insights on self-manage, integrated, and optimized cleaner production systems. The proposed model has the capability of controlling necessary production parameters viz., capacity, sensors costs, machine costs, energy consumption, the flow of products, product allocation to machines, and market demand. From Table 6, it can be inferred that product r1 is allocated on medium precision machine viz., m4, m1, and m3 at i1, i2, and i3 plant locations whereas product r2 is allocated on low precision machine i.e., l1 at plant i1 and medium precision machine viz., m3 at plant i2 and i3 respectively. Similarly, product r3 is allocated on m1, m4, and m2 medium precision machines at i1, i2 and i3 plant locations in t1 time period.

Post sequence allocation of the product on machines, the unit of products r1, r2 and r3 is produced and shipped from respective plants to warehouses. Table 7 and Fig. 2 signifies that the 225 unit of product r1 is manufactured at plant i1 and shipped to warehouse j1; likewise, 125 unit of product r1 is produced at plant i2 and 290 unit of product r1 is produced at plant i3 and shipped to warehouse j1 in t1 time period. Similar inferences can be made from Figs. 3 and 4a, b and from the nomenclature denoted in the previous section which illustrates the results obtained for moderate and large instances. Further, the 115 unit of product r1 is shipped from warehouse j1 to market k1, and 225 unit of product and 300 unit of product is shipped from warehouse j1 to markets k2 and k3 to satisfy the customer demand and can be illustrated from Table 8 and same can be inferred from the nomenclature. The allocation of products to machines is based on the requirements of the integrated Industry 4.0 manufacturing firm. The results in the form of nomenclature can be analyzed in a similar manner for moderate instance and large instance (provided in Appendix B). It can also be seen that in Table 6, medium precision machines: m4, m1, and m3 are sequenced to manufacture product r1; medium and low precision machines: l1, m3, and m3 are sequenced to manufacture product r2; and m1, m4, and m2 are sequenced to manufacture product r3. This is practical from the firms' viewpoint as it reduces the costs of manufacturing the product on hth high precision machines which could incur high cost to the firm; therefore, it brings tangible benefits to the firm. The proposed Industry 4.0 mathematical model substantially reduces energy consumption which is considered as the data transmission energy emitted from high-end processors/machines energy. This aligns the proposed model towards the CE and cleaner production and induces the industry practitioners to propose an integrated Industry 4.0-CE system that is ethically, environmentally, and economically designed. The total cost of the model may be increased but the production is cleaner and ethically optimizes the emission by optimal allocation of product-machine. The overall model is solvable in polynomial time and fulfills the sustainability criteria i.e., economical, ethical, and environmental.

6

6 Contribution, implications, and limitations of the studyThis section highlights the contribution, practical insights, and limitations gained from the proposed mathematical model to allocate multi-product and multi-machines in a data-driven Industry 4.0 manufacturing firm. These are discussed in the following subsections.

6.1

6.1 Contribution

- The paper highlights the proposed mathematical model through which Industry 4.0 dynamic facilities could be established, and real-time production data capturing and transmission could take place through deployed sensors.

- The proposed model aims to contribute to achieving the CE and cleaner production by optimal product-machine allocation in Industry 4.0 ecosystem.
- Integrated Industry 4.0-CE can dynamically monitor and control the operations of sustainable production and consumption through improved production efficiency and accuracy.
- Other factors such as energy consumed by the machines, maintenance of the machines or sensors, resource usage, or information feed-back control are also monitored to implement sustainable models aligned with cleaner production and business ethical practices of social and producer responsibility.
- The paper proposes a mathematical model for product-machine allocation in Industry 4.0 environment by jointly addressing energy consumption and cost in the manufacturing system. The model is beneficial to design a cleaner, sustainable, and economical production network for Industry 4.0.
- The proposed mathematical model optimizes the total cost i.e., machine costs, energy consumption costs, sensors costs, and transportation costs. Its practicality is validated through three randomly generated instances with varying parameters.

6.2

6.2 Implications

- The proposed mathematical model considers multi-products and multi-machines with energy consumption cost and machine costs. The proposed model has the potential to allocate the product on a machine that has low energy consumption and minimal machine costs. Thus, assisting the industry experts to establish an optimal trade-off between the energy consumption and costs for manufacturing the products.
- The model considers different sensors with its associated costs which ensure the manufacturing firm the minimum requirement of sensors for deployment in Industry 4.0 to incur an optimal cost to the firm.
- The proposed mathematical model can support highly-innovative customized products as the manufacturing is processed in an open, interconnected, and dynamic Industry 4.0 environment.
- The model generates voluminous data that could be used for predictive and cognitive analytics.
- The proposed model provides a sustainable, economical, and ethical way to minimize emissions and wastages as well as maximize production output.
- CE practices can be enhanced by means of Industry 4.0 to improve competitiveness and ethical business agenda of the manufacturing process.
- The model sheds light not only on the potentials of Industry 4.0 but also in terms of cleaner production and CE.
- The model has the capability to establish an ethical business model integrated with cleaner production and gains economic and environmental aspects of CE.

6.3

6.3 Limitations

- The proposed model can be extended further to incorporate big data and carbon constraints to monitor the emissions of high precision machines.
- The model is proposed for deterministic demand, which can be further extended for probabilistic data.
- The model has not considered transshipment which could be a future scope of the work.
- The model has not considered the reverse supply chain through which sustainability can be improved.

