Proceedings of the International MultiConference of Engineers and Computer Scientists 2010 Vol III,
IMECS 2010, March 17 - 19, 2010, Hong Kong

Decision Support for the Dynamic Reconfiguration of Machine Layout and Part Routing in Cellular Manufacturing

Hao W. Lin, and Tomohiro Murata

***Abstract*—A mathematical based approach is presented to evaluate the dynamic cellular reconfiguration problem in a CM system. The model developed is a multi-objective Goal Programming problem that simultaneously considers performance in machine utilization, inter-cellular part movements, and machine reallocation. The merit of the approach presented in this paper is the utilization of meta-goals to represent decision-makers' preferences and to ensure the meta-goals can effectively guide the underlying model to reach a solution that best satisfies decision-makers' preferences. This approach significantly improves decision-support capabilities, and it is critical for the development of decision-support systems. A hypothetical numerical example is provided in this paper to verify the strength of the presented approach.**

***Index Terms*—Machine Layout, Cellular Manufacturing, Decision Support, Optimization**

I. Introduction

This paper is focused on discussing the development of a mathematical model based decision-support approach to solve the dynamic machine layout configuration problem presented in Cellular Manufacturing (CM). CM is a paradigm derived from the concept of Group Technology (GT) [1], where the key idea is to improve production performance by grouping parts with similar production flows and grouping machines with the right mix for producing a particular family of parts within a cell. Previous study and implementation of CM in actual manufacturing systems have confirmed improvements in production efficiency, end product quality, and part flow control on work-floor. It is generally accepted that CM is most suitable for medium production volume and medium product mix systems [2]. In our study, we emphasized on the problem that production demand fluctuates dramatically, and that the machine layout and part routing of the CM system must be dynamically adjusted to ensure the overall efficiency of the system. Further, our study concentrates on the incorporation of Decision-Makers' (DMs) preferences into the mathematical model, so that the corresponding optimal solution that best satisfies the preferences can be effectively found. This mechanism would pave the way for a better designed decision-support tool, as it significantly improves the quality of analysis interactions between DMs and the underlying decision model.

Manuscript received January 10, 2010. This work was supported by KAKENHI <20-08764>, and in part by the Japan Society for the Promotional of Science (JSPS).

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II. Background

The classical problem of setting up a CM system mainly focuses on determining the optimal allocation of machines to each cell and the routing of parts between the production cells. In general, the optimal objective was to eliminate Exceptional Elements (EE) [3]. EE are classified into exceptional machines and exceptional parts. Exceptional machines refer to the machines within a cell that are only utilized by a few of the parts assigned to that cell. Exceptional parts however, refer to those parts that must be routed through more than one cell to complete their production. Exceptional machines and exceptional parts are inversely related to each other, but they both have negative effects on the performance of the overall CM system. Excessive exceptional machines require significantly higher machine investment, and usually they would experience lower utilization levels. Excessive exceptional parts dramatically increase material handling costs and inter-cellular dependency. Intra-cell part movements are performed manually over a close distance one unit at a time. Inter-cell movements though, parts are usually moved in lots and navigates over a relatively longer distance using costly material handling resources and often through a complex routed factory floor. Hence it is generally accepted that the overall costs of inter-cell movements are significantly higher than intra-cell movements. Further, when parts are assigned to be processed on multiple cells, then production schedules between these cells must be synchronized in order to reduce Work-In-Progress (WIP). This type of inter-dependency between the cells is difficult to manage and it often prevents each cell operating at an optimal condition.

Conventionally, the layout configuration of a CM system is considerably static. In general, the average demand of each product is predicted over a relatively long foreseeable future, and that the cell layouts are planned accordingly once off. In [2], Groover has discussed a simple clustering approach to determine a cell formation for processing all the products in consideration. This method however only analyzed the production routing relationship of each part, and it does not consider the effects of demand variations between parts. In

ISBN: 978-988-18210-5-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

[4], Defersha and Chen applied mathematical based approach to analyze the cell configuration problem. The problem is however NP-hard, and thus the calculation time is generally long even for a relatively small problem. Kioon, Bulgak, and Bektas [5] have proposed a linearization approach that improves evaluation time by eliminating non-linear relationships in the model. As reported in [6] and [7], heuristic approaches have also been attempted to improve calculation time with slightly comprised result quality.

