Dynamic Cellular Remanufacturing System (DCRS) Design

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***Abstract*—**An efficient remanufacturing network lead to an efficient design of sustainable manufacturing enterprise. In remanufacturing network, products are collected from the customer zone, disassembled and remanufactured at a suitable remanufacturing facility. In this respect, another issue to consider is how the returned product to be remanufactured, in other words, what is the best layout for such facility. In order to achieve a sustainable manufacturing system, Cellular Manufacturing System (CMS) designs are highly recommended, CMSs combine high throughput rates of line layouts with the flexibility offered by functional layouts (job shop). Introducing the CMS while designing a remanufacturing network will benefit the utilization of such a network. This paper presents and analyzes a comprehensive mathematical model for the design of Dynamic Cellular Remanufacturing Systems (DCRSs). In this paper, the proposed model is the first one to date that considers CMS and remanufacturing system simultaneously. The proposed DCRS model considers several manufacturing attributes such as multi period production planning, dynamic system reconfiguration, duplicate machines, machine capacity, available time for workers, worker assignments, and machine procurement, where the demand is totally satisfied from a returned product. A numerical example is presented to illustrate the proposed model.

***Keywords*—**Cellular Manufacturing System, Remanufacturing, Mathematical Programming, Sustainability.

I. Introduction

THE concept of Design for Sustainable Manufacturing Enterprise (DFSME) has been introduced by [8]. In order to achieve a sustainable manufacturing enterprise, an efficient remanufacturing network design needed. In the remanufacturing network, products are collected from the customer zone, disassembled and then remanufactured in an appropriate remanufacturing facility.

Manufacturing plants applying the remanufacturing option have reported benefits such as saving in labor, material and energy costs, shorter production lead times, balanced production lines, new market development opportunities, a positive socially concerned image for firms, and may offer a better alternative to capacity constraint on new product manufacturing [2]. One of the most recommended layout for the design of a manufacturing plant is the Cellular system layout [8]. CMSs combine high throughput rates of line layouts with the flexibility offered by functional layouts (job shops) [1].

A literature review on remanufacturing can be found in [10]; also definitions for different processes in the remanufacturing enterprise have been given. Reference [6] presented a production planning mixed integer programming model for designing a remanufacturing system which incorporate disassembly, reprocessing, reassembly and disposal operations. Reference [5] has studied the design of a recovery network which incorporates both forward and reverse flow. The objective function minimizes the total cost including opening cost, production cost, transportation cost, disassembly, disposal, collection and purchasing costs. Recently, a mixed integer programming model to the design of Hybrid Manufacturing- Remanufacturing Systems (HMRS), where manufacturing new products and remanufacturing returned products can be done in the same facility, sharing same resources has been presented by [3].

Mathematical programming approaches are widely employed in the design of cellular manufacturing systems. Their objective model aims to minimize the reconfiguration costs for changing from one family to the next one, and under-utilization costs for not using the RMT resources [7]. In their model [9] designed a dynamic reconfigurable cellular manufacturing system by introducing a two-objective dynamic mathematical model; minimizing the total cell load variation and the sum of the miscellaneous costs. Reference [1] incorporated intercell material handling cost, intracell material handling cost, internal part production cost, outsourcing cost, inventory holding cost, relocation cost, machine maintenance, and overhead cost in their model. Reference [11] presented a mixed integer nonlinear model in CMS design that integrates production planning, dynamic system reconfiguration, and multiple routings. Various CMS aspects has been introduced in [4]; such as dynamic cell reconfiguration, alternative routings, lot splitting, sequence of operations, and machine adjacency constraints.

II. The Proposed Model

In this section, we present the mathematical model which consists of the objective function and the constraints.

A. Sets

$p = \{1, 2, 3\ldots P\}$ Index set of part types.
$m = \{1, 2, 3\ldots M\}$ Index set of machine types.
$c = \{1, 2, 3\ldots C\}$ Index set of cells.
$t = \{1, 2, 3\ldots T\}$ Index set of time periods.
$w = \{1, 2, 3\ldots W\}$ Index set of worker types.

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j = {1, 2, 3… J} Index of product types.