7

7 Conclusion and future research directionsThe paper proposes a MILP formulation to establish a dynamic Industry 4.0 facility through multi-product and multi-machine allocation. The model discussed in this paper considers various parameters linking the plant to the warehouse to market. Also, the model features sensors costs considering the unit cost, installation, calibration, and maintenance cost of sensors in an integrated Industry 4.0 manufacturing environment. The proposed model establishes an optimal trade-off between energy consumption and machine costs which lead towards economical and sustainable responsibilities. The main objective of the paper is the sequence allocation of products on three variants of machines based on energy consumption and machine costs. The model suggests that the products are allocated and produced on machines that have low energy consumption and low machines costs to optimally reduce the total manufacturing cost. On the other hand, if the products are allocated on machine type which has high energy consumption but low machine costs or vice-versa will increase the total manufacturing costs and energy consumption rate. Therefore, this has been taken care of in the proposed mathematical model by balancing optimal trade-off. The three different case illustrations i.e., small, moderate, and large instances depict optimal overall cost to establish Industry 4.0 in any manufacturing or service industries.

The proposed mathematical model of Industry 4.0 is a novel attempt and contemplates with CE and cleaner production and ethically minimizes the energy consumption of machines by effective product-machine allocation. The model provides not only the sustainable and environmental solution but also economic solution and linked with business ethical practices of producer and social responsibility. In the shorter run, the economical aspects cannot be minimized but in the longer run, it maximizes and provides a fruitful solution in terms of reduced energy consumption and enhanced cleaner production in the integrated Industry 4.0-CE environment.

As a future scope, the model can be further extended with carbon constraint, economical and sustainable features. Besides, it can also include the quantitative synergistic of information, material, and energy flow. Furthermore, the transshipment network and sensors deployment in warehouses also would be an addition to the proposed work.

Author contributionShubhangini Rajput Writing - original draft, Writing - review & editing, developed the proposed model as well as the numerical case. She solved the proposed OR based model in LINGO and prepared the revised paper considering the reviewers comments. She also drafted the paper. Surya Prakash Singh provided the initial research idea of the proposed and assisted in LINGO coding. He also assisted on improving the paper based on reviewer's comments. Overall, the paper was discussed and prepared by these above two authors where several round of discussion happened.

Declaration of competing interestThe authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

```
Model:
SETS:
HIGHMACHINE/1..3/;
MEDIUMMACHINE/1..5/;
LOWMACHINE/1..6/;
PLANT/1..3/;
WAREHOUSE/1..2/;
MARKET/1..3/;
PRODUCT/1..3/;
TIME/1..5/;
PXRXH(PLANT,PRODUCT,HIGHMACHINE,TIME):P1,MC,EC,PTH,UPH,INH,CAH,MAH;
PXRXM(PLANT,PRODUCT,MEDIUMMACHINE,TIME):P2,MM,ECM,PTM,UPM,INM,CAM,MAM;
PXRXL(PLANT,PRODUCT,LOWMACHINE,TIME):P3,LM,ECL,PTL,UPL,INL,CAL,MAL;
PXRXW(PLANT,PRODUCT,WAREHOUSE,TIME):Q,TC1_;
WXRXM(WAREHOUSE,PRODUCT,MARKET,TIME):W,TC2_;
PXRXT(PLANT,PRODUCT,TIME):PQ;
RXKXT(PRODUCT,MARKET,TIME):D;
ENDSETS

DATA:
!Import data from excel file;
MC,EC,PTH,UPH,INH,CAH,MAH,MM,ECM,PTM,UPM,INM,CAM,MAM,LM,ECL,PTL,UPL,INL,CAL,M
AL,TC1_,TC2_,PQ,D= @OLE('C:\Users\Dell\Desktop\industry 4.0 code\instances
data\instance1.xlsx');
!Export output to excel file;
@OLE('C:\Users\Dell\Desktop\instance1 op.xlsx')=
MC,EC,PTH,UPH,INH,CAH,MAH,MM,ECM,PTM,UPM,INM,CAM,MAM,LM,ECL,PTL,UPL,INL,CAL,M
AL,TC1_,TC2_,PQ,D,Q,W;
ENDDATA

!Objective function;
Z1=@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(HIGHMACHINE(H):@SUM(TIME(T):(P1(I,R,H,T
)*MC(I,R,H,T))))))+@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(MEDIUMMACHINE(M):@SUM(T
IME(T):(P2(I,R,M,T)*MM(I,R,M,T))))))+@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(LOWMA
CHINE(L):@SUM(TIME(T):(P3(I,R,L,T)*LM(I,R,L,T))))));

Z2=@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(HIGHMACHINE(H):@SUM(TIME(T):(P1(I,R,H,T
)*(EC(I,R,H,T)+PTH(I,R,H,T)))))))+@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(MEDIUMMA
CHINE(M):@SUM(TIME(T):(P2(I,R,M,T)*(ECM(I,R,M,T)+PTM(I,R,M,T)))))))+@SUM(PLAN
T(I):@SUM(PRODUCT(R):@SUM(LOWMACHINE(L):@SUM(TIME(T):(P3(I,R,L,T)*(ECL(I,R,L,
T)+PTL(I,R,L,T)))))));

Z3=@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(HIGHMACHINE(H):@SUM(TIME(T):(P1(I,R,H,T
)*(UPH(I,R,H,T)+INH(I,R,H,T)+CAH(I,R,H,T)+MAH(I,R,H,T)))))))+@SUM(PLANT(I):@S
UM(PRODUCT(R):@SUM(MEDIUMMACHINE(M):@SUM(TIME(T):(P2(I,R,M,T)*(UPM(I,R,M,T)+I
NM(I,R,M,T)+CAM(I,R,M,T)+MAM(I,R,M,T)))))))+@SUM(PLANT(I):@SUM(PRODUCT(R):@SU
M(LOWMACHINE(L):@SUM(TIME(T):(P3(I,R,L,T)*(UPL(I,R,L,T)+INL(I,R,L,T)+CAL(I,R,
L,T)+MAL(I,R,L,T)))))));

Z4=@SUM(PLANT(I):@SUM(PRODUCT(R):@SUM(WAREHOUSE(J):@SUM(TIME(T):(Q(I,R,J,T)*T
C1_(I,R,J,T))))))+@SUM(WAREHOUSE(J):@SUM(PRODUCT(R):@SUM(MARKET(K):@SUM(TIME(
T):(W(J,R,K,T)*TC2_(J,R,K,T))))));

MIN= Z1+Z2+Z3+Z4;

!Constraints;
@FOR(PLANT(I):@FOR(TIME(T):@FOR(PRODUCT(R):(@SUM(HIGHMACHINE(H):P1(I,R,H,T)))
+@SUM(MEDIUMMACHINE(M):@SUM(PRODUCT(R):P2(I,R,M,T)))+@SUM(LOWMACHINE(L):@SUM(
PRODUCT(R):P3(I,R,L,T)))<=PQ(I,R,T))));


@FOR(PLANT(I):@FOR(TIME(T):@FOR(PRODUCT(R):@SUM(WAREHOUSE(J):Q(I,R,J,T))=
@SUM(HIGHMACHINE(H):@SUM(PRODUCT(R):P1(I,R,H,T)))+@SUM(MEDIUMMACHINE(M):@SUM(
PRODUCT(R):P2(I,R,M,T)))+@SUM(LOWMACHINE(L):@SUM(PRODUCT(R):P3(I,R,L,T))))));

@FOR(WAREHOUSE(J):@FOR(TIME(T):@FOR(PRODUCT(R):@SUM(PLANT(I): Q(I,R,J,T))=
@SUM(MARKET(K):W(J,R,K,T) ))) );

@FOR(MARKET(K):@FOR(TIME(T):@FOR(PRODUCT(R):@SUM(WAREHOUSE(J):W(J,R,K,T)) >=
D(R,K,T))));

!Integer variables;
@FOR(PLANT(I):@FOR(PRODUCT(R):@FOR(HIGHMACHINE(H):@FOR(TIME(T):@GIN(P1)))));
@FOR(PLANT(I):@FOR(PRODUCT(R):@FOR(MEDIUMMACHINE(M):@FOR(TIME(T):@GIN(P2)))))
;
@FOR(PLANT(I):@FOR(PRODUCT(R):@FOR(LOWMACHINE(L):@FOR(TIME(T):@GIN(P3)))));
@FOR(PLANT(I):@FOR(PRODUCT(R):@FOR(WAREHOUSE(J):@FOR(TIME(T):@GIN(Q)))));
@FOR(WAREHOUSE(J):@FOR(PRODUCT(R):@FOR(MARKET(K):@FOR(TIME(T):@GIN(W)))));
```

