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Integrated Dynamic Cellular Manufacturing Systems and Hierarchical Production Planning with Worker Assignment and Stochastic Demand

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A B S T R A C T

This study deals with the interaction of dynamic cellular manufacturing (DCM) and hierarchical production planning (HPP) problems with stochastic demands for the first time. Each of these alone does not consider the system factors such as stochastic demands and dynamic cellular formation separately. Accordingly, to fill this gap, this paper presents an integrated optimized model incorporating the most comprehensive design of DCM systems and HPP problems with stochastic demands. This model helps administrators get the optimal size and number of cells to decrease costs. Also, the model applies the principles of HPP to reduce the complexity of the integrated model. Since demands are uncertain, they need to be accurately predicted. Therefore, this study aims to combine the most precise decision variables with the most realistic conditions. A case study from an agriculture mechanization and industrial development company shows that an integrated model can provide managers with a feasible solution to meet demand, reconfigure cells in each period, provide new machinery to increase the required production capacity, and adjust production capacity to help them cope with demand fluctuations. A sensitivity analysis was performed and the results show that increase in forecast error and inter-cell move cost cause less significant changes in total cost but the total cost is sensitive to intra-cell move cost, available time capacities and cell quantity. It is also shown that the total cost was very sensitive to available regular time and available over time and the system should try to increase the time capacity.

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1. INTRODUCTION

Cellular manufacturing (CM) is a well-known just-in-time manufacturing process which aims to increase production efficiency by assigning multi-skilled workers, parts, and machines into cells significantly cheaper than other kinds of producing processes [1-4]. CM systems can produce medium-volume and medium-variety parts to decrease setup cost, lead time, inventory cost, worker allocation cost, worker salary cost, and inventory cost and improve material flow and product quality [5, 6]. Production planning models create production schedules that minimize inventory and worker costs in response to changing demand over time. In order to develop a comprehensive production plan, uncertain parameters (especially market demand) must be paid attention. CM and production planning are connected and solved simultaneously and need to be integrated [7]. Production planning requires complex selections from a large number of attributes. One of the best options to simplify this complexity is the hierarchical production planning (HPP) approach. This approach aggregates items into three steps including aggregate production planning for product types to assign capacity among product types, class (or family) disaggregation to allocate product types into classes, and item disaggregation to preserve items with inventory [7].

2. LITERATURE REVIEW

Production planning is a novel topic studied by many researchers for different industries [8-10]. Many studies

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in the literature assume that in the planning period, demand is constant. However, in real conditions, demands can alter rapidly and variations over different periods cause different optimal fabrication cells [11]. Hence, the cellular formation has to change over periods. Accordingly, predicting demand is an undeniably important topic which needs to be addressed. CM systems research has been extended to the development of integrated models and methods, as discussed by Song and Choi [12].

CM systems have been employed and implemented with many other techniques for studying the current status, possible improvement and barriers of different organizations. Ebrahimi et al. [13] studied the scheduling and cell loading in CM systems, considering the consumption of speed power together with the price elasticity of demand. Sharma et al. [14] presented a fuzzy analytic hierarchy process model of CM systems to improve success in an organization. Kumar et al. [15] employed the interpretative structural modelling technique to investigate and define the barriers/enablers in the implementation of CM systems in sports industries. Saraçoğlu et al. [16] presented a parallel multi-stage CM model and improved the cell loading efficiency using a genetic algorithm (GA). Guo et al. [17] employed a CM digital twin-based flexible model for optimizing the performance of air conditioner lines. Akturk and Turkcan [18] presented an algorithm that solves the problem of part family and machine cell configuration problems using a holistic approach that considers inter-cell movement and independent cells. In another research, Mahdavi et al. [19] presented a model for cell configuration in CM systems to minimize the exceptional elements and increase cell utilization.

For cell formation, Defersha and Chen [20] present a comprehensive model for dynamic cell formation derived from tools accessible on the machine and the tool necessity of the products. Computational results appeared that a critical cost saving can be accomplished by considering cell formation and system adaptability. Feng et al. [21] presented an integrated model of cell formation and worker allocation problems. The model was solved with a hybrid approach and swarm optimization, taking into account workload balancing and production planning. Alimian et al. [7] presented a novel production planning in the DCM model that integrates four attributes including production planning, maintenance planning, cell formation and group scheduling. They argue that there is a contradiction between the total integrated cost and the total availability of the system. They did not incorporate workers and uncertain environments. Saxena and Jain [22] proposed an integrated model of supply chain design and DCM considering attributes like multiple markets, multiple plant locations and multiple periods customized for strategic, tactical and operational decisions. Chen and Cao [23] presented an integrated model for the production planning of cell production systems, including features such as inter-cell material handling and cell relocation. They applied the tabu search method to solve the model and compared it with the traditional model. However, their model uses only production and inventory to meet the demand. Defersha and Chen [24] have studied the effect of lot sizing on production quality by developing a mathematical model which integrates CM systems, cell relocation and lot sizing. As the model was NP-hard, a real size problem could not be solved and GA was developed to solve it.

In another study, Safaei and Tavakkoli-Moghaddam [25] extended the model as reported in the literature [26]. They proposed a multi-period mathematical model that integrates CM systems and production planning which focuses on the impact of subcontracting and production trade-off on cell relocation. Their results showed that subcontracting can lead to spasmodic behaviour on cell relocation.

