Framework for Part Family Formation Based on Setup Similarity Coefficient

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***Abstract*— Post-industrial revolution led to the emergence of Reconfigurable Manufacturing Systems as result of increasing market and manufacturing demands. Shorter product life-cycle, competitive pricing, diverse needs and highly customized designs with more flexibility, efficiency and reactivity redefined the manufacturing paradigms. Products as well as parts exhibiting close similarity in features, generally followed similar manufacturing patterns and thus were suggested to be grouped together in part families and configurations. Optimizing the setup changes to the minimum possible number is the ultimate target in several part productions. This research focuses on formulation of approach to develop an optimized arrangement of product to form family. The methodology depends on coefficients of similarity using intelligent sequencing of setup, group-based machining features and identification of datum. It considers the product setup sequence based BMIMS coefficient of similarity derived by incorporating concepts of LCS and SCS. The prime objective is to enhance the production performance of Cellular/Reconfigurable Manufacturing.**

***Index Terms*— Reconfigurable Manufacturing Systems (RMS); Longest Common Subsequence (LCS); Bypass Moves and Idle Machines in Setup (BMIMS); Shortest Common Super-sequence (SCS).**

I. INTRODUCTION

RECONFIGURABLE manufacturing Systems (RMS) is an open-ended system that allows flexible customization rather than replacement to improve, upgrade or reconfigure a particular part family. . The objective of an RMS is to provide the functionality and capacity on need-to-need basis. This makes RMS a configuration that is either dedicated or flexible, or in between. Research conducted so far has resulted in providing different perspectives for the identification of part/product families and machine cells. In context to hierarchical clustering of part similarities among each other, similarity coefficient of parts holds an important role. RMS is built for a part family and immediately reconfigured later for next part family in turn due to rapid market requirements. Similarity & Dissimilarity coefficients with reference to Longest Common Subsequence (LCS) & Edit Distance has been the attention of several field experts. Quantitative and qualitative aspects of products along with operational similarities form the basis of product family identification [1]. For product family formation, Galan [2] took into account an approach based on product modularity, compatibility, commonality, reusability and product demand. Kashkoush [3] employed concept of product assembly sequence tree, parts commonality and demand similarity coefficients for product family formation. On the other hand, Rakesh [4] adopted an alternate process plan and applied Jaccard similarity coefficient. Goyal, Choobineh, Ho, Askin and Zhou, Tam, and Irani and Huang [5-9] used similarity coefficient based on operation sequence to develop part families. The work of Choobineh highlights the similarity between operation sequence of two different parts based on sequences of length 1 to L. Number of operations per sequence were considered by Ho. et. al. these could be either in-sequence or by-passing in both forward and backward directions. In another work, by Gupta et al. [10] an agglomerative hierarchical k-means clustering algorithm was utilized for part family formations in RMS. Goyal's methodology, calculated using minimum bypass moves & idle time for any longest common subsequence (LCS) between parts. Another approach to form part family formation in Reconfigurable Manufacturing Systems utilize an intelligent classification of data based on neural networks [11]. This incorporate extracting trends and patterns in databases using classification and prediction modelling. The reliability and throughput can be evaluated by method developed by Farouq Alhourani et al. [12] in which similarity coefficient equation form the basis. Whereas Javed Navaei et al. [13] proposed a sequencing and product variants schemes to evaluate the same.

II. PART OPERATION SEQUENCE BASED TECHNIQUES

For part family formation, there are some constraints. For instance, Jaccard similarity coefficient does not follow part operation sequence according to precedence constraints however it does cater for part operations commonality. Examples of similarity coefficients developed between two operation sequence strings include:

- LCS (longest common subsequence)
- Merger coefficient
- Compliant Index
- BMIM

Summary of developed techniques for part family formation are shown in Table I.