B. Parameters

D_{pt} Demand for part type *p* in time period *t*
V_p^{inter} Intercell movement cost of part type *p*
μ_{pmw} = 1, if machine type *m* is able to process part type *p* with worker *w*,
= 0, otherwise.
λ_{pm} = 1, if part type *p* needs machine type *m*,
= 0, otherwise.
t_{pmw} Processing time part type *p* on machine type *m* with worker type *w*
T_{mt} Time capacity of one machine of type *m* for one time period *t*
LL_c Minimum number of machines limit in cell *c*
UL_c Maximum number of machines limit in cell *c*
LW_c Minimum size of cell *c* in terms of the number of workers
R_m^+ Relocation cost of installing one machine of type *m*
R_m^- Relocation cost of removing one machine of type *m*
L^p a large positive number
H_{pt} Part holding cost per part type *p* per time period *t*
A_m Quantity of machine type *m* available at time period *t=1*
A_w Number of worker type *w* available
RW_{wt} Available time for worker type *w* at time period *t*
S_{wt} Salary cost of worker type *w* within period *t*
HI_{wt} Hiring cost of worker type *w* within period *t*
F_{wt} Firing cost of worker type *w* within period *t*
OP_m Procurement cost per machine type *m*
$£_p$ Internal production cost per part type *p*
$AQ_{j,t}$ Unit cost to acquire returned product *j* in time period *t*
$SD_{j,t}$ Setup cost to disassembling returned product *j* in time period *t*
$RD_{j,t}$ Unit cost to disassemble returned product *j* in time period *t*
$IN_{j,t}$ Unit inventory cost for storing returned product *j* in time period *t*
UR_i Average recovering rate of part *i* from all returned products
$B_{i,j}$ Number of component *i* contained in product *j*

C. Model Decision Variables

N_{mct} Number of type *m* machines to present at cell *c* at beginning of time period *t*
Y_{mct}^+ Number of type *m* machines added in cell *c* at beginning of time period *t*
Y_{mct}^- Number of type *m* machines removed from cell *c* at beginning of time period *t*
BN_{mt} Number of machines of type m procured at time t
A_{mt}^* Quantity of machine type m available at time period t after accounting for machines that have been procured
Q_{pt} Number of part inventory of type *p* kept in time period *t* and carried over to period *(t+1)*
β_{pt} Production volume of part type p to be produced in time period t
L_{wct}^+ Number of workers of type *w* added to cell *c* during period *t*
L_{wct}^- Number of workers of type *w* removed from cell *c* during period *t*
N_{wct} Number of workers of type *w* allotted to cell c in period *t*
v_{pct} = 1, if part type p is processed in cell c in period t.
= 0, otherwise.
z_{pmwct} = 1, if part type p is to be processed on machine type m with worker w in cell c in period t.
= 0, otherwise.

d_{jt} Number of returned product *j* to disassemble in time period *t*
r_{jt} Number of returned product *j* to acquire in time period *t*
$f_{j,t}$ Number of returned product *j* in inventory at the end of time period *t*
δ_{jt} = 1, if returned product *j* will be disassembled in time period *t*
= 0, otherwise.

The objective function and constraints of the model are as follows:

Minimize

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^+ . Y_{mk}^+(t) \quad (1)$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M} R_m^- . Y_{mk}^-(t) \quad (2)$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P} Q_{pt} . H_{pt} \quad (3)$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} S_{wt} . N_{wct} \quad (4)$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} HI_{wt} . L_{wct}^+ \quad (5)$$

$$+\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{w=1}^{W} F_{wt} . L_{wct}^- \quad (6)$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P}\left[\left(\sum_{c=1}^{C} v_{pct}\right)-1\right] . V_p^{inter} . \beta_{pt} \quad (7)$$

$$+\sum_{t=1}^{T}\sum_{m=1}^{M} BN_{mt} . OP_m \quad (8)$$

$$+\sum_{t=1}^{T}\sum_{p=1}^{P} \beta_{pt} . £_p \quad (9)$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} AQ_{jt} . r_{jt} \quad (10)$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} SD_{jt} . \delta_{jt} \quad (11)$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} RD_{jt} . d_{jt} \quad (12)$$

$$+\sum_{t=1}^{T}\sum_{j=1}^{J} IN_{jt} . f_{jt} \quad (13)$$

Subject to

$$\beta_{pt} + Q_{p(t-1)} - Q_{pt} = D_{pt}\,; \forall(p,t) \quad (14)$$

$$v_{pkt} = \min(1, \sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct})\;;\; \forall(p,c,t) \quad (15)$$