In a volatile market, the demands for each product is subjecting to significant fluctuations over relatively short time intervals. Inherently, the CM based machine layout must be reconfigured dynamically to ensure the production floor is used optimally for producing the overall demands of the system at different production periods. This type of problems have been tackled by [8] and [9] with satisfying results.

In our study, we have noticed that while planning for each reconfiguration, DMs must convey real-time situation and be allowed to specify their performance preferences for the new cell configuration. These preferences must be concisely incorporated to the model in order to find the corresponding solution that best satisfies the scenario at time. This problem has not been actively addressed in previous studies, and it is the main contribution of this study. In this study the performance factors considered are the utilization level of each machine, the number of inter-cell movements for each product, and the number of machines to reallocate. The authors of this paper have developed a Goal Programming (GP) [10] model to evaluate this multi-objective cell reconfiguration problem. Further the concepts of meta-goal [11] is applied to convey DMs' preferences, and to build the necessary interface between DMs and the underlying model. This mechanism is significantly important for the development of decision support systems.

III. Problem Definition and Model Formulation

The problem considered in this study assumes that production order of each part in the upcoming production period has been determined. The cell reconfiguration model is then applied to determine a cellular formation that would optimally produce the parts. The solution of this model indicates what machines are allocated to each cell, but it does not provide the actual arrangement of machines within a cell. Machine arrangement in each cell is determined by the production sequences of the parts that are assigned to a cell and this is not within the scope of this study. It is also assumed in this study that the machines can be reallocated economically. In each planning period, the demand for each part fluctuates dramatically. Hence by reallocating the machines, it is expected that intercellular material handling would be dramatically reduced, and that the resources saved from material handling justifies the resources that are required to perform the reallocation of machines. Overall, the model considers three objectives, which are minimizing inter-cellular part movements, maximizing machine utilization, and minimizing machine reallocation. This multi-objective problem is modeled using the GP technique. Inter-cellular part movement is inversely proportional to machine utilization, and machine reallocation. It is expected that DMs understand their operational environments and have clearly distinguishable preferences on the attainment level of each objective. The model must accurately convey these preferences and effectively determine the corresponding optimal solution for the system. In this study, the interface between the DMs' preferences and the model is established based on the concept of meta-goals.

A. *Meta-Goals*

In general, classical GP models use weighting factors and normalization to represent the relative importance of each original goal and solve the immeasurability problem respectively. These techniques alone are unable to concisely and accurately portray DMs' fulfillment preferences for decision problems that consist of relatively higher number of goals especially. By applying the concept of meta-goals [11], this problem can be effectively addressed. The main idea behind meta-goal is the simultaneous cognitive evaluation on the degree of attainments for original decision goals considered in a GP model. In a Meta-GP model, a meta-goal is represented by appropriate constraint functions and target parameters for the undesired deviations of the original goals.

In this study, three meta-goals have been formulated to represent the DMs' preferences on the achievement of the cell reconfiguration model. Each meta-goal offers a unique way of expressing and manipulating the overall achievement for a particular class of the original decision goals. These decision goals are classified based on the objectives of optimizing inter-cellular part movements, machine utilization, and machine reallocation. Through the use of these meta-goals, it eliminates the needs to directly manipulate the underlying original GP model when the desired operational preferences of the DMs are modified, which inherently reinforces the elimination of human error. Furthermore, meta-goals allow DMs to more swiftly identify an overall picture on the strengths and the weaknesses of the particular cell formation under consideration. Meta-goal targets can then be adjusted accordingly to setup the required condition for finding a solution with better overall performance with respect to all the preferences considered.

B. *Modulated GP Model with Meta-Goals*

The dynamic cell reconfiguration model is intended to be evaluated by Lingo 11 optimization solver released by Lindo Incorporated [12]. The basic structure of the model can be categorized into four major groups, which are *variable type declaration*, *constraint function*, *original goal function*, and *meta-goal function* components. The type declaration group is for declaring the data type and range limitation for each variable. The constraint function group includes equations that convey physical inter-relationships between the decision variables and operational parameters of actual decision problems. The original function group is for specifying the performance objectives of the model. Lastly the meta-goal function group is for specifying equations that convey DMs' preferences on the fulfillment level of the original goal functions. Inherently, the system must automatically identify the appropriate constraint functions, original goal functions, and meta-goal functions to be included in building a complete model that specifically portray the corresponding preferences. This feature is enabled by the Sub-model and Logic control functionalities that are supported by Lingo 11. The cell configuration model is formally defined below.