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Appendix C

Appendix C Supplementary dataSupplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123853.

Appendix A

Lingo code

Appendix B

Nomenclature represents the result corresponding to the sequence of allocation of rth product on hth, mth and lth machines{ [$(0^{i1}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1},0^{i2}, 0^{i3}, 340^{i4})$ $(123^{i1}, 0^{i2}, 500^{i3},0^{i4}, 312^{i5})$ $(630^{i1},0^{i2}, 0^{i3}, 0^{i4}, 300^{i5})$ $(0^{i1}, 410^{i2},450^{i3}, 0^{i4})$ $(0^{i2}, 450^{i3}, 0^{i4})$ $(0^{i2}, 0^{i3}, 0^{i4})$ $(320^{i2}, 0^{i3}, 345^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 0^{i5})$], [$(0^{i1}, 0^{i2}, 0^{i3})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 490^{i4})$ $(0^{i1}, 420^{i2}, 0^{i3}, 0^{i4}, 286^{i5})$ $(174^{i1}, 430^{i2}, 0^{i3}, 0^{i4}, 310^{i5})$ $(450^{i2}, 440^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i5})$ $(0^{i2},0^{i3}, 390^{i4}, 0^{i5})$ $(0^{i1}, 410^{i2}, 0^{i4}, 0^{i5})$ $(0^{i1},37^{i2}, 0^{i3},0^{i4},0^{i5})$], [$(0^{i1}, 445^{i2}, 0^{i3}, 40^{i4})$ $(590^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 430^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(390^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 385^{i5})$ $(197^{i1}, 250^{i2}, 0^{i3}, 0^{i4}, 290^{i5})$ $(0^{i1}, 650^{i3}, 40^{i4})$ $(0^{i3}, 375^{i4}, 0^{i5})$ $(0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 275^{i4},0^{i5})$ $(0^{i1},0^{i2}, 0^{i3},217^{i4})$], [$(545^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i3},0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 420^{i4},0^{i5})$ $(375^{i1}, 390^{i2}, 0^{i3}, 0^{i4}, 25^{i5})$ $(420^{i1}, 375^{i2}, 0^{i3}, 0^{i4}, 226^{i5})$ $(0^{i2}, 295^{i3},0^{i4})$ $(0^{i2}, 0^{i3}, 376^{i4},0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4})$ $(0^{i1}, 510^{i2}, 0^{i4}, 0^{i5})$ $(0^{i1},0^{i2}, 0^{i3},310^{i4},0^{i5})$], [$(0^{i1}, 390^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4},0^{i5})$ $(445^{i1}, 445^{i2}, 0^{i3}, 0^{i4}, 215^{i5})$ $(510^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(349^{i2}, 0^{i3},0^{i4})$ $(0^{i2}, 0^{i3}, 154^{i4})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(102^{i2}, 0^{i3}, 0^{i4}, 320^{i5})$ $(0^{i2}, 0^{i3},390^{i4},0^{i5})$], [$(396^{i3}, 479^{i4}, 345^{i5})$ $(300^{i2}, 0^{i4}, 0^{i5})$ $(520^{i2}, 380^{i3}, 0^{i5})$ $(221^{i1}, 0^{i2}, 350^{i3}, 0^{i4}, 389^{i5})$ $(380^{i2}, 0^{i3}, 0^{i4}, 395^{i5})$ $(0^{i2}, 550^{i3},398^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 280^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3},0^{i5})$], [$(0^{i1}, 545^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i4}, 0^{i5})$ $(375^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(310^{i1}, 410^{i2}, 520^{i3}, 285^{i4}, 265^{i5})$ $(430^{i1}, 590^{i2}, 0^{i3}, 200^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3},0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i4})$ $(0^{i1}, 0^{i3})$ $(0^{i1}, 0^{i2}, 0^{i3},0^{i4})$], [$(606^{i1}, 545^{i3}, 0^{i4})$ $(0^{i1}, 445^{i2}, 0^{i3}, 0^{i4})$ $(450^{i1}, 595^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(400^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 460^{i2}, 0^{i3}, 0^{i4}, 370^{i5})$ $(445^{i1}, 0^{i2}, 350^{i3},0^{i4}, 137^{i5})$ $(520^{i1}, 500^{i2}, 216^{i3}, 0^{i4})$ $(0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(387^{i4},0^{i5})$], [$(345^{i2}, 0^{i3}, 0^{i4},0^{i5})$ $(0^{i1}, 234^{i2}, 0^{i3}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(392^{i1}, 520^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(357^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 270^{i5})$ $(480^{i1}, 330^{i3},428^{i4}, 0^{i5})$ $(595^{i1}, 0^{i2}, 0^{i4}, 0^{i5})$ $(335^{i4}, 0^{i5})$ $(287^{i4}, 0^{i5})$ $(0^{i2},0^{i4})$], [$(0^{i1}, 0^{i3}, 0^{i4},0^{i5})$ $(590^{i1}, 420^{i2}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(358^{i1}, 374^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(290^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 200^{i5})$ $(460^{i1}, 103^{i2}, 290^{i3},0^{i4}, 290^{i5})$ $(520^{i1}, 240^{i3}, 260^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ (375^{i4})].