A novel model that integrates HPP and DCM in a deterministic environment was recently proposed by Xue and Offodile [27]. The model was solved with a simple branch and bound approach but the model ignores worker allocation and uncertainty in demand. Mahdavi et al. [28] proposed a multi-objective model that integrates production planning and dynamic virtual CM with a fuzzy approach. The proposed model takes into account changes in demand and part variation over multiple planning periods with employee flexibility.

TABLE 1. List of attributes in integration of cellular manufacturing and production planning

Attributes	Definition	Attributes	Definition	Attributes	Definition
1	Worker salary	9	Backordering cost	17	Intra-cell material handling cost
2	Worker over allocation cost	10	Outsourcing cost	18	Production cost
3	Worker hiring cost	11	Stochastic demand	19	Cell capacity
4	Worker training cost	12	Deterministic demand	20	Dynamic cell formation
5	Procurement cost	13	Setup cost	21	Robust cell formation
6	Cell reconfiguration cost	14	Inventory holding cost	22	Tool consumption
7	Machine operation cost	15	Lot splitting		
8	Maintenance and overhead cost	16	Inter-cell material handling cost		

Koopman and Lit [29] developed a score-driven model based on the predictive probability function score. This model has similar prediction accuracy compared to a correctly specified parameter-driven model. There are many attributes that impact the integration of production planning and cellular manufacturing, as summarized in Table 1. Table 2, gives a review and comparison of these attributes in earlier studies and this paper.

This paper develops a mathematical model that integrates dynamic cellular manufacturing (DCM) and HPP with stochastic demand and worker allocation with attributes like worker salary, operation cost, material movement cost, outsourcing and backordering. Accordingly, this paper is structured as follows. Section 2, gives a literature review showing a gap in analyzing real-world demands. Section 3 presents a novel mathematical model for integrated multi-period DCM systems and HPP problems with dynamic stochastic demand. Section 4 explains the solution procedure via an introduction of a case study on an agricultural mechanization and industrial development company. Section 5 deals with a detailed sensitivity analysis of the proposed model for cell quantities, inter and intra-cell movement cost, setup cost, demands and capacity. Finally, section 6 gives a conclusion to highlight the benefits of employing the developed model.

From Tables 1 and 2, it can be seen that this paper covers the gaps in previous works by including both worker assignment and stochastic demand and providing a detailed analysis of cell quantity, costs, demand, setup time and time capacity.

3. DEVELOPMENT OF THE MODEL

3. 1. Mathematical model The mathematical model includes two phases. Phase 1 presents a model for forecasting probabilistic [29]. Then in phase 2, a novel mathematical model is developed to integrate multi-period DCM systems with aggregate production planning, class disaggregation, and item disaggregation model with dynamic stochastic demand is presented. The following describes the two cited phases

Phase 1:

In an observation-driven model, time series demands are extracted as a function of past demand data. X_T denotes unobserved demands and Y_T denotes observed demands.

$$X_T = \xi + b_1 X_{T-1} + b_2 Z_{T-1} \tag{1}$$

$$Z_T = -E_{T-1}\left[\frac{\partial^2 \ln P(y_T \mid Y_{T-1}, X_T; P)}{\partial X_T X_T^{'}}\right]^{-1/2} \times \left[\frac{\partial \ln P(y_T \mid Y_{T-1}, X_T; P)}{\partial X_T}\right] \tag{2}$$

The mechanism for updating demands is given by an autoregressive equation where ξ is a constant vector and $b_1$and b_2 are unknown coefficients estimated using the maximum likelihood estimation (MLE) method for simulated series. Z_T in Equation (2) is a function of the past. When an observation demand is realized, X_T will be updated to the next period using Equation (1).

Phase 2:

Sets:

t = 1, 2, 3, …, T (set of periods)
w = 1, 2, 3, …, W (set of worker types)
m = 1, 2, 3, …, M (set of machine types)
c = 1, 2, 3, …, C (set of cells)
p = 1, 2, 3, …, P (set of product types)
$o(p)$ = 1, 2, 3,…,O_p (set of operations for product p)
$j(m)$ = 1,2,3,…,J_m (set of worker that can operate machine type m)
$k(p,o)$ = 1,2,3,…,K_{po} (set of machine types to process operation o for product type p)
f = 1, 2, 3, …, F (set of classes)
$PF(f)$ = 1, 2, 3, …, PF_f (set of product p classified in f)

TABLE 2. Attributes used in literature of the integrated cellular manufacturing and production planning problems

Models	Attributes																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Alimian et al. [7]						*				*		*	*	*		*		*	*	*		
Safaei & Tavakkoli-Moghaddam [25]					*	*	*		*	*		*		*		*	*			*		
Xue & Offodile [27]					*	*	*	*	*	*		*	*	*		*	*	*	*	*		
Mahdavi et al. [28]	*						*		*			*		*						*		
Feng et al. [21]	*	*	*	*	*					*		*			*	*		*	*		*	
Defersha & Chen [24]					*	*	*			*		*	*	*	*	*			*	*		
Defersha & Chen [20]					*	*	*	*		*		*			*	*			*	*		*
Saxena & Jain [22]					*	*	*	*		*		*	*	*		*	*		*	*		*
Chen and Cao [23]					*	*	*	*	*	*		*	*	*		*	*	*	*	*		
Present study	*	*			*	*	*	*	*	*	*		*	*		*	*	*	*	*		