Decision model indices and basic sets:

i Indexing integer for parts

j Indexing integer for machine types

k Indexing integer for production cells

$\mathbf{P} = \{p_1, p_2, p_3, ..., p_i, ...p_I\}$ Set of parts to be produced, I is the total number of different parts to be produced

$\mathbf{M} = \{m_1, m_2, m_3, ..., m_j, ...m_J\}$ Set of machine types available, J is the total number of different machine types

$\mathbf{C} = \{c_1, c_2, c_3, ..., c_k, ...c_K\}$ Set of production cells to be reconfigured, K is the maximum number of different cells

Decision model parameters:

D_i Total unit in demand for part i

T_j Total unit of machine(s) available for machine type j

S_k^{min} Minimum unit of machine(s) required in cell k

S_k^{max} Maximum unit of machine(s) allowed in cell k

W Total unit of production time available for every machine

$O_{i,j}$ Represents if operation of part i on machine type j is required, value 1 implies required and 0 implies otherwise

$L_{i,j}$ Average production lead-time of part i on machine type j, 0 if part i is not to be operated on machine type j

$I_{j,k}$ Represents the initial machine layout configuration, I machine units of machine type j allocated in cell k

$\gamma^{utilise}$ Meta-goal objective that represents the DMs' preference on machine utilization level

γ_i^{move} Meta-goal objective that represents the DMs' preferred number of inter-cellular part movements for part i

γ_j^{alloc} Meta-goal objective that represents the DMs' preferred number of machine reallocations for machine type j

Decision model variables:

$A_{i,j,k}$ Represents if part i is assigned to operate on machine type j that is allocated to cell k, 1 implies assigned, 0 implies otherwise

$R_{i,k}$ Represents if part i has any operations performed in cell k, 1 implies at least one operation of part i is performed in cell k, 0 implies otherwise

$N_{j,k}$ Represents the new cell configuration, number of units of machine type j to be allocated to cell k

$X_{i,k}^{intra}$ Total number of intra-cell movements for part i in cell k

X_i^{inter} Total number of inter-cell movements for part i

$Y_{j,k}^{-}$, $Y_{j,k}^{+}$ Represents how much production time capacity is underutilized and over-utilized for machine type j in cell k respectively

$Z_{j,k}^{in}$, $Z_{j,k}^{out}$ Represents how many units of machine type j is to be moved into and moved out of cell k respectively

$\eta^{utilise}$, $\mu^{utilise}$ Respectively, slack and surplus variables of the meta-goal that represents the utilization level preference of all machines

η_i^{move}, μ_i^{move} Respectively, slack and surplus variables of the meta-goal that represents the number of inter-cellular part movement preference for part i

η_j^{alloc}, μ_j^{alloc} Respectively, slack and surplus variables of the meta-goal that represents the number of machine reallocation preference for machine type j

Decision model functions:

SUBMODEL DATATYPE_DECLARE:

$$A_{i,j,k} \in \{0,1\}; \forall i, \forall j, \forall k \quad (1)$$

$$N_{j,k} \geq 0, \in Integer; \forall j, \forall k \quad (2)$$

$$R_{i,k} \in \{0,1\}; \forall i, \forall k \quad (3)$$

DATATYPE_DECLARE is for explicitly declaring data type and range for variables that are not default positive real numbers as assumed by Lingo. In the model, $A_{i,j,k}$ is for representing the assignment of parts and that $R_{i,k}$ is for representing the process routing of each part. Both $A_{i,j,k}$ and $R_{i,k}$ can only take a logical value of either true or false and these values are represented by a binary number of 1 or 0 respectively. $N_{j,k}$ is for representing the allocation of machines in cells, and since each machine can only be considered as an individual unit, $N_{j,k}$ is declared as a real integer number by (3).