TABLE I. Developed techniques based on Operation Sequence

Author	Techniques for part family formation	
Ho (1993)	Compliant index	$CO_{AB} = \frac{(CF_A + CB_A)}{2 * N_A}$
Askin and Zhou (1998)	LCS	$S_{AB} = max\left\{\frac{\lvert LCS_{AB}\rvert}{\lvert A\rvert}, \frac{\lvert LCS_{AB}\rvert}{\lvert B\rvert}\right\}$
Irani and Huang (2000)	Merger similarity coefficient	$mc_{(A,B)} = max\left[1 - \frac{md_{(A,B)} + \frac{id_{(A,B)}}{\lvert A\rvert}}{\lvert B\rvert + 1}\right] \quad If\ \lvert A\rvert > \lvert B\rvert$

Huang (2003)	Modified Merger similarity coefficient	$mc_{(A,B)} = max\left[1 - \frac{md_{AB} + \frac{ud_{(B,A)}}{O_{max}} + \frac{\lvert A\rvert + \lvert B\rvert}{O^2_{max}}}{\lvert B\rvert}, 0\right]$ $If\ \lvert A\rvert > \lvert B\rvert$
Goyal (2013)	BMIM	$S_{AB} = 1 - \left\{ \left[\frac{BPM_A}{2 * \lvert TM_A\rvert} + \frac{BPM_B}{2 * \lvert TM_B\rvert}\right] + \left[\frac{IM_A}{2 * \lvert SCS_{AB}\rvert} + \frac{IM_B}{2 * \lvert SCS_{AB}\rvert}\right] \right\}$

The Ho et al. (1993) considers the matched operations, however neglected the sequence interruptions in forward & backward directions. The method of Askin and Zhou (1998) only focuses on matches in the longest common subsequence between two operation sequences are considered but ignores the distance between those matches. Therefore, this could result in grouping of parts that would experience significant bypass travel distance between consecutive operations. Irani and Huang (2000) and Huang (2003) similarity coefficients are unable to distinguish between the similarities due to the unmatched operations falling in between the LCS or falling before the start and at the end of LCS. The unmatched operations in between the LCS will result in the bypassing moves and idle machines. The BMIM similarity coefficient developed by Goyal et al. (2013) which considers the effects of idle machines and bypassing moves also contains some serious anomalies and limitations. The most fundamental problem with BMIM similarity coefficient is that it considers equal contribution of both the operation sequences in constituting the similarity coefficient, however a little reflection makes it quite clear that it is only applicable for operation sequences which has more operations common between them.

However, no such research has been conducted on part family formation using setup formation based upon machining features. In order to benefit from the minimum number of setups for maximum number of operations to attain optimum accuracy and tolerance, BMIMS similarity coefficient has been developed. With an aim to avoid frequent setup changes, tool change option to complete maximum operations in a setup is implemented by BMIMS. The setups are designed based upon machining processes. The Part family formation is based on setup sequencing, setup formation is done based on machining features, Ratio between tool required to operation sequence is consider in finding similarity coefficient between different parts. In view of the research conducted it can be deduced that operation sequencing-based part family formation is an efficient and viable strategy to sort parts in specific groups for reconfigurable manufacturing. However, simply relying on the length of longest common sequence isn't an intelligent and sufficient approach. In order to address this lack of criterion, thus this research also takes into account the Bypass Moves and Idle Machines Setup (BMIMS) while comparing the similarity in operation between two parts. The aim of the proposed technique is to minimize waste during excessive method handling and ineffective resource utilization, thus deriving an optimum similarity coefficient between the parts.

III. Proposed Methodology Based on Setup Sequence

The methodology proposed for part family formation involves setup sequencing similarity coefficient including operation sequence. The focus will be on setup sequences and associated part groups using BMIMS similarity coefficient to form different phases of setup sequence and similarity coefficient. Flow chart of proposed methodology is shown in Fig. 1.