[$(225^{i1}, 390^{i3}, 595^{i4})$ $(350^{i2}, 400^{i3}, 576^{i4}, 224^{i5})$ $(300^{i1}, 395^{i2}, 520^{i3}, 0^{i4})$ $(0^{i1}, 485^{i2}, 0^{i3}, 275^{i4}, 0^{i5})$ $(0^{i1}, 390^{i2}, 280^{i3}, 280^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3},490^{i4})$ $(0^{i2}, 0^{i3}, 486^{i4})$ $(417^{i2}, 0^{i3}, 390^{i4})$ $(0^{i2}, 0^{i3}, 0^{i4}, 100^{i5})$ $(265^{i1},0^{i3},290^{i4}, 285^{i5})$], [$(500^{i1}, 245^{i2}, 530^{i3})$ $(450^{i1}, 360^{i2}, 490^{i3}, 285^{i4})$ $(170^{i1}, 340^{i2}, 475^{i3}, 0^{i4})$ $(322^{i1}, 0^{i2}, 350^{i3}, 380^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 400^{i3}, 410^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 410^{i4},20^{i5})$ $(291^{i2}, 0^{i3}, 444^{i5})$ $(375^{i2}, 0^{i3}, 0^{i4}, 420^{i5})$ $(62^{i1}, 0^{i2}, 415^{i4}, 290^{i5})$ $(287^{i1},0^{i2},0^{i3}, 317^{i4}, 310^{i5})$], [$(445^{i1}, 0^{i2}, 490^{i3}, 0^{i4})$ $(0^{i1}, 345^{i2}, 400^{i3}, 335^{i4}, 430^{i5})$ $(365^{i1}, 240^{i2}, 390^{i3}, 300^{i4})$ $(0^{i1}, 175^{i2}, 385^{i3}, 285^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 300^{i3}, 335^{i4}, 0^{i5})$ $(580^{i1}, 0^{i3}, 0^{i4})$ $(0^{i3}, 0^{i4})$ $(0^{i3}, 450^{i4}, 241^{i5})$ $(0^{i1}, 290^{i2}, 0^{i3}, 0^{i4}, 279^{i5})$ $(380^{i1},0^{i2},0^{i3}, 0^{i4})$], [$(0^{i2}, 567^{i3}, 33^{i4})$ $(530^{i2}, 585^{i3},0^{i5})$ $(255^{i1}, 300^{i2}, 434^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 510^{i3}, 190^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 247^{i3}, 235^{i4}, 0^{i5})$ $(495^{i2}, 0^{i3}, 450^{i4})$ $(390^{i2}, 0^{i3}, 0^{i4}, 44^{i5})$ $(480^{i1}, 0^{i3}, 390^{i4})$ $(288^{i1}, 0^{i2}, 285^{i4}, 270^{i5})$ $(0^{i1}, 480^{i2},0^{i3},0^{i4}, 260^{i5})$], [$(169^{i1}, 0^{i2}, 335^{i3}, 435^{i4})$ $(20^{i1}, 410^{i2}, 400^{i3}, 390^{i4}, 0^{i5})$ $(520^{i2}, 445^{i3}, 540^{i4}, 325^{i5})$ $(0^{i1}, 0^{i2}, 350^{i3}, 335^{i4}, 0^{i5})$ $(0^{i1}, 380^{i2}, 300^{i3}, 200^{i4})$ $(0^{i2}, 0^{i3}, 476^{i4})$ $(470^{i2}, 0^{i3}, 0^{i4})$ $(530^{i2}, 0^{i3}, 376^{i4},19^{i5})$ $(0^{i2}, 0^{i3}, 520^{i4},0^{i5})$ $(555^{i2},0^{i3},0^{i4}, 12^{i5})$], [$(0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 565^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i5})$ $(0^{i1}, 400^{i2}, 0^{i3}, 250^{i4}, 0^{i5})$ $(0^{i2}, 375^{i3}, 280^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 290^{i4})$ $(0^{i2}, 410^{i4}, 86^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 520^{i5})$ $(0^{i1},0^{i3},126^{i5})$], [$(201^{i1}, 0^{i3}, 334^{i4}, 0^{i5})$ $(440^{i1}, 390^{i4}, 0^{i5})$ $(0^{i2}, 90^{i3}, 435^{i4}, 390^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 450^{i3}, 0^{i4}, 260^{i5})$ $(0^{i2}, 0^{i3}, 345^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 410^{i4})$ $(0^{i2}, 366^{i4})$ $(0^{i1}, 0^{i3})$ $(0^{i1}, 0^{i2},0^{i3},280^{i5})$], [$(0^{i1}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 400^{i2}, 430^{i3}, 250^{i4}, 0^{i5})$ $(198^{i1}, 0^{i2}, 350^{i3}, 200^{i4}, 0^{i5})$ $(0^{i1}, 490^{i2}, 0^{i3}, 328^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 269^{i4})$ $(302^{i4}, 257^{i5})$ $(295^{i4}, 280^{i5})$ $(0^{i4},275^{i5})$], [$(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(445^{i1}, 0^{i2}, 0^{i3}, 0^{i5})$ $(60^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 