SUBMODEL ALLOCATE_MACHINES:

$$\sum_{j=1}^{J} N_{j,k} \geq S_k^{min}; \forall k \in \mathbf{C} \quad (4)$$

$$\sum_{j=1}^{J} N_{j,k} \leq S_k^{max}; \forall k \in \mathbf{C} \quad (5)$$

$$\sum_{k=1}^{K} N_{j,k} \leq T_j; \forall j \in \mathbf{M} \quad (6)$$

ALLOCATE_MACHINES defines the machine allocation constraints for the model. Equation (4) and (5) specifies the minimum and maximum number of machines that must be assigned to a cell respectively. Equation (6) specify that for each machine type, the total number of machine units allocated to all of the cells is less or equal to the number of available machine units.

SUBMODEL ASSIGN_PARTS:

$$\sum_{k=1}^{K} A_{i,j,k} = O_{i,j}; \forall i \in \mathbf{P}, \forall j \in \mathbf{M} \quad (7)$$

$$\sum_{i=1}^{I} A_{i,j,k} \times D_i \times L_{i,j} + Y_{j,k}^{-} - Y_{j,k}^{+} = N_{j,k} \times W; \forall j \in \mathbf{M}, \forall k \in \mathbf{C} \quad (8)$$

ASSIGN_PARTS specifies part assignment constraints and utilization goal functions for the dynamic cell reconfiguration problem. Equation (7) specifies that a valid operation step of a part must be entirely assigned for production on the corresponding machine type of a single

ISBN: 978-988-18210-5-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

cell. In this equation, $A_{i,j,k}$ applies a constraint that the entire production demand of a particular operation of a part is only assigned for production in a single cell. This approach would reduce the needs to synchronize production activities between multiple cells, and thus reducing the complexity of intercellular scheduling activities. Further, as the entire lot of parts has the same production path, it significantly improves production traceability for every product produced in the system. Equation (8) is a goal function that specifies workloads for producing the part demands must be less or equal to the production capacities. The purpose of the goal function is to detect and minimize over-utilization and under-utilization of the available resources.

SUBMODEL INTRA_INTER_MOVES:

$$X_{i,k}^{intra} = \sum_{j=1}^{J} A_{i,j,k} \times D_i ; \forall i \in \mathbf{P}, \forall k \in \mathbf{C} \quad (9)$$

$$X_{i,k}^{intra} \geq R_{i,k} ; \forall i \in \mathbf{P}, \forall k \in \mathbf{C} \quad (10)$$

$$X_{i,k}^{intra} \times R_{i,k} - X_{i,k}^{intra} = 0; \forall i \in \mathbf{P}, \forall k \in \mathbf{C} \quad (11)$$

$$X_{i}^{inter} = \sum_{k=1}^{K} R_{i,k} \times D_i ; \forall i \in \mathbf{P} \quad (12)$$

INTRA_INTER_MOVES applies functions to detect the intra-cellular and inter-cellular part handling movements. Equation (9) calculates the number of intra-cellular part handling movements for a particular part in a particular cell. Equations (10) and (11) are formulated to determine if a part is to be routed through a certain cell in order to complete its production. Based on this routing information, Equation (12) is used to determine the number of inter-cellular part handling movements for each part.

SUBMODEL MT_MOVEMENTS:

$$I_{j,k} + Z_{j,k}^{in} - Z_{j,k}^{out} = N_{j,k} ; \forall j \in \mathbf{M}, \forall k \in \mathbf{C} \quad (13)$$

MT_MOVEMENTS consists of a goal function to specific the machine movement objectives. Equation (13) indicates that it is best to keep the machine formation unchanged in order to save machine reallocation resources. Due to demand fluctuation however, machine movements are performed to improve production efficiencies. In (13), the number of machines of a particular machine type moving into a cell or moving out of the cell is determined.