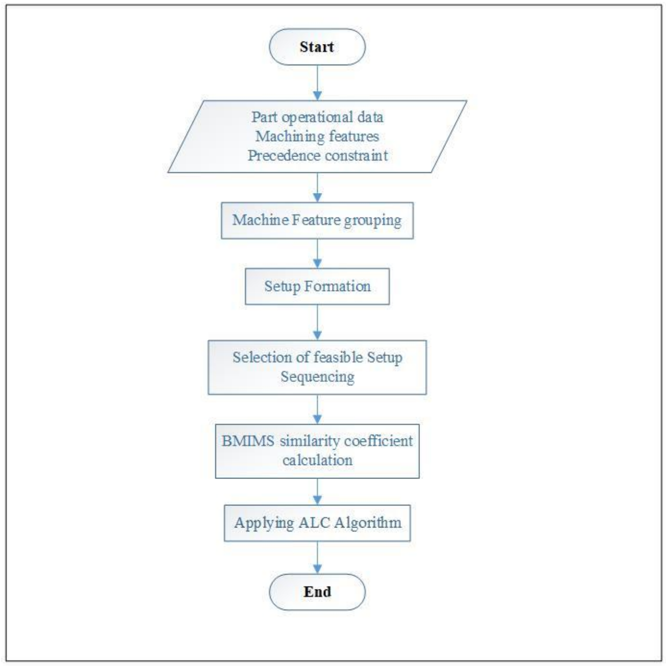


Fig. 1. Flow chart of proposed methodology

A. Development of BMIMS Symmetry Coefficient

To ensure achievement of better dimensional tolerances and smooth material flow setup sequencing symmetry is the technique applied in this research. Another aspect catered is the time reduction factor, which is the outcome of utilizing minimum number of setups and hence avoiding dimensional tolerance errors resulting from repeatedly changing setups.
BMIMS is calculated using similar parameters as of Goyal [5] BMIM similarity coefficient. However, instead of two-part operation sequence a two-part setup sequence is used. Incompliance with the precedence constraints, LCS is found using the list of longest common setups in both setup sequences. Similar type of operations dictates the setup similarity of two different parts and it does not require the exact operation sequence be followed in both setups. However, tool change options can be used to perform the operations. Proposed methodology algorithm is shown in Fig. 2.

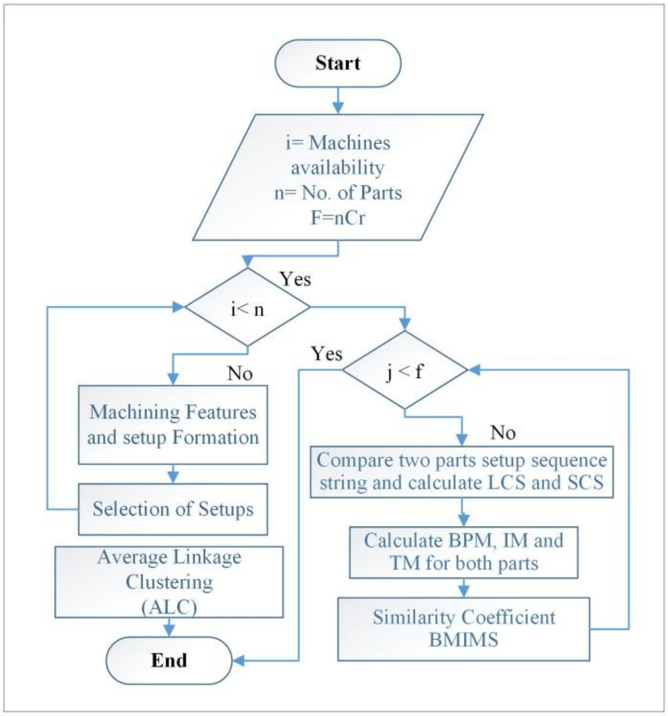


Fig. 2. Proposed Methodology Algorithm

B. Finding of LCS and SCS

Askin [9] subsequence formulation is used to calculate the longest common subsequence. For example, consider two operation sequences X = {a d e g h} & Y = {d f e g k m}. {d e}, {e g} and {d e g} are some of the sub-sequences constructed from the two sequences X and Y. Thus, the LCS of X and Y is the longest common subsequence from all the possible constructed sub-sequences i.e. {d e g} is the LCS of X and Y. Finding the LCS between two operation sequence is not the one followed by Wagner and later given by Goyal. The algorithm developed is shown in Fig. 2. has the following features.

- LCS_string presents the list of operation in LCS satisfying the precedence constraints.
- LCS_length gives the cardinality of LCS_string i.e. the length or the number of operations in the longest common subsequence.

C. Shortest Common Super-Sequence (SCS)

SCS is obtained from the LCS using the two given sequences. However, in the present work, the SCS gives minimum bypass moves and the minimum number of idle machines selected for further calculation of similarity. The length of SCS (cardinality_SCS) between two operation sequences X and Y may be obtained as:
cardinality_SCS = cardinality_X + cardinality_Y – cardinality_LCS

D. BMIMS Similarity Mathematical Model

For SCS, operations left out of LCS are appended. There are two categories to obtain SCS.