Parameters:

wc_w: salary cost for worker type w

$arw_w(t)$: Available regular time of worker w in period t

$aow_w(t)$: Available overtime of worker w in period t

$arm_m(t)$: Available regular time of machine type m

$aom_m(t)$: Available overtime of machine type m

owc_w: Overtime cost of worker type w per unit time

$D_f(t)$: Forecasted demand for class f in period t

mhc_p^{inter}: Inter-cell material handling cost of product p

mhc_p^{intra}: Intra-cell material handling cost per product p

$moc_m(t)$: Maintenance and overhead costs of machine m

rc_m: Relocation cost of machine type m

oc_m: Operating cost of machine type m per unit time

pc_p: Production cost of product per unit type p

tp_{pmow}: Time to process product type p on machine type m for operation o by worker type w

$hc_f(t)$: Holding cost of class f in period t

$oc_f(t)$: Outsourcing cost of class f in period t

$bc_f(t)$: Backordering cost of class f in period t

$cp_m(t)$: Procurement cost of machine type m in period t

st_{pmo}: Setup time for production p on machine type m for operation o

$sc(t)$: Unit setup cost in period t

$LF_f(t)$: Lower bound proportion of product type p classified in class f in period t

$UF_f(t)$: Upper bound proportion of product type p classified in class f in period t

LM_c: Lower bound of the number of machines in cell c

UM_c: Upper bound of the number of machines in cell c

Decision variables:

$NW_{wc}(t)$: Number of worker type w allocated to cell c

$NM_{mc}(t)$: Number machines type m allocated to cell c

$NP_{pmcow}(t)$: Number of product p on machine type m in cell c processed by operation o by worker type w

$NMA_{mc}(t)$: Number machine type m added to cell c

$NMR_{mc}(t)$: Number machine m removed from cell c

$NAI_f(t)$: Number of available Inventory of class f

$NO_f(t)$: Number of class f outsourced in period t

$NB_f(t)$: Number of backordering in class f in period t

$NPF_f(t)$: Number of production of class f in period t

$U_p(t)$: 1 (if product p is processed), and 0 otherwise

The objective function is defined as:

$$
\begin{aligned}
\min Z = & \sum_{w\in W}\sum_{c\in C}\sum_{t\in T} wc_w.NW_{wc}(t) \\
& +\sum_{t\in T}\sum_{w\in j(m)}\sum_{c\in C} owc_w \max\{\sum_{o\in O(p)}\sum_{m\in K(p,o)}\sum_{p\in P} tp_{pmow}.NP_{pmcow}(t) - NW_{wc}(t).arw_w(t), 0\} \\
& +\sum_{t\in T}\sum_{c\in C}\sum_{o\in O(p)}\sum_{m\in K(p,o)}\sum_{p\in P} mhc_p^{\text{intra}}[\min\{\sum_{w\in J(m)}\sum_{m\in(p,o+1)} NP_{pmc,o+1,w}(t), \sum_{w\in J(m)}\sum_{m\in(p,o)} NP_{pmcow}(t)\}] \\
& +\sum_{t\in T}\sum_{c\in C}\sum_{o\in O(p)}\sum_{p\in P}\frac{1}{2} mhc_p^{\text{inter}}\left|\sum_{w\in J(m)}\sum_{m\in K(p,o+1)} NP_{pmc,o+1,w}(t) - \sum_{w\in J(m)}\sum_{m\in K(p,o)} NP_{pmcow}(t)\right| \\
& +\sum_{t\in T}\sum_{c\in C}\sum_{m\in M} N_{mc}(t).moc_m(t) + \sum_{t\in T}\sum_{c\in C}\sum_{m\in M} rc_m.(NMA_{mc}(t)+NMR_{mc}(t)) \\
& +\sum_{t\in T}\sum_{c\in C}\sum_{o\in O(p)}\sum_{m\in K(p,o)}\sum_{p\in P}\sum_{w\in J(m)} oc_m.tp_{pmow}.NP_{pmcow}(t) \\
& +\sum_{t\in T}\sum_{c\in C}\sum_{m\in K(p,1)}\sum_{p\in P}\sum_{w\in J(m)} pc_p.NP_{pmc1w}(t) + \sum_{t\in T}\sum_{f\in F} hc_f(t).NAI_f(t) \\
& +\sum_{t\in T}\sum_{f\in F} oc_f(t).NO_f(t) + \sum_{t\in T}\sum_{f\in F} bc_f(t).NB_f(t) \\
& +\sum_{t\in T}\sum_{m\in M} cp_m(t)(\sum_{c\in C} NM_{mc}(t) - NM_{mc}(t-1)) + \sum_{t\in T}\sum_{p\in P}\sum_{m\in K(p,o)}\sum_{o\in O(p)} U_p(t).sc(t).st_{pmo}
\end{aligned}
\tag{3}
$$

where Equation (3), as the objective function, minimizes the total cost. The first term of this equation represents worker salary cost. The second term represents overtime cost; this cost occurs when the available regular time of workers finishes and the model uses available overtime of workers. The third term denotes intra-cell material handling cost. The fourth term represents inter-cell material handling cost. The fifth term represents the maintenance and overhead costs. The sixth term denotes configuration cost. The seventh term represents operation cost. The eighth term denotes production cost. The ninth term represents inventory holding cost. The tenth term represents outsourcing costs. The eleventh term represents backordering cost. The twelfth term denotes procurement cost and the last term denotes setup cost.