SUBMODEL OBJECTIVE_FUNC:

$$Min \quad 10000 \times \sum_{j=1}^{J}\sum_{k=1}^{K} Y_{j,k}^{+} + \sum_{j=1}^{J}\sum_{k=1}^{K} Y_{j,k}^{-} + \sum_{i=1}^{I} X_i^{inter} + 100 \times \sum_{j=1}^{J}\sum_{k=1}^{K} Z_{j,k}^{in} + Z_{j,k}^{out} ; \quad (14)$$
$$\forall i \in \mathbf{P}, \forall j \in \mathbf{M}, \forall k \in \mathbf{C}$$

*OBJECTIVE_FUNC define*s an objective function (14) for the underlying GP model. A high weighting factor is assigned to minimize over-utilization variable as demand fulfillment is most prioritized. A moderate weighting factor is assigned to the machine reallocation variables as their magnitude scale is considerably smaller than the other factors. The objective function is merely the minimization of the sum of the undesired deviations. The solution obtained with respect to this objective function would be used as a performance reference point, and would provide tradeoffs guidance for the DMs. Thus, the DMs would gain better understanding of the model and thus formulate better meta-goals to search for the preferred final solution.

SUBMODEL MG_UTILISE:

$$@\,\mathrm{MAX}(Y_{j,k}^{-}) + \eta^{utilise} - \mu^{utilise} = \gamma^{utilise} ; \quad \forall j \in \mathbf{M}, \forall k \in \mathbf{C} \quad (15)$$

MG_UTILISE is used to define a meta-goal function (15) that represents the DMs' preferred fulfillment level for the original machine utilization goal. This meta-goal allows DMs to specify an under-utilization level commonly accepted for every machine in the system.

SUBMODEL MG_INTERMOVE:

$$\sum_{k=1}^{K} R_{i,k} + \eta_i^{move} - \mu_i^{move} = \gamma_i^{move} ; \forall i \in \mathbf{P} \quad (16)$$

MG_INTERMOVE is used to define a meta-goal function (16) that represents the DMs' preferred fulfillment level for the original part movement goal. This meta-goal allows DMs to specify a unique maximum number of inter-cellular movements allowed for each part produced in the system.

SUBMODEL MG_MTMOVES:

$$\sum_{k=1}^{K} Z_{j,k}^{in} + Z_{j,k}^{out} + \eta_j^{alloc} - \mu_j^{alloc} = \gamma_j^{alloc} ; \forall j \in \mathbf{M} \quad (17)$$

MG_MTMOVES is used to define a meta-goal function (17) that represent the DMs' preferred fulfillment level for the original machine reallocation (both moving into and out of each cell) goal. This meta-goal allows DMs to specify the unique maximum number of machine movements allowed for each machine type in the system.

CALC:

If scenario 1 {*OBJECTIVE_FUNC* model}:
  @SOLVE(*DATATYPE_DECLARE, ALLOCATE_MACHINES, Assign Parts, INTR_INTER_MOVES, MT_MOVEMENTS, OBJECTIVE_FUNC*)
ELSE-If scenario 2 {*MG_UTILISE* model}:
  @SOLVE(*DATATYPE_DECLARE, ALLOCATE_MACHINES, Assign Parts, INTR_INTER_MOVES, MT_MOVEMENTS, MG_UTILISE*)
ELSE-If scenario 3 {*MG_INTERMOVES* model}:
  @SOLVE(*DATATYPE_DECLARE, ALLOCATE_MACHINES, Assign Parts, INTR_INTER_MOVES, MT_MOVEMENTS, MG_INTERMOVES*)
ELSE-If scenario 4 {*MG_MTMOVES* model}:
  @SOLVE(*DATATYPE_DECLARE, ALLOCATE_MACHINES, Assign Parts, INTR_INTER_MOVES, MT_MOVEMENTS, MG_MTMOVES*)
END IF

The *CALC* section builds the final model for analyzing the cell reconfiguration problem corresponding to a particular scenario. In the current model, four scenarios are supported. The first scenario is to evaluate the problem using the *OBJECTIVE_FUNC* minimization objective function, and thus obtain an initial solution that serves as a performance tradeoffs reference point for DMs. The other scenarios are to evaluate the problem with respect to the meta-goals. Each meta-goal represents a preferred fulfillment objective for the original goals, and they are described as per sub-model section above under *MG_UTILISE, MG_INTERMOVES, and MG_MTMOVES* headings respectively.