400^{i3}, 320^{i4}, 215^{i5})$ $(0^{i1}, 350^{i2}, 450^{i3}, 300^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 9^{i5})$ $(0^{i1}, 183^{i2}, 467^{i4}, 235^{i5})$ $(0^{i4}, 280^{i5})$ $(0^{i4}, 265^{i5})$ $(179^{i2},296^{i4})$], [$(413^{i1}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 400^{i3}, 320^{i4}, 279^{i5})$ $(0^{i1}, 300^{i2}, 470^{i3}, 265^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 287^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 225^{i5})$ $(385^{i4}, 260^{i5})$ $(429^{i4}, 40^{i5})$ (0^{i4})].

[$(0^{i1}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(60^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(318^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2},500^{i3}, 0^{i4})$ $(0^{i2}, 450^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1},300^{i3}, 0^{i4}, 0^{i5})$], [$(0^{i1}, 0^{i2}, 0^{i3})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 560^{i3}, 0^{i5})$ $(0^{i2}, 69^{i3},0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2},250^{i3}, 0^{i4}, 0^{i5})$], [$(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4})$ $(545^{i3}, 0^{i4})$ $(450^{i3},0^{i4}, 0^{i5})$ $(181^{i1}, 0^{i2}, 250^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 210^{i2},250^{i3}, 0^{i4})$], [$(0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 0^{i3}, 434^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 66^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 530^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1},487^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i4}, 0^{i5})$ $(127^{i1}, 0^{i2},220^{i3}, 0^{i4},0^{i5})$], [$(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 370^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(0^{i2}, 600^{i3}, 0^{i4})$ $(0^{i2}, 580^{i3}, 0^{i4})$ $(0^{i2}, 430^{i3},0^{i4}, 0^{i5})$ $(0^{i2}, 220^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2},200^{i3}, 0^{i4},0^{i5})$], [$(0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i4}, 420^{i5})$ $(0^{i2}, 0^{i3}, 560^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(142^{i2}, 0^{i3}, 0^{i4})$ $(245^{i1}, 475^{i2}, 430^{i3}, 0^{i4})$ $(386^{i2}, 0^{i4}, 0^{i5})$ $(89^{i1}, 245^{i3}, 0^{i4}, 0^{i5})$ $(400^{i1},275^{i3}, 0^{i5})$], [$(0^{i1}, 0^{i3}, 0^{i4}, 300^{i5})$ $(0^{i1}, 0^{i4}, 420^{i5})$ $(0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(410^{i2}, 530^{i3}, 0^{i5})$ $(300^{i1}, 320^{i2}, 300^{i3}, 0^{i4})$ $(430^{i2}, 0^{i4})$ $(423^{i1}, 300^{i3})$ $(49^{i1}, 610^{i2},290^{i3}, 0^{i4})$], [$(0^{i1}, 165^{i3}, 157^{i4})$ $(40^{i1}, 0^{i2}, 500^{i3}, 445^{i4})$ $(0^{i1}, 0^{i2}, 391^{i3}, 300^{i4}, 259^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4})$ $(430^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$], [$(0^{i2}, 400^{i3}, 392^{i4}, 246^{i5})$ $(0^{i1}, 0^{i2}, 450^{i3}, 325^{i5})$ $(0^{i1}, 400^{i2}, 370^{i3}, 270^{i4}, 425^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(0^{i2}, 0^{i4})$], [$(0^{i1}, 345^{i3}, 345^{i4}, 285^{i5})$ $(0^{i1}, 0^{i2}, 300^{i4}, 290^{i5})$ $(0^{i2}, 0^{i3}, 295^{i4}, 380^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i2}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i1}, 0^{i3}, 0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ $(0^{i4}, 0^{i5})$ (0^{i4})].