- Append left out operations in between LCS.
- Append left out operations before or after the LCS.

Addition of tools ratio required and operation for each setup are added in the main equation to find out similarity of setups with reference to two-part setups. For same setup sequence for two parts, the similarity coefficient is calculated using the difference in tools required and operations ratios for each setup. The BMIMS similarity coefficient developed as a result will be similar to Goyal BMIM similarity coefficient. However, the only constraint is that all operations in the sequence have separate setups.

The mathematical model parameters are:

- u, v — Setup sequences of part U and part V
- LCS_{uv} — Longest Common Subsequence for setup part U and part V
- SCS_{uv} — Shortest Common Super-Sequence for setup parts U and V
- NBL_u — Number of setups for U, appended before LCS_{uv} to form SCS_{uv}
- NAL_u — Number of setups for U, appended after LCS_{uv} to form SCS_{uv}
- NIL_u — Number of setups for U, appended in between LCS_{uv} to form SCS_{uv}
- ξ_u — Bypass moves before LCS_{uv} while producing part U
- φ_u — Bypass moves after LCS_{uv} while producing part U
- TR_{ui} — Tool required in ith setup of part U where i=1, 2, 3…n
- OP_{ui} — Operations in ith setup of part U

Equations (1) and (2) are used for calculating minimum bypass moves before LCS while producing part U.

$$\xi_u = \begin{cases} NBL_v & If\ (NBL_v \leq NBL_u) \\ 0, & otherwise \end{cases} \tag{1}$$

$$\varphi_u = \begin{cases} NAL_v & If\ (NAL_v \leq NAL_u) \\ 0, & otherwise \end{cases} \tag{2}$$

Similarly, ξ_v and φ_v can be calculated accordingly. To calculate exact number of bypass moves for part U and part V, equations 3 and 4 are used.

$$BPM_u = NIL_v + \xi_u + \varphi_u \tag{3}$$

$$BPM_v = NIL_u + \xi_v + \varphi_v \tag{4}$$

Total moves while producing part U can be computed as.

$$TM_u = BPM_u + |u| + 1 \tag{5}$$

Similarly, for part V can be calculated as follows:

$$TM_v = BPM_v + |v| + 1 \tag{6}$$

Idle Machines (ID) are machines that remain idle while producing part U or part V and can calculated using equations (7) and (8) respectively.

$$IM_u = |SCS_{uv}| - |u| \tag{7}$$

$$IM_v = |SCS_{uv}| - |v| \tag{8}$$

BMIMS coefficient of similarity is computed as below:

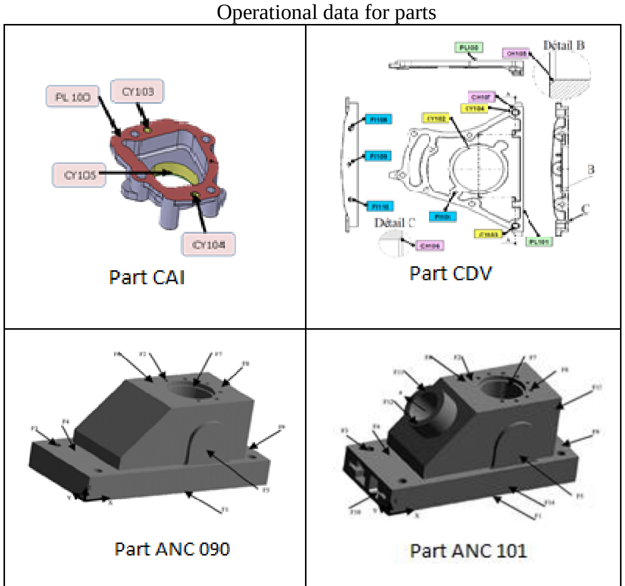
$$S_{uv} = 1 - \left\{ \frac{1}{2*|u|} \sum_{i=1}^{n} \frac{|TR_{ui}|}{|OP_{ui}|} \left[\frac{BPM_u}{|TM_u|} + \frac{IM_u}{|SCS_{uv}|} \right] + \frac{1}{2*|v|} \sum_{j=1}^{m} \frac{|TR_{vj}|}{|OP_{vj}|} \left[\frac{BPM_v}{|TM_v|} + \frac{IM_v}{|SCS_{uv}|} \right] + \left[\left| \frac{1}{|u|} \sum_{i=1}^{n} \frac{|TR_{ui}|}{|OP_{ui}|} - \frac{1}{|v|} \sum_{j=1}^{m} \frac{|TR_{vj}|}{OP_{vj}} \right| \right] \right\} \tag{9}$$

Range: $0 \leq S_{uv} \leq 1$.