ISBN: 978-988-18210-5-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

IV. NUMERICAL EXAMPLE

A hypothetical example is applied to here to demonstrate the application of the dynamic cell reconfiguration model formally defined in Section III. It is assumed that the manufacturing firm considered in this example has a weekly fixed interval planning period. In total, there are 2100 working minutes available per machine in operation. The data sets and various parameter values of the hypothetical problem are summarized below. Decision solutions will also be presented for the original *OBJECTIVE_FUNC* model, and the meta-goal models, which are the *MG_UTILISE*, *MG_INTERMOVES*, and *MG_MTMOVES* models.

Data sets for the numerical example:

$\mathbf{P}=\{p_1, p_2, p_3, p_4, p_5, p_6, p_7\}$, $\mathbf{C} = \{c_1, c_2, c_3, c_4, c_5\}$

$\mathbf{M} = \{m_1, m_2, m_3, m_4, m_5, m_6\}$

$D_i = \{3200, 1500, 3500, 3300, 2000, 1000, 3500\}$

$S_k^{min} = \{0, 0, 0, 0, 0\}$, $S_k^{max} = \{8, 8, 8, 8, 8\}$

$T_j = \{6, 6, 6, 6, 6, 6\}$

$$L_{i,j} = \begin{Bmatrix} 1.2 & 0 & 1.3 & 0 & 0 & 0 \\ 0.8 & 0.9 & 0 & 0 & 1 & 0 \\ 0 & 0.7 & 0.9 & 0.6 & 0.8 & 0 \\ 0.7 & 0.7 & 0 & 0.6 & 0.6 & 0.6 \\ 0 & 0.8 & 0.9 & 1 & 0 & 0 \\ 0 & 0 & 0.8 & 0.7 & 0.6 & 0.7 \\ 0 & 0.6 & 0.7 & 0.5 & 0.8 & 0.9 \end{Bmatrix}$$

Table 1 below summarizes the initial cell layout configuration and production routes for each part considered in the example. The data is expressed as duplets. For each duplet, the number before the colon indicates how many unit of a machine type is assigned to a cell. The values after the colon indicate what parts are assigned to the machine type that is located within the particular cell.

Table 1. Initial cell configuration and production routes

Initial Setup	C_1	C_2	C_3	C_4	C_5
$\mathbf{m_1}$	2:P_1	----	----	2:P_2,P_4	----
$\mathbf{m_2}$	1:P_3	----	2:P_5,P_7	2:P_2,P_4	----
$\mathbf{m_3}$	2:P_1,P_3	----	2:P_5	----	2:P_6,P_7
$\mathbf{m_4}$	1:P_3	----	2:P_5,P_7	1:P_4	1:P_6
$\mathbf{m_5}$	1:P_3	----	----	2:P_2,P_4	2:P_6,P_7
$\mathbf{m_6}$	----	----	----	1:P_4	2:P_6,P_7

In the initial analysis, the model is solved using the *OBJECTIVE_FUNC* model. Corresponding solution of the model is summarized in Table 2, and it is the optimal setup for cell configuration and production routes when all objectives are considered with equal importance. It is assumed now that the DMs have some specific preferences to satisfy. Firstly this numerical example considers a meta-goal where each machine type in each cell must not have more than 1500 of unutilized production minutes. Secondly, the example considers that each unit of parts should be allowed a maximum number of inter-cellular movements of {1,2,1,2,2,2,1}. Finally, it is considered that every machine type should not have more than a maximum of 2 reallocations. The solutions for these three problem setups are summarized in Table 3, Table 4, and Table 5 respectively.

Table 2. Solution of the *OBJECTIVE_FUNC* model

New Setup	C_1	C_2	C_3	C_4	C_5
$\mathbf{m_1}$	2:P_1	----	2: P_2 ,P_4	----	----
$\mathbf{m_2}$	----	----	2:P_2,P_4	2:P_3,P_5	1: P_7
$\mathbf{m_3}$	2:P_1	----	----	4: P_3,P_5,P_6,P_7	----
$\mathbf{m_4}$	1:P_6	----	1:P_4	2:P_5,P_7	1:P_3
$\mathbf{m_5}$	----	----	2: P_2,P_4	----	3:P_3,P_6 ,P_7
$\mathbf{m_6}$	----	----	1: P_4	----	2:P_6,P_7