Nomenclature represents the result corresponding to the unit shipped from ith plant to jth warehouse to kth market[$(225^{11}, 390^{32}, 595^{43}, 125_{12}, 100_{14}, 300_{23}, 90_{25}, 115_{31}, 100_{32}, 30_{35}, 190_{36}, 160_{37})$ $(1^{31}, 224^{51}, 159^{32}, 576^{42}, 350^{23}, 240^{33}, 225_{15}, 245_{21}, 200_{22}, 290_{26}, 225_{33}, 200_{34}, 165_{37})$ $(300^{11}, 395^{22}, 340^{42}, 520^{33}, 20_{11}, 80_{12}, 200_{14}, 135_{21}, 320_{26}, 280_{27}, 120_{32}, 150_{33}, 250_{35})$ $(123^{12}, 485^{22}, 500^{32}, 275^{42}, 312^{53}, 310_{21}, 330_{23}, 180_{24}, 145_{25}, 218_{26}, 200_{27}, 290_{32}, 22_{36})$ $(55^{31}, 280^{41}, 630^{12}, 390^{22}, 225^{32}, 300^{52}, 335_{17}, 200_{21}, 275_{22}, 310_{23}, 220_{24}, 200_{25}, 340_{26})$ $(490^{41}, 60^{12}, 410^{22}, 450^{33}, 130_{13}, 110_{14}, 250_{16}, 120_{22}, 20_{23}, 330_{27}, 200_{31}, 60_{34}, 190_{35})$ $(318^{21}, 215^{32}, 486^{42}, 235^{33}, 129_{12}, 9_{14}, 180_{17}, 266_{21}, 138_{23}, 131_{24}, 166_{25}, 235_{36})$ $(500^{31}, 115^{41}, 417^{22}, 275^{42}, 165_{13}, 220_{16}, 230_{17}, 178_{21}, 180_{22}, 171_{24}, 163_{25})$ $(450^{31}, 345^{41}, 320^{22}, 100^{53}, 175_{12}, 235_{15}, 170_{16}, 215_{17}, 135_{21}, 145_{23}, 40_{26}, 100_{34})$ $(300^{31}, 285^{51}, 265^{13}, 290^{43}, 167_{12}, 109_{13}, 100_{15}, 209_{16}, 120_{31}, 35_{33}, 190_{34}, 210_{37})$] [$(500^{11}, 35^{21}, 530^{32}, 210^{23}, 200_{11}, 115_{12}, 220_{14}, 200_{23}, 200_{25}, 130_{27}, 100_{35}, 110_{36})$ $(65^{21}, 285^{41}, 450^{12}, 295^{22}, 45^{32}, 445^{33}, 350_{14}, 300_{21}, 150_{25}, 180_{26}, 160_{27}, 145_{32}, 300_{33})$ $(170^{11}, 490^{41}, 475^{32}, 340^{23}, 250_{11}, 210_{15}, 200_{17}, 150_{22}, 150_{23}, 175_{24}, 50_{33}, 30_{35}, 260_{36})$ $(208^{12}, 350^{32}, 114^{13}, 420^{23}, 380^{43}, 286^{53}, 310_{23}, 248_{24}, 220_{31}, 250_{32}, 190_{35}, 275_{36}, 265_{37})$ $(400^{31}, 174^{12},$