This objective function is subjected to constains shown as follows:

$$
\begin{aligned}
& \sum_{c\in C}\sum_{m\in k(p,o)}\sum_{p\in P}\sum_{o\in O(p)} tp_{pmow}.NP_{pmcow}(t) + \qquad \forall t\in T, \forall w\in W \\
& \sum_{p\in P}\sum_{m\in K(p,o)}\sum_{o\in O(p)} U_p(t).st_{pmo} \le \sum_{c\in C} NW_{wc}(t).(arw_w(t)+aow_w(t))
\end{aligned}
\tag{4}
$$

where constraints (4) are regular and over available time limitations for workers,

$$
\begin{aligned}
& \sum_{c\in C}\sum_{p\in P}\sum_{o\in O(p)}\sum_{w\in J(m)} tp_{pmow}.NP_{pmcow}(t) \qquad \forall t\in T, \forall m\in M, \forall c\in C \\
& \quad +\sum_{p\in P}\sum_{o\in O(p)} U_p(t).st_{pmo} \le NM_{mc}(t).(arm_m(t)+aom_m(t))
\end{aligned}
\tag{5}
$$

where constraints (5) are regular and over available time limitations for machines,

$$
\begin{aligned}
& D_f(t) = NPF_f(t) - (NAI_f(t) - NAI_f(t-1)) \\
& \quad + NO_f(t) + (NB_f(t) - NB_f(t-1)) \qquad \forall t\in T, \forall f\in F
\end{aligned}
\tag{6}
$$

where constraints (6) ensures that all forecast demand for classes will be satisfied by production, inventory, backordering or outsourcing,

$$
\sum_{p\in PF(f)}\sum_{c\in C}\sum_{m\in K(p,1)}\sum_{w\in J(m)} NP_{pmc1w}(t) = NPF_f(t) \qquad \forall t\in T, \forall f\in F \tag{7}
$$

where the set of constraints (7) ensures that the number of product types in each class is equal to the number of productions in that class,

$$
\sum_{c\in C}\sum_{m\in K(P,1)}\sum_{w\in J(m)} NP_{pmc1w}(t) \le UF_f(t).NPF_F(t) \qquad \forall t\in T, \forall P\in PF(f) \tag{8}
$$

$$
\sum_{c\in C}\sum_{m\in K(P,1)}\sum_{w\in J(m)} NP_{pmc1w}(t) \ge LF_f(t).NPF_F(t) \qquad \forall t\in T, \forall P\in PF(f) \tag{9}
$$

where the set of constraints (8) and (9) are the upper and lower bounds of the production level, respectively. Besides,

$$
\sum_{m\in M} NM_{mc}(t) \ge LM_c \qquad \forall t\in T, \forall c\in C \tag{10}
$$

$$\sum_{m\in M} NM_{mc}(t) \le UM_c \quad \forall t\in T, \forall c\in C \tag{11}$$

where the set of constraints (10) and (11) are the lower and upper bounds of the cell size is lower bound of cell size, respectively. Moreover

$$NM_{mc}(t+1) - NM_{mc}(t) - NMA_{mc}(t) + NMR_{mc}(t) = 0 \quad \forall t\in T, \forall c\in C, \forall m\in M \tag{12}$$

where the set of constraints (12) ensures that the number of machines removed and added is equal to the difference between the total machines in this period and the next period.

$$\sum_{c\in C}\sum_{m\in K(p,o)}\sum_{w\in J(m)} NP_{pmcow}(t) = \sum_{c\in C}\sum_{m\in K(p,o+1)}\sum_{w\in J(m)} NP_{pmc,o+1,w}(t) \quad \forall t\in T, \forall p\in P, \forall o\in O(p) \tag{13}$$

where the set of constraints (13) ensures that the total number of products for an operation is equal to the total number of products for the next operation.

$$\sum_{c\in C}\sum_{m\in K(p,o)}\sum_{w\in J(m)} NP_{pmcow}(t) = \sum_{c\in C}\sum_{m\in K(p,o+1)}\sum_{w\in J(m)} NP_{pmc,o+1,w}(t) \quad \forall t\in T, \forall p\in P, \forall o\in O(p) \tag{14}$$

$$\sum_{c\in C}\sum_{m\in K(P,1)}\sum_{w\in J(m)} NP_{pmc1w}(t) \le M.U_p(t) \quad \forall t\in T, \forall p\in P \tag{15}$$

Sets of constraints (14) and (15) indicate that if product type *p* is produced, the binary variable of *Up*(*t*) will be 1 if product *p* is processed, otherwise 0.

$$NW_{WC}(t) >= 0 \text{ and integer } \forall t\in T, \forall c\in C, \forall w\in W \tag{16}$$

$$NM_{mc}(t) >= 0 \text{ and integer } \forall t\in T, \forall c\in C, \forall m\in M \tag{17}$$

$$\sum_{m\in M} NM_{mc}(t) \le UM_c \quad \forall t\in T, \forall c\in C$$
$$NMA_{mc}(t) >= 0 \text{ and integer } \forall t\in T, \forall c\in C, \forall m\in M \tag{18}$$

$$\sum_{m\in M} NM_{mc}(t) \le UM_c \quad \forall t\in T, \forall c\in C$$
$$NMR_{mc}(t) >= 0 \text{ and integer } \forall t\in T, \forall c\in C, \forall m\in M \tag{19}$$

$$\sum_{m\in M} NM_{mc}(t) \le UM_c \quad \forall t\in T, \forall c\in C$$
$$NP_{pmcow}(t) >= 0 \text{ and integer } \forall t\in T, \forall c\in C, \forall m\in M, \forall p\in P, \forall o\in O, \forall w\in W \tag{20}$$

$$NAI_F(t) >= 0 \text{ and integer } \forall t\in T, \forall f\in F \tag{21}$$

$$NO_F(t) >= 0 \text{ and integer } \forall t\in T, \forall f\in F \tag{22}$$

$$NB_F(t) >= 0 \text{ and integer } \forall t\in T, \forall f\in F \tag{23}$$

$$NPF_F(t) >= 0 \text{ and integer } \forall t\in T, \forall f\in F \tag{24}$$

$$U_p(t) \in (0,1) \quad \forall t\in T, \forall p\in P \tag{25}$$

and finally, constraints (16-25) ensure that variables are positive and integer and Up(t) is binary.