Table 3. Solution of the *MG_UTILISE* model

New Setup	C_1	C_2	C_3	C_4	C_5
$\mathbf{m_1}$	----	----	----	1: P_2	3: P_1,P_4
$\mathbf{m_2}$	2: P_2 ,P_3	----	----	1:P_7	2: P_4,P_5
$\mathbf{m_3}$	----	----	----	6: P_1,P_3,P_5,P_6,P_7	----
$\mathbf{m_4}$	1: P_3	1: P_6	2: P_4 ,P_7	----	1:P_5
$\mathbf{m_5}$	2: P_3	----	3: P_2,P_6,P_7	----	1:P_4
$\mathbf{m_6}$	----	----	3: P_4,P_6,P_7	----	----

Table 4. Solution of the *MG_INTERMOVES* model

New Setup	C_1	C_2	C_3	C_4	C_5
$\mathbf{m_1}$	----	----	----	2: P_2,P_4	2: P_1
$\mathbf{m_2}$	2: P_3	----	1: P_7	2: P_2,P_4	1: P_5
$\mathbf{m_3}$	2: P_3,P_6	----	2: P_5,P_7	----	2: P_1
$\mathbf{m_4}$	2: P_3,P_6	----	1: P_7	1: P_4	1: P_5
$\mathbf{m_5}$	2: P_3,P_6	----	2: P_7	2: P_2,P_4	----
$\mathbf{m_6}$	----	----	2: P_6,P_7	1: P_4	----

Table 5. Solution of the *MG_MTMOVES* model

New Setup	C_1	C_2	C_3	C_4	C_5
$\mathbf{m_1}$	2:P_1	----	----	2: P_2,P_4	----
$\mathbf{m_2}$	----	----	3: P_3,P_5 ,P_7	2: P_2,P_4	----
$\mathbf{m_3}$	2:P_1	----	2: P_5,P_7	----	2: P_3,P_6
$\mathbf{m_4}$	----	----	3: P_3,P_5,P_7	1: P_4	1: P_6
$\mathbf{m_5}$	----	----	----	2: P_2,P_4	3: P_3,P_6 ,P_7
$\mathbf{m_6}$	----	----	----	1: P_4	2:P_6,P_7

V. RESULT ANALYSIS AND DISCUSSION

The performance of the CM system when different meta-goal is applied in the model is analyzed in this section. The solution obtained from Section IV is used as the basis of this analysis. As mentioned earlier, machine utilization, inter-cellular part movement, and machine reallocation are the three objectives considered in this study. It is attempted to verify here that when a DM has a specific preferred achievement level for these objectives, his/her preference can be represented by a meta-goal and that a corresponding optimal solution would be found by the model.

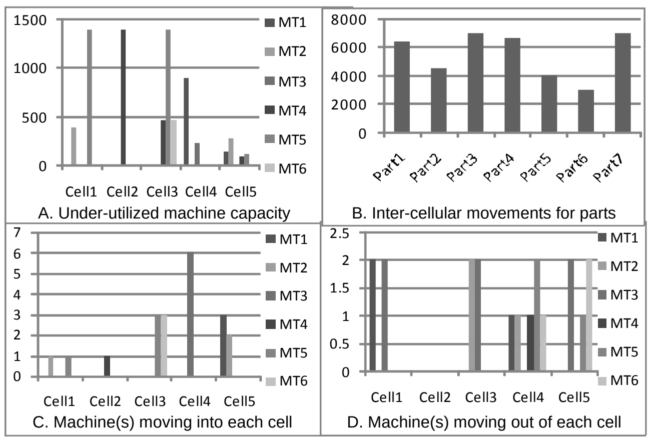

Figure 1. Performance for *MG_UTILISE* model

ISBN: 978-988-18210-5-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Firstly, let's analyze the *MG_UTILISE* model, where satisfying machine utilization is considered the most important. In Fig. 1, various performance parameters for the *MG_UTILISE* model are depicted using bar graphs. It can be observed in Fig. 1.A that every machine type has an under utilization level that satisfy the DMs' preference, and that other objectives are minimized provided that the DMs' preference is met. In Fig. 1.B to Fig. 1.D, it can be clearly observed that inter-cellular part movements and machine reallocation are strongly compromised in order to satisfy the machine utilization meta-goal.