$$\sum_{c=1}^{C} z_{pmwct} \le \mu_{mpw}\;;\; \forall(p,m,w,t) \quad (16)$$

$$\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} = \lambda_{pm}; \forall(p,m,t) \quad (17)$$

$$N_{mct} = N_{mc(t-1)} + Y_{mct}^+ - Y_{mct}^-;\ \forall(m,c,t) \quad (18)$$

$$LB_c \le \sum_{m=1}^{M} N_{mct} \le UB_c;\ \forall(c,t) \quad (19)$$

$$\sum_{w=1}^{W} N_{wct} \ge L_{wc},\ \forall(c,t) \quad (20)$$

$$\sum_{m=1}^{M}\sum_{p=1}^{P} z_{pmwct} . t_{pmw} . \beta_{pt} \le N_{wct} RW_{wt}\ ,\forall(w,c,t) \quad (21)$$

$$\sum_{w=1}^{W}\sum_{p=1}^{P} z_{pmwct} . t_{pmw} . \beta_{pt} \le N_{mct} . T_{mt}\ ,\forall(m,c,t) \quad (22)$$

$$N_{wc(t-1)} + L^{+}_{wct} - L^{-}_{wct} = NW_{wct}, \forall(w,c,t) \quad (23)$$

$$\sum_{c=1}^{C} N_{wct} \le AW_w, \forall(w,t) \quad (24)$$

$$\sum_{c=1}^{C}\sum_{w=1}^{W}\sum_{m=1}^{M} z_{pmwct} \le \beta_{pt}.L^p; \forall(p,t) \quad (25)$$

$$A^{*}_{m(t=1)} = A_{m(t=1)} + BN_{m(t=1)}, \forall(m) \quad (26)$$

$$A^{*}_{m(t+1)} = A^{*}_{mt} + BN_{m(t+1)}, \forall(m) \quad (27)$$

$$\sum_{c=1}^{C} N_{mct} \le A^{*}_{mt}; \forall(m,t) \quad (28)$$

$$f_{j,t} + d_{j,t} + f_{j,t-1} = r_{j,t} \quad (29)$$

$$d_{j,t} \le M\delta_{j,t} \quad (30)$$

$$\sum_{m=1}^{M}\sum_{c=1}^{C} \overline{X}_{imct} \le UR_i \sum_{j=1}^{J} B_{i,j} d_{j,t} \quad (31)$$

$$\begin{aligned} &N_{mct}; Y^{+}_{mct}; Y^{-}_{mct} \ge 0 \text{ and integer } \forall(m,c,t) \\ &L^{+}_{wct}; L^{-}_{wct}; N_{wct} \ge 0 \text{ and integer } \forall(w,c,t) \\ &Q_{pt}; \beta_{pt}; O_{pt} \ge 0 \text{ and integer } \forall(p,t) \\ &BN_{mt}; A^{*}_{mt} \ge 0 \text{ and integer } \forall(m,t) \\ &v_{pct} \in \{0,1\} \forall(p,c,t) \\ &z_{pmwct} \in \{0,1\} \forall(p,m,w,c,t) \end{aligned} \quad (32)$$

The objective function has several terms: Equation (1) represents relocation cost of machines installation, (2) represents relocation cost of machines removal, (3) represents part holding cost, (4) represents the salary worker cost, (5) represents the hiring worker cost, (6) represents the firing worker cost, (7) represents part intercellular movement cost, (8) represents machine procurement cost, (9) represents the internal production cost, (10) represents the cost of acquiring the returned products, (11) represents the setup cost for disassembly operations, (12) represents disassembly cost, (13) represents the inventory cost of the returned products.