IV. CASE STUDY

To evaluate BMIMS similarity coefficient, phases of setups (of parts) are developed. The process involves finding out machine process similarity by applying the method on CAI, CDV, ANC-090 and ANC-101parts.Precedence constraints and operations as formulated by Aamer baqai [19] are followed and respective precedence matrix is calculated for each part.

TABLE II.
Operational data for parts



PART CAI

Feature	Description	Operation ID	Operation No	Operation TAD	Machining Feature
PL 100	Plane Surface	1	1	-Z,	M
		2	2	+X, -X, +Y, -Y	M
CY 103	Hole	3	3	-Z	D
		4	4	-Z	R
CY 104	Hole	3	5	-Z	D
		4	6	-Z	R
CY 105	Through Hole	3	7	+Z	D
		4	8	+Z	R
CY 107	Threaded Hole	7	9	+Z	T
CY 108	Threaded Hole	7	10	+Z	T

PART CDV

Feature	Description	Operation ID	Operation No	Operation TAD	Machining Feature
PL 100	Plane Surface	1	11	-Z, +X, -X, +Y, -Y	M
		2	12	-Z, +X, -X, +Y, -Y	M
PL 101	Plane Surface	1	13	-Z, +Z, -X, +Y, -Y	M
		2	14	-Z, +Z, -X, +Y, -Y	M
CY 102	Through Hole	3	15	+Z, -Z	D
		4	16	+Z, -Z	R
CY 103	Hole	3	17	-Z	D
		4	18	-Z	R
CY 104	Hole	3	19	-Z	D
		4	20	-Z	R
FL 106	Fillet	8	21	-Z	F
FL 108	Fillet	8	22	-X	F
FL 109	Fillet	8	23	-X	F
FL 110	Fillet	8	24	-X	F

PART ANC-090

Feature	Description	Operation ID	Operation No	Operation TAD	Machining Feature
F1	Planner Surface	1	25	+Z	M
F2		1	26	-Z	M
F3	4 Holes replicated	3	27	+Z, -Z	D
F4	A Step	1	28	-Z, +X	M
F5	A Protrusion-rib	1	29	-Z, +Y	M
F6	A Protrusion	1	30	+Z, -Y	M
F7	Compound Hole	3	31	-Z	D
		4	32	-Z	R
		5	33	-Z	B
F8	6 Holes replicated	3	34	-Z	D
		7	35	-Z	T
F9	A Step	1	36	-Z, -X	M

PART ANC-101

Feature	Description	Operation ID	Operation No	Operation TAD	Machining Feature
F1	Planner Surface	1	37	+Z	M
F2	Planner Surface	1	38	-Z	M
F3	4 Holes replicated	3	39	+Z, -Z	D
F4	A Step	1	40	-Z, +X	M
F5	A Protrusion-rib	1	41	-Z, +Y	M
F6	A Protrusion	1	42	+Z, -Y	M
F7	Compound Hole	3	43	-Z	D
		4	44	-Z	R
		5	45	-Z	B
F8	9 Holes replicated	3	46	-Z	D
		7	47	-Z	T
F9	A Step	1	48	-Z, -X	M
F10	2 Pockets	1	49	+X	M
F11	A Compound Hole	3	50	-a	D
		4	51	-a	R
		5	52	-a	B
F12	A Pocket	1	53	-X	M
F13	A Compound Hole	4	54	+X	R
		5	55	+X	B

The longest common subsequence for parts CAI and CDV is (1 2 3 3 4 3 4). Table III shows the illustration of LCS calculation of the parts under consideration.