3. 2. Linearization of the model The developed model is not linear due to the second, third and fourth terms of Equation (3). Hence, the model is simplified as follows:

To linearize the second term of Equation (3), one can define:

$$\alpha_{wc}(t) = \max\{\sum_{o\in O(p)}\sum_{m\in K(p,o)}\sum_{p\in P} tp_{pmow}.NP_{pmcow}(t) - NW_{wc}(t).arw_w(t), 0\} \tag{26}$$

with additional constraints as:

$$\alpha_{wc}(t) \ge \sum_{o\in O(p)}\sum_{m\in K(p,o)}\sum_{p\in P} tp_{pmow}.NP_{pmcow}(t) - NW_{wc}(t).arw_w(t) \quad \forall w\in W, \forall c\in C, \forall t\in T \tag{27}$$

$$\alpha_{wc}(t) \ge 0 \quad \text{and integer } \forall w\in W, \forall c\in C, \forall t\in T \tag{28}$$

To linearize the third term of Equation (3), one can define

$$\beta_{pco}(t) = \min\{\sum_{w\in J(m)}\sum_{m\in(p,o+1)} NP_{pmc,o+1,w}(t), \sum_{w\in J(m)}\sum_{m\in(p,o)} NP_{pmcow}(t)\} \tag{29}$$

with additional constraints as:

$$\beta_{pco}(t) \le \sum_{w\in J(m)}\sum_{m\in(p,o+1)} NP_{pmc,o+1,w}(t) \quad \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{30}$$

$$\beta_{pco}(t) \le \sum_{w\in J(m)}\sum_{m\in(p,o)} NP_{pmcow}(t) \quad \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{31}$$

$$\beta_{pco}(t) \ge 0 \quad \text{and integer } \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{32}$$

To linearize the fourth term of Equation (3), one can define:

$$\theta_{pco}(t) + \vartheta_{pco}(t) = \left|\sum_{w\in J(m)}\sum_{m\in K(p,o+1)} NP_{pmc,o+1,w}(t) + \sum_{w\in J(m)}\sum_{m\in K(p,o)} NP_{pmcow}(t)\right| \tag{33}$$

and the following constraints are added.

$$\theta_{pco}(t) - \vartheta_{pco}(t) = \sum_{w\in J(m)}\sum_{m\in K(p,o+1)} NP_{pmc,o+1,w}(t) - \sum_{w\in J(m)}\sum_{m\in K(p,o)} NP_{pmcow}(t) \quad \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{34}$$

$$\theta_{pco}(t) \ge 0 \text{ and integer } \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{35}$$

$$\vartheta_{pco}(t) \ge 0 \text{ and integer } \forall p\in P, \forall c\in C, \forall o\in O, \forall t\in T \tag{36}$$

4. CASE STUDY

This section employs the production data of an agricultural mechanization and industrial development

TABLE 3. Data of the products of case study

Product type	Machine	Processing time (minute)	Setup time (min)	Inter cell move cost	Intra cell move cost
1	1	30	10	100	20
	4	10	5		
	3	25	10		
	2	35	10		
	5	20	10		
2	1	35	10	110	25
	2	10	15		
	3	20	10		
	5	20	5		
3	1	35	15	100	20
	4	20	5		
	1	25	10		
	2	20	5		
4	1	40	10	90	15
	4	10	15		
	5	20	10		
5	1	35	15	100	20
	4	20	5		
	1	20	10		
	5	10	5		

company, as a case study, to validate the proposed model. There are five product types classified into two classes. Class 1 includes product types 1, 2 and 3 and class 2 includes product types 4 and 5. Also, five types of machines including cutting machines, hydraulic pressing machines, welding machines, assembling machines and spray machines are used for manufacturing their hatchery and incubation products.

Table 3 provides product information from a case study. As can be seen, the minimum processing time of this case is 10 minutes and the maximum is 40 minutes. Also, setup times are between 5 and 15 minutes, and the unit cost of intra cell move cost is less than inter cell move cost, since intra cell movement travels less distance.

Table 4 shows the relationship between machines and workers, and each worker, based on their skills, has the ability to work with specific machines. Table 5 provides information on workers. Available regular time and available over time are the same in each period. Besides, workers receive a bonus for overtime in addition to salary costs.

TABLE 4. The ability of worker types to work with machines

		Machine types				
		1	2	3	4	5
Worker types	1		*			*
	2	*		*		
	3		*		*	
	4	*		*		

Moreover, Table 6 contains information about machines such as available regular time, available over time, reconfiguration cost, procurement cost, operation cost, maintenance and overhead cost.