In order to satisfy the part inter-cellular preferences, *MG_INTERMOVES* model is applied. The corresponding performance parameters are summarized in Fig. 2. It can be observed in Fig. 2.B that inter-cellular movements for every part are significantly reduced. In order to achieve this preferred performance level however, more exceptional machines are needed and that machine utilization and machine movements are compromised.

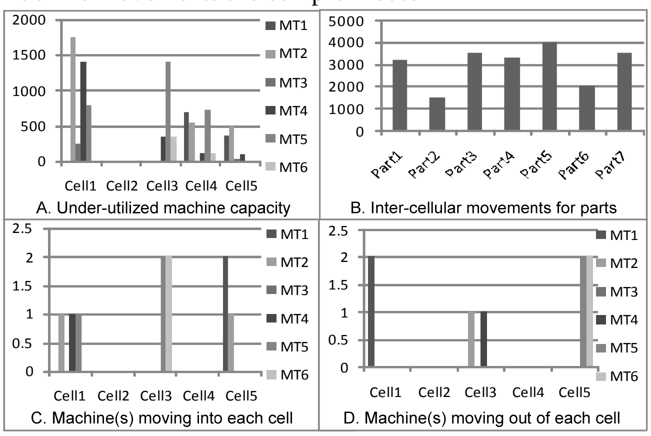

Figure 2. Performance for *MG_INTERMOVES* model

Lastly, let's assume the DMs preferred to have a maximum of two machine reallocation for each machine type. It is demonstrated in Fig. 3 that this preference can be achieved but at the price of increased inter-cellular movements for parts as depicted in Fig. 3.B.

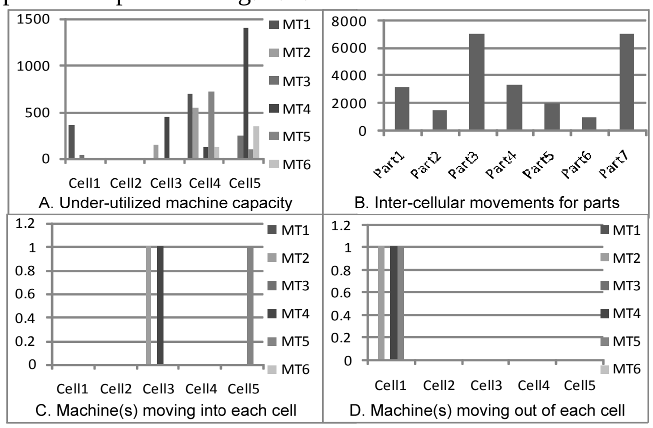

Figure 3. Performance for *MG_MTMOVES* model

Based on the analysis provided above, it can be concluded that in a reconfigurable CM system, the objective value of inter-cellular part movement is inversely proportional to machine utilization and machine reallocation. Further, it is verified that the model presented in this paper enables DMs to express their unique preferences using meta-goals. It is further demonstrated that optimal solution that best satisfy the preferences can be effectively evaluated.

In this study, the models are solved on a Dell computer system with a Pentium Dual Core 1.6MHz CPU. Using the global optimization extension on Lingo, lengthy calculation time is required to evaluate each model. However, it has been observed that highly valid local optimal solutions, for a problem size similar to the ones considered in the numerical example, would be found in between 10 to 20 minutes. Thus by relaxing the global optimization tolerance, a balance between result quality and calculation time can be obtained.

VI. Conclusion

In this paper, a mathematical optimization based approach has been presented to evaluate the dynamic cellular reconfiguration problem in a CM system. The merit of the approach is to improve the interface between end users and the mathematical model. Using the concept of meta-goal, DMs' preference can be incorporated into the model, and that a corresponding optimal solution that closely satisfies the DMs' preferences can be evaluated with acceptable calculation lead time. In this study, it has been demonstrated that a single meta-goal is applied in each scenario. Our future study will consider the simultaneous consideration of multiple conflicting meta-goals preferred by multiple DMs. Hence the approach can be utilized in group decision-analysis environment. Based on this approach, it is intended that a web-based decision-support system will be developed to enable online group decision-making activities.

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ISBN: 978-988-18210-5-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)