$410^{42}, 310^{52}, 430^{23}, 185_{16}, 215_{17}, 265_{21}, 94_{22}, 310_{23}, 200_{25}, 25_{26}, 196_{32},$ $234_{34}) (410^{41}, 450^{23}, 440^{33}, 20^{53}, 35_{11}, 165_{12}, 210_{15}, 145_{31}, 145_{33}, 170_{34},$ $250_{36}, 200_{37}) (291^{22}, 235^{32}, 325^{33}, 444^{53}, 156_{23}, 190_{25}, 180_{26}, 178_{31},$ $194_{32}, 167_{34}, 230_{37}) (50^{21}, 69^{31}, 390^{41}, 325^{22}, 420^{53}, 145_{14}, 130_{15}, 234_{17},$ $135_{21}, 190_{26}, 65_{31}, 180_{32}, 175_{33}) (62^{11}, 36^{41}, 290^{51}, 140^{22}, 270^{23}, 379^{43},$ $178_{14}, 210_{15}, 140_{22}, 120_{31}, 165_{33}, 175_{36}, 189_{37}) (37^{21}, 310^{51}, 287^{12}, 70^{32},$ $180^{33}, 317^{43}, 60_{11}, 180_{14}, 107_{17}, 170_{25}, 187_{26}, 97_{31}, 190_{32}, 210_{33})] [$ $(360^{11}, 80^{21}, 85^{12}, 490^{32}, 365^{23}, 40^{43}, 300_{12}, 140_{15}, 225_{23}, 190_{25}, 160_{26},$ $225_{31}, 180_{37}) (115^{12}, 345^{22}, 140^{32}, 335^{42}, 260^{33}, 430^{53}, 225_{21}, 270_{24},$ $240_{25}, 200_{27}, 170_{32}, 335_{33}, 185_{36}) (180^{21}, 365^{12}, 60^{23}, 390^{33}, 300^{43},$ $180_{14}, 100_{22}, 225_{23}, 40_{26}, 200_{31}, 150_{35}, 190_{36}, 210_{37}) (390^{12}, 285^{42},$ $385^{52}, 175^{23}, 385^{33}, 230_{21}, 190_{22}, 200_{23}, 240_{26}, 200_{27}, 250_{34}, 200_{35},$ $110_{37}) (197^{12}, 335^{42}, 250^{23}, 300^{33}, 290^{53}, 102_{21}, 200_{22}, 230_{27}, 118_{31},$ $145_{33}, 167_{34}, 200_{35}, 210_{36}) (650^{31}, 580^{12}, 40^{43}, 250_{11}, 140_{13}, 250_{16}, 10_{17},$ $200_{22}, 120_{24}, 100_{25}, 160_{27}, 40_{37}) (265^{31}, 280^{32}, 39^{42}, 336^{43}, 100_{15}, 165_{17},$ $134_{23}, 185_{26}, 115_{31}, 121_{32}, 100_{34}) (450^{41}, 450^{32}, 241^{53}, 18_{13}, 130_{14}, 190_{15},$ $112_{17}, 142_{21}, 192_{22}, 116_{23}, 34_{31}, 207_{36}) (250^{31}, 275^{41}, 134^{12}, 47^{13}, 290^{23},$ $279^{53}, 176_{11}, 200_{15}, 149_{16}, 134_{22}, 220_{33}, 190_{34}, 26_{36}, 180_{37}) (210^{21},$ $250^{31}, 380^{12}, 217^{42}, 135_{12}, 145_{15}, 180_{16}, 100_{21}, 179_{23}, 150_{24}, 168_{27})] [$ $(100^{31}, 545^{22}, 33^{42}, 467^{33}, 100_{15}, 300_{21}, 200_{22}, 78_{24}, 115_{33}, 72_{34}, 130_{36},$ $150_{37}) (340^{51}, 585^{32}, 530^{23}, 94^{53}, 120_{14}, 220_{17}, 275_{22}, 76_{25}, 234_{26},$ $200_{31}, 150_{33}, 274_{35}) (300^{21}, 434^{31}, 255^{12}, 66^{52}, 420^{43}, 165_{12}, 109_{13},$ $220_{14}, 240_{16}, 91_{23}, 230_{72}, 155_{31}, 35_{32}, 230_{35}) (190^{41}, 370^{12}, 510^{32}, 5^{13},$ $390^{23}, 25^{53}, 190_{13}, 210_{21}, 170_{22}, 50_{23}, 250_{25}, 200_{27}, 230_{34}, 190_{36}) (247^{31},$ $420^{12}, 152^{22}, 226^{52}, 223^{23}, 235^{43}, 155_{14}, 92_{17}, 289_{21}, 235_{22}, 210_{25}, 64_{27},$ $273_{33}, 185_{36}) (495^{21}, 125^{31}, 450^{42}, 170^{33}, 150_{11}, 165_{12}, 155_{13}, 150_{16},$ $190_{25}, 50_{26}, 210_{27}, 170_{34}) (530^{31}, 355^{42}, 390^{23}, 21^{43}, 44^{53}, 100_{14}, 250_{15},$ $180_{17}, 170_{23}, 185_{26}, 150_{31}, 195_{32}, 110_{34}) (320^{12}, 487^{32}, 160^{13}, 390^{43},$ $220_{21}, 210_{22}, 190_{23}, 187_{24}, 140_{35}, 195_{36}, 215_{37}) (133^{21}, 285^{41}, 377^{22},$ $288^{13}, 270^{53}, 172_{11}, 165_{12}, 81_{17}, 184_{24}, 193_{25}, 180_{33}, 214_{36}, 164_{37}) (127^{11},$ $220^{31}, 37^{51}, 310^{42}, 25^{52}, 480^{23}, 198^{53}, 165_{12}, 219_{16}, 125_{21}, 210_{23}, 250_{34},$ $146_{35}, 282_{37})] [(224^{21}, 169^{12}, 166^{22}, 335^{32}, 435^{43}, 224_{11}, 130_{22}, 150_{24},$ $250_{25}, 140_{26}, 170_{32}, 100_{33}, 165_{37}) (20^{11}, 410^{21}, 200^{31}, 390^{41}, 200^{32},$ $370^{53}, 200_{14}, 270_{15}, 280_{16}, 270_{17}, 200_{22}, 190_{31}, 150_{33}, 30_{35}) (190^{41},$ $325^{51}, 520^{22}, 445^{32}, 350^{43}, 