5. RESULTS AND DISCUSSION

This section analyses the proposed model in four subsections including sensitivity analysis of cell quantity, sensitivity analysis of setup time and inter- and intra-cell move costs, sensitivity analysis of demands and sensitivity analysis of capacity. The results include the application of the HPP system and DCM system in five periods and in each period, production decisions are made and the model is updated. The model is solved with GAMS on a computer with 8 GB of RAM and Core-i5 CPU.

TABLE 5. Time capacity and costs of workers of case study

	Worker type			
	1	2	3	4
Available regular time	300	300	300	300
Available over time	100	100	100	100
Salary costs	4000	3000	3000	3000
Over time cost per unit time	40	30	30	30

TABLE 6. Time capacity and costs of machines of case study

	Machine type				
	1	2	3	4	5
Available regular time	300	300	300	300	300
Available over time	100	100	100	100	100
Reconfiguration cost	300	250	300	400	250
Procurement cost	15000	10000	15000	20000	10000
Operation cost	20	10	20	15	10
Maintenance and overhead cost	400	500	400	600	550

5. 1. Sensitivity Analysis of Cell Quantity In this study, three cells, five types of machines, five types of products and two types of classes are taken for the mathematical modelling. However, other production control parameters may affect cell size and quantity. This subsection first analyzes the effect of different numbers of cells on the objective function and then determines the optimal number of cells under the assumption that the number of machines and the cost of displacement are constant. For this analysis, the number of cells is assumed to vary from three to eight. For the given range of cells, the corresponding focused values are shown in Table 7. It may be visible that the complexity of the answer will increase with the number of cells. Besides, for the case study concerned in this paper, it is shown that the ideal optimal cell amount is eight as it gives the lowest total cost. As result, managers should increase the number of cells in order to reach optimal total cost.

5. 2. Sensitivity Analysis of Setup Time and Inter- and Intra-cell Move Cost This subsection first, studies the effect of setup cost on the total cost by three different approaches. In the first approach, the condition is the same as the baseline condition and does not change. In the second approach, the setup time is five times higher and in the third approach, the setup time is 10 times higher. As can be seen from Table 8, although the total cost has significantly increased, there is no significant difference in inventory holding cost and overtime cost, indicating that changes in setup cost do not have much effect on production decisions.

In the next study, to analyze the effect of inter-cell move cost and intra-cell move cost, four different situations have been considered. In the first situation, intra-cell move costs are fixed and inter-cell move costs are considered twice as normal. In the second situation, intra-cell move costs are fixed and inter-cell move costs are considered four times higher than normal. In the third situation, intra-cell move costs are considered twice as normal and inter-cell move costs are fixed. In the fourth situation, the intra-cell move costs are considered four times higher than normal and the inter-cell move costs are fixed.

As shown in Table 9, the results are as follows. In the first and second situations, it is observed that the total cost does not change significantly with increases in inter-cell move cost. The reason is that due to the dynamics of

TABLE 7. Total cost changes according to the different total number of cells

	Total number of cells				
	3	4	5	6	7
Total cost	84738600	84254600	83961800	82523100	80974500

TABLE 8. Costs according to the different setup times

	Product type	Machine	Setup time (minute)
Approach: 1	1	1	10
		4	5
		3	10
		2	10
		5	10
Overtime cost: 6314500	2	1	10
		2	15
		3	10
		5	5
Inventory holding cost: 8649100	3	1	15
		4	5
		1	10
		2	5
Total cost: 84738600	4	1	10
		4	15
		5	10
	5	1	15
		4	5
		1	10
		5	5
Approach: 2	1	1	50
		4	25
		3	50
		2	50
		5	50
Overtime cost: 6430100	2	1	50
		2	75
		3	50
		5	25
Inventory holding cost: 8716400	3	1	75
		4	25
		1	50
		2	25
Total cost: 104112400	4	1	50
		4	75
		5	50
	5	1	75
		4	25
		1	50
		5	25

	1	1	100
		4	50
		3	100
		2	100
Approach: 3		5	100
	2	1	100
		2	150
Overtime cost: 6491200		3	100
		5	50
	3	1	150
Inventory holding cost: 8781000		4	50
		1	100
		2	50
	4	1	100
Total cost: 12819700		4	150
		5	100
	5	1	150
		4	50
		1	100
		5	50

TABLE 9. Total costs change according to the different inter and intra-cell move costs

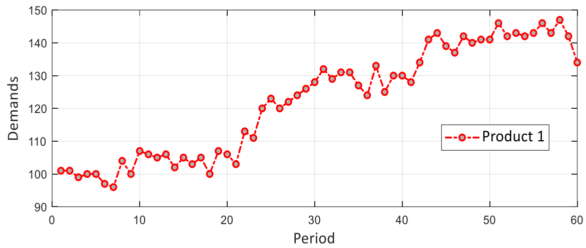
Situations	Product type	Inter cell move cost (per unit)	Intra cell move cost (per unit)	Total cost
1	1	200	20	84829400
	2	220	25	
	3	200	20	
	4	180	15	
	5	200	20	
2	1	400	20	84964300
	2	440	25	
	3	400	20	
	4	360	15	
	5	400	20	
3	1	100	40	89711300
	2	110	50	
	3	100	40	
	4	90	30	
	5	100	40	
4	1	100	80	93122100
	2	110	100	
	3	100	80	
	4	90	60	
	5	100	80	

the cells of the model, with increasing inter-cell move cost, the model avoids intercellular displacement as much as possible. In order to reduce inter-cell movement, managers could increase machines in cells.