The objective function is subjected to constraints as follows: Equation (14) shows that demand of part type p, in each time period t is satisfied through internal part production, and/or part inventory carried over from previous period, (15) is to determine whether part type p is processed within cell c in period t, (16) and (17) is to make sure that only one worker is assigned for each part on each machine type, (18) is to ensure that the number of machines type m in current period is equal to the number of machines in the previous period, adding the number of machines moved in and subtracting the number of machines moved out of the cell c. By (19), lower and upper bounds on sizes of cell in terms of the number of machines are enforced, (20) ensures that the minimum number of workers to be assigned to cell k in each period, (21) and (22) ensure that the available time for workers and capacity of machines are not exceeded, respectively, (23) balances the number of workers between consecutive time periods, (24) guarantees that the total number of workers of each type assigned to different cells in each period will not exceed total available number of workers of that type, (25) ensures that If $\beta_{pt} = 0$, no machines, worker and cell should be considered, (26) relates to the machine availability constraint for period 1, taking into consideration the extra machines introduced through the machine procurement option, (27) relates to the machine availability constraint for the subsequent time periods. It takes into consideration the extra machines introduced through the machine procurement option in the period under consideration as well as those procured in all of the previous periods, (28) ensures that the total number of machines in each cell will not exceed the number of available machines, (29) shows that the number of returned product to disassemble in period t and the number of returned product to be kept in inventory to the next period is equal to the number in inventory from the previous period and the number to be acquired in period t, (30) is a logical constraint for disassemble, (31) gives the limit of the parts obtained from the returned products based on the quality level and bill of material, (32) is the logical binary and non-negativity integer requirements on the decision variable.

III. LINEARIZATION OF THE OBJECTIVE FUNCTION

Objective function is a nonlinear integer equation due to nonlinear terms (7) in the objective function and (15), (21) and (22). To transform these terms to linear terms, the following new variables are defined [12]:

$$F_{pct} = v_{pct} * \beta_{pt}$$
$$J_{pmwct} = z_{pmwct} * \beta_{pt}$$

By considering these equations, following constraints must be added to the model:

$$F_{pct} \ge \beta_{pt} - L^p(1 - v_{pct}) \ \forall(p,c,t) \quad (33)$$

$$F_{pct} \le \beta_{pt} + L^p(1 - v_{pct}) \ \forall(p,c,t) \quad (34)$$

$$J_{pmwct} \ge \beta_{pt} - L^p(1 - z_{pmwct}) \ \forall(p,m,w,c,t) \quad (35)$$

$$J_{pmwct} \le \beta_{pt} + L^p(1 - z_{pmwct}) \ \forall(p,m,w,c,t) \quad (36)$$

$$F_{pct} \ge 0 \text{ and is integer } \quad \forall(p,c,t) \quad (37)$$

$$J_{pmwct} \ge 0 \text{ and is integer } \quad \forall(p,m,w,c,t) \quad (38)$$

Also to linearize the proposed model, (3) should be replaced by these two constraints:

$$\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} \le L^p * \beta_{pt}, \ \forall(p,c,t) \quad (39)$$

$$\sum_{m=1}^{M}\sum_{w=1}^{W} z_{pmwct} \ge \beta_{pt}, \ \forall(p,c,t) \quad (40)$$

Therefore, the proposed linear mathematical programming model is as follows:

$$\text{Min Equation (1) to (6)} + \sum_{t=1}^{T}\sum_{p=1}^{P}\left[\left(\sum_{c=1}^{C} F_{pct}\right) - \beta_{pt}\right].V_p^{inter} + \text{(9) to (13)}$$

TABLE I
MACHINE INFORMATION

	Part1				Part2				Part3				Part4			
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
M1	0.04	0.02	0.04	0.06	0.04	0.01	0.03	0.04	0.02	0.03			0.04	0.03	0.02	0.01
M2	0.05	0.03	0.02	0.03	0.05	0.01	0.04	0.03	0.04	0.03	0.02	0.01			0.03	0.02
M3	0.01	0.02	0.02	0.02	0.04	0.03	0.02	0.01	0.01		0.02		0.03		0.04	

St.: Constraints (14), (16)-(20), (23)-(40) and the new version of constraints (21) and (22) are:

$$\sum_{m=1}^{M}\sum_{p=1}^{P} J_{pmwct} * t_{pmw} \leq N_{wct} * RW_{wt}, \forall(w,c,t) \quad (41)$$

$$\sum_{w=1}^{W}\sum_{p=1}^{P} J_{pmwct} * t_{pmw} \leq N_{mct} * T_{mt}, \forall(m,c,t) \quad (42)$$

IV. NUMERICAL EXAMPLE

In this example there will be four types of parts, three types of machines, 2 cells, and four types of workers. Each cell should have at least 3 workers and 2 machines; also, the total number of machines should not exceed 5 machines in each cell. In Table I represents the processing time for each part type on each machine by each worker, in Table II the machines input data are represented. The numbers of components contained in the different products are shown in Table III, in Table IV parts information and the machine-part matrix are represented, Table V gives all parts information as well as machine-worker incidence matrix. Table VI gives products costs.