135_{12}, 380_{16}, 100_{21}, 35_{22}, 300_{23}, 330_{24},$ $200_{27}, 350_{35}) (445^{12}, 350^{32}, 35^{42}, 445^{23}, 300^{43}, 215^{53}, 230_{21}, 300_{23},$ $300_{27}, 250_{32}, 290_{34}, 200_{35}, 220_{36}) (235^{31}, 510^{12}, 65^{32}, 200^{42}, 380^{23},$ $235_{16}, 20_{21}, 200_{22}, 175_{24}, 180_{25}, 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210_{21}, 170_{25}, 165_{33}) (280^{41}, 49^{12}, 290^{32}, 610^{23}, 79_{14}, 201_{16},$ $145_{22}, 175_{23}, 19_{26}, 120_{31}, 111_{34}, 164_{35}, 215_{37})] [(606^{11}, 565^{32}, 157^{43},$ $145_{11}, 167_{12}, 134_{13}, 160_{16}, 237_{24}, 153_{25}, 175_{27}, 157_{35}) (400^{41}, 500^{32}, 40^{13},$ $445^{23}, 45^{43}, 190_{14}, 210_{15}, 150_{22}, 130_{23}, 220_{26}, 210_{31}, 70_{33}, 250_{37}) (280^{31},$ $300^{41}, 134^{12}, 595^{22}, 111^{32}, 316^{13}, 259^{53}, 310_{13}, 270_{15}, 230_{21}, 300_{24},$ $310_{27}, 290_{32}, 285_{36}) (400^{11}, 250^{41}, 400^{22}, 277^{52}, 430^{33}, 230_{13}, 200_{14},$ $145_{15}, 75_{16}, 390_{21}, 105_{26}, 182_{27}, 380_{32}, 50_{37}) (198^{11}, 350^{31}, 370^{51}, 65^{22},$ $200^{42}, 395^{23}, 300_{11}, 220_{12}, 208_{13}, 190_{16}, 26_{23}, 239_{24}, 200_{35}, 195_{37})$ $(328^{41}, 137^{51}, 445^{12}, 250^{22}, 350^{32}, 240^{23}, 215_{14}, 250_{15}, 220_{21}, 190_{22},$ $310_{23}, 105_{24}, 220_{27}, 240_{36}) (500^{21}, 216^{31}, 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$200_{27}, 200_{34}, 20_{35}, 300_{36}) (350^{21}, 300^{41}, 270^{51}, 357^{12}, 450^{33}, 200_{11},$ $230_{13}, 290_{15}, 200_{17}, 222_{22}, 135_{24}, 70_{33}, 145_{34}, 235_{36}) (480^{11}, 38^{31},$ $428^{42}, 292^{33}, 9^{53}, 190_{11}, 215_{12}, 113_{15}, 186_{23}, 62_{25}, 180_{26}, 156_{34}, 145_{37})$ $(595^{11}, 35^{51}, 183^{22}, 467^{42}, 200^{53}, 210_{13}, 145_{14}, 275_{16}, 35_{21}, 190_{22}, 235_{25},$ $190_{27}, 200_{31}) (196^{31}, 280^{51}, 485^{12}, 335^{43}, 136_{11}, 35_{13}, 186_{14}, 119_{16}, 39_{21},$ $210_{25}, 236_{27}, 195_{32}, 140_{33}) (390^{21}, 87^{31}, 120^{41}, 190^{52}, 410^{13}, 167^{43}, 75^{53},$ $410_{11}, 187_{17}, 190_{22}, 164_{33}, 180_{34}, 174_{35}, 134_{36}) (435^{31}, 390^{12}, 179^{22},$ $296^{43}, 41_{12}, 218_{15}, 176_{16}, 207_{21}, 149_{22}, 213_{24}, 12_{31}, 180_{33}, 104_{37})] [$ $(123^{11}, 345^{31}, 267^{41}, 78^{42}, 285^{52}, 290^{13}, 195_{12}, 150_{13}, 200_{15}, 190_{17}, 185_{21},$ $178_{24}, 290_{36}) (300^{41}, 590^{12}, 290^{52}, 420^{23}, 200_{15}, 30_{16}, 70_{17}, 230_{21},$ $250_{22}, 185_{24}, 215_{26}, 210_{33}, 210_{37}) (350^{31}, 100^{32}, 295^{42}, 356^{52}, 196^{23},$ $24^{53}, 250_{16}, 100_{17}, 167_{21}, 184_{22}, 190_{23}, 210_{24}, 220_{35}) (102^{11}, 143^{41}, 374^{22},$ $400^{32}, 177^{42}, 279^{52}, 256^{13}, 245_{13}, 310_{21}, 280_{24}, 200_{25}, 220_{26}, 220_{27},$ $256_{32}) (200^{11}, 90^{12}, 300^{22}, 470^{33}, 265^{43}, 200^{53}, 200_{11}, 200_{22}, 190_{24},$ $30_{32}, 210_{33}, 200_{35}, 245_{36}, 250_{37}) (287^{41}, 460^{12}, 290^{32}, 103^{23}, 290^{53},$ $202_{12}, 85_{13}, 210_{21}, 130_{23}, 200_{26}, 210_{27}, 28_{32}, 190_{34}, 175_{35}) (520^{11}, 260^{42},$ $240^{33}, 225^{53}, 65_{11}, 145_{12}, 125_{16}, 185_{17}, 210_{23}, 50_{26}, 110_{31}, 190_{34}, 165_{35})$ $(217^{11}, 128^{22}, 385^{42}, 183^{13}, 260^{53}, 217_{12}, 61_{21}, 230_{23}, 115_{24}, 107_{27}, 124_{31},$ $102_{35}, 217_{36}) (389^{21}, 285^{41}, 144^{42}, 370^{13}, 230^{33}, 40^{53}, 243_{13}, 197_{14}, 55_{15},$ $179_{17}, 144_{21}, 176_{32}, 255_{35}, 209_{36}) (375^{41}, 352^{13}, 350^{33}, 123_{13}, 38_{15},$ $214_{16}, 180_{31}, 143_{32}, 87_{34}, 125_{35}, 167_{37})]$

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