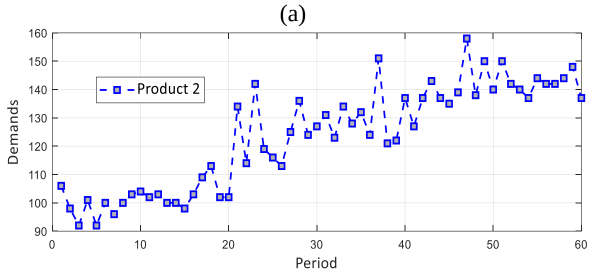
Besides, it is observed in the third and fourth situations that with an increase in intra-cell move cost, the total cost also changes significantly. This is because intra-cell movement naturally has to be performed and the model cannot reduce the total cost. Therefore, managers should reduce inter-cell movement as much as possible.

5. 3. Sensitivity Analysis of Demands For sensitivity analysis of demands, demands for two types of classes are accurately forecasted using historical factory data of an agricultural mechanization and industrial development company. For each of these products, demand fluctuations are determined by solving datasets shown in Figure 1. Historical data sets with moderate demand fluctuations follow the Poisson distribution. In Figures 2-4, the demand for each period is calculated based on different error rates.

Table 10 shows the results of running these four scenarios, which denote that the change in the error rate does not have a significant impact on the periodic demand trend of these products and higher forecasting errors do not necessarily lead to higher backordering cost and total cost. Even if the company has a higher demand fluctuation in their planning horizon, leading to a higher total cost of production planning, and even under 20% forecast errors, the integrated model developed in this paper performs reasonably. As result, the proposed model adapts to demand fluctuations to avoid total cost increases and helps managers in production decisions.

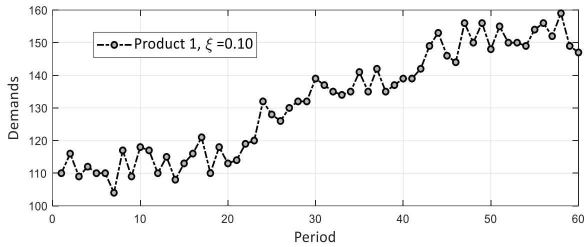


(a)

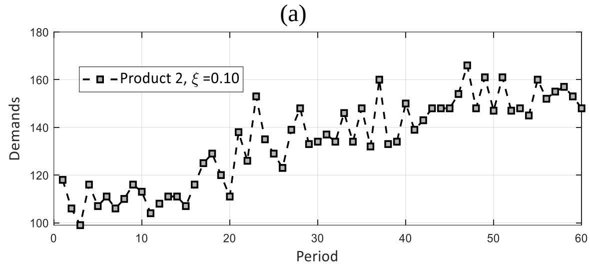


(b)

Figure 1. Demand-period for (a) product class 1, (b) product class 2



(a)



(b)

Figure 2. Demand-period with ξ=0.1 for (a) product class 1, (b) product class 2

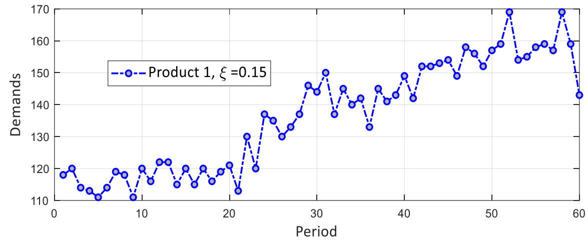
TABLE 10. Total costs changes according to different forecasting errors

Forecasting errors	**0%**	**10%**	**15%**	**20%**
Total cost	84738600	85021300	85534800	86174900

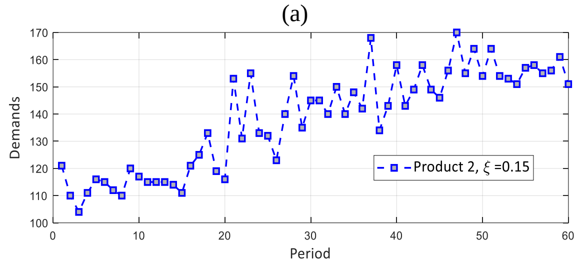
5. 4. Sensitivity Analysis of Time Capacity

This subsection, examines the impact of available regular time and available over time on total cost is examined by considering two modes. In the first mod, the amount of available regular time and available over time have decreased, and in the second model, the amount of available regular time and available over time have increased. As can be seen from Table 11, when the cited times decrease, the total cost increases, and when the cited times increase, the total cost decreases. This indicates that the total cost is very sensitive to available regular time and available over time and the system managers should try to increase the time capacity.

It is noteworthy that this study primarily used an exact optimization approach to solve the problem. For large instances, one may employ different optimization algorithms. There are many different domains where advanced optimization algorithms have been applied as solution approaches, such as online learning, scheduling, multi-objective optimization, transportation, medicine, data classification, and others [30-34]. Moreover, there are many studies on manufacturing, remanufacturing, assembly, and disassembly operations including the research performed by Zhang et al. [35], Yuan et al. [36], Golmohammadi et al. [37] and Yazdani et al. [38] which provided detailed analysis using different algorithms.