In order to satisfy the demand for each part type, and as we mentioned earlier that all the internal production will be made by using the returned products, 125 items of product type 2 and 567 of type 3 needed to satisfy the demand. The production in period 1 will be as follow: 800 of P1, 900 of P2, 1700 of P3, and 1700 of P4. In period 2 the production will be as follow: 750of P1, 600 of P2, 500 of P3, and 300 of P4. There will be different paths to produce these quantities, Table I represent these different paths which will work simultaneously in order to produce the required amount, for example part type 3, will be produced in the first period and in the first cell by worker type 3 using machine type1 and by worker type 2 using machine type 3, in the second period the production for part type 3 will take place in the second period by using the same options was in the first period. There will be 800 items of part type 2 to be held in inventory from period 1 to period 2.

TABLE II
THE PROCESSING TIME

Machine Type	Machine Information					
	A_m	R_m^+	R_m^-	T_{m1}	T_{m2}	OP_m
1	0	550	140	30	30	4000
2	0	530	130	30	30	2000
3	0	560	150	30	40	2000

V. CONCLUSION AND FUTURE RESEARCH

In this paper, a mixed integer nonlinear programming model in cellular remanufacturing system has been developed. To the best of the authors' knowledge this is the first model which considers CMS and remanufacturing system simultaneously. This is, accordingly one preliminary step towards the Design for Sustainable Manufacturing Enterprise (DFSME). The model integrates many manufacturing attributes such as production planning, machine cost, machine capacity as well as several workforce management issues such as worker capacities, worker assignments, salary, hiring and firing costs for the workers. The future work in this research is to design a Cellular Hybrid Manufacturing-Remanufacturing System (CHMRS) which is a system where manufacturing and remanufacturing operations occur simultaneously with shared resources.

TABLE III
NUMBER OF PARTS INCLUDE IN EACH PRODUCT

Product \ Part	1	2	3	4
1	10	10	8	13
2	12	12	10	12
3	15	11	3	8

TABLE IV
INPUT DATA OF MACHINE-PART INCIDENCE MATRIX

		Machine Type			Parts Information						
		1	2	3	UR_i	D_{p1}	D_{p2}	$£_p$	H_{p1}	H_{p2}	V_p^{inter}
Part Type	1	1	1	1	0.5	0	1550	20	4	4	11
	2	1	1	0	0.5	900	600	21	6	6	9
	3	1	0	1	0.6	1700	500	23	8	8	8
	4	0	1	1	0.2	1700	300	24	10	10	10

TABLE V
INPUT DATA FOR WORKER-MACHINE INCIDENCE MATRIX

		Machine Type			Worker Information							
		1	2	3	A_w	S_{w1}	S_{w2}	HI_{w1}	HI_{w2}	F_{w2}	RW_{w1}	RW_{w2}
Worker Type	1	1	0	1	2	470	490	270	285	145	30	30
	2	1	0	0	2	460	485	260	290	145	30	30
	3	0	1	1	2	455	475	200	250	155	30	30
	4	0	1	0	2	450	480	265	280	140	30	30

TABLE VI
RETURNED PRODUCTS DATA

	Cost											
	Product 1				Product 2				Product 3			
t	RD	SD	IN	AQ	RD	SD	IN	AQ	RD	SD	IN	AQ
1	30	22	40	25	25	35	50	35	20	30	30	25
2	35	30	40	15	30	25	50	20	18	28	30	28

TABLE VII
PRODUCTION ROUTES

Time Period 1				
Cell 1: P2- M1 W3 P3 M1 W3 P4 M2 W1	 P2 M2 W4 P3 M3 W2 P4 M3 W2	Cell 2: P1 M1 W2 M3 W4	P1 M2 W2	P1
Time Period 2				
Cell 1: P2 M1 W3 P4 M2 W1	 P2 M2 W4 P4 M3 W2	Cell 2: P1 M1 W2 M3 W4 P3 M1 W3	P1 M2 W2 P3 M3 W2	P1

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