(a)

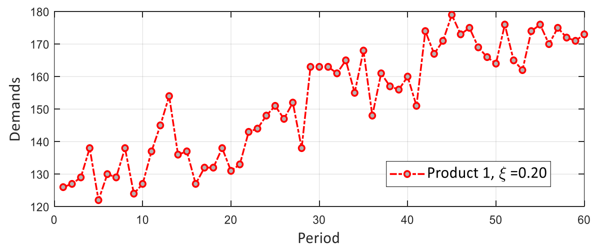


(b)

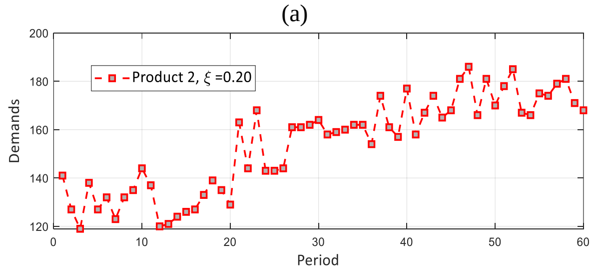
Figure 3. Demand-period with ξ=0.15 for (a) product class 1, (b) product class 2

TABLE 11. Total costs change according to different available regular and over times

Mods	**Available regular time**	**Available over time**	**Total cost**
1	150	50	1190322300
2	450	150	67447600



(a)



(b)

Figure 4. Demand-period with ξ=0.2 for (a) product class 1, (b) product class 2

6. CONCLUSION

In this paper, a new model was developed to integrate a dynamic cellular manufacturing system, hierarchical production planning problem under stochastic demands and several other features such as multiple periods and worker assignment. The purpose of this study is to combine the most precise decision variables with the most realistic conditions by considering stochastic demand and worker assignment. Using some linearization techniques, this nonlinear model was converted to an integer linear model. The model is capable of determining the optimal cell design and production plan for any type of product in each period for all the planning horizons. A real case study of an agricultural mechanization and industrial development company was given to validate the model and the integrated linear optimization model was solved in GAMS. It was shown that:

- Historical data on the company's demands were recorded and demands for the desired periods were predicted using the autoregressive model. It was shown that demand for the products of this company follows the bivariate Poisson distribution.
- By varying the total number of cells, it was shown that the optimal situation is when eight cells were selected, and this amount depends on the capacity of the factory and the total number of machines.
- An increase in forecast errors causes less significant changes in total cost. The results showed that aggregate forecasts can be more precise and give a significant explanation to the model.
- For the studied case, it is observed that the total cost does not change significantly with increasing inter-cell move cost. The reason is that due to the dynamic cells of the model, with increasing inter-cell movement cost, the model avoids intercellular movement as much as possible.
- For the studied case, it is observed that with increasing intra-cell move cost, the total cost also changes significantly. This is because intracellular movement naturally has to be performed and the model cannot reduce the total cost. Therefore, managers should reduce intercellular movement as much as possible.
- There was no significant difference in inventory holding cost and overtime cost indicating that changes in setup cost do not have much effect on production decisions.
- The total cost was very sensitive to available regular time and available over time and the system should try to increase the time capacity.

7. STATEMENTS AND DECLARATIONS

The 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.

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Persian Abstract

چکیده

این مطالعه به تعامل سیستم تولید سلولی پویا و برنامه ریزی تولید سلسله مراتبی با تقاضاهای غیرقطعی می پردازد. هر یک از این مسائل به تنهایی پارامترهایی مانند تقاضای غیرقطعی و تشکیل سلولی پویا را به طور جداگانه در نظر نمی گیرند. بر این اساس، برای پر کردن این شکاف، این مقاله یک مدل بهینه‌سازی یکپارچه را ارائه می‌کند که جامع‌ترین طراحی سیستم‌های تولید سلولی پویا و مسائل برنامه ریزی تولید سلسله مراتبی با تقاضای غیرقطعی را در خود جای داده است. این مدل به مدیران کمک می کند تا سایز و تعداد سلول های بهینه را برای کاهش هزینه ها بدست آورند. این مدل همچنین از اصول برنامه‌ریزی تولید سلسله مراتبی استفاده می‌کند تا جابه‌جایی مواد بین سلولی و درون‌سلولی و تخصیص کارگر برای هر قسمت را برای کاهش پیچیدگی مدل یکپارچه تسهیل نماید. در بسیاری از مطالعات قبلی، محققان تقاضای دوره ای را قطعی فرض میکردند، اما در واقعیت، از آنجایی که تقاضا غیر قطعی است، نیاز به پیش بینی دقیق دارد. بنابراین، این مطالعه با هدف ترکیب دقیق ترین متغیرهای تصمیم گیری با واقعی ترین شرایط، انجام شده است. یک مطالعه موردی از یک شرکت توسعه صنعتی و مکانیزاسیون کشاورزی نشان می‌دهد که مدل یکپارچه می‌تواند راه‌حلی عملی برای پاسخگویی به تقاضا، پیکربندی مجدد سلول‌ها در هر دوره، ارائه ماشین‌آلات جدید برای افزایش ظرفیت تولید مورد نیاز و تنظیم ظرفیت تولید برای کمک به مدیران ارائه دهد. مقابله با نوسانات تقاضا تجزیه و تحلیل حساسیت بر روی کمیت سلول، زمان راه اندازی، هزینه های جابجایی بین سلولی و درون سلولی، تقاضاها و ظرفیت زمانی انجام شده است و نتایج نشان می دهد که افزایش خطای پیش بینی و هزینه جابجایی بین سلولی باعث تغییرات کمتری در هزینه کل می شود اما هزینه کل به جابجایی درون سلولی ، ظرفیت های زمانی موجود و کمیت سلول حساس است.