TABLE III.
LCS calculation of parts CAI and CDV

		Part CDV													
		1	2	1	2	3	4	3	4	3	4	8	8	8	8
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PART CAI 1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	1	2	2	2	2	2	2	2	2	2	2	2	2	2
3	0	1	2	2	2	3	3	3	3	3	3	3	3	3	3
3	0	1	2	2	2	3	3	4	4	4	4	4	4	4	4
4	0	1	2	2	2	3	4	4	5	5	5	5	5	5	5
4	0	1	2	2	2	3	4	4	5	5	6	6	6	6	6
3	0	1	2	2	2	3	4	5	5	6	6	6	6	6	6
4	0	1	2	2	2	3	4	5	6	6	7	7	7	7	7
7	0	1	2	2	2	3	4	5	6	6	7	7	7	7	7
7	0	1	2	2	2	3	4	5	6	6	7	7	7	7	7

Key: LCS; Path followed by SCS

Fig. 3 shows the associated setup formation and setup sequencing for part CAI & CDV. Computational illustration of similarity coefficient i.e. BMIMS for Part CAI and part CDV is shown in Fig. 4.

PART CAI

Setup	Setup1	Setup2	Setup3
Op ID	1 2	3 3 4 4 3 4	7 7
Machining	M M	D D R R D R	T T

PART CDV

Setup	Setup1	Setup2	Setup3
Op ID	1 2 1 2	3 4 3 4 3 4	8 8 8 8
Machining	M M M M	D R D R D R	F F F F

Fig. 3. Setup Formation of Part CAI & CDV

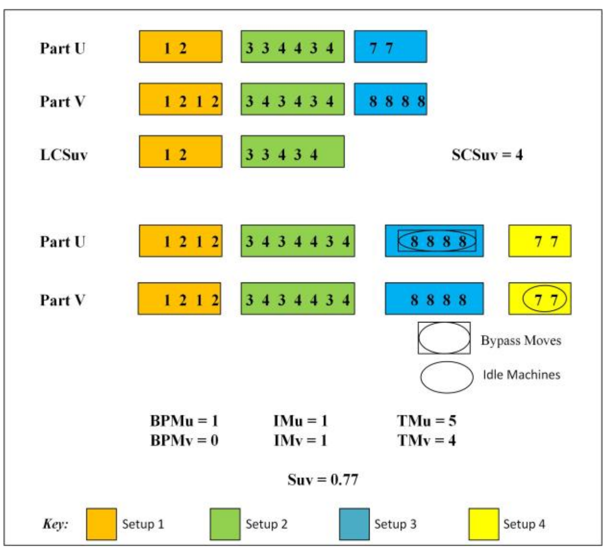


Fig. 4. Computation of BMIMS

V. RESULT AND ANALYSIS

Setup sequence-based similarity coefficient between parts is employed to ensure smooth material flow along with parts production on a common plant setup. In context with family's similarity identification, BMIMS algorithm calculated from LCS and SCS proved to be useful. Previously discussed work in literature has not consider setup sequencing, as they are based on operation sequencing. Table IV below shows the result of all the methods discussed earlier. It illustrates the limitations of developed approaches after their application on the four sample parts. The values of similarity index as tabulated below have been calculated keeping under consideration the precedence relationship and constraints of every approach.

TABLE IV.
Different similarity coefficient

Parts	Compliant Index	LCS	Merger Coefficient	Modified Coefficient	BMIM Coefficient	BMIMS Coefficient
	1993	1998	2000	2003	2013	2018
A-B	0.65	0.6	0.7208	0.6908	0.4975	0.77
B-C	0.454	0.5	0.5219	0.4813	0.473	0.52
C-D	0.917	1	1	0.9983	0.8	0.85
A-C	0.5	0.6	0.6288	0.5903	0.5521	0.69
A-D	0.55	0.6	0.7045	0.6725	0.3871	0.62
B-D	0.5	0.57	0.5833	0.5525	0.5046	0.67

The major aspects of the calculations are discussed below:

- For parts (CAI & ANC-090) and (CDV & ANC-101) compliant index similarity is 0.5.
- The limitation of the approach is clear from LCS similarity coefficient value (0.6) for parts groups (CAI & CDV), (CAI & ANC-090) and (CAI & ANC-101).
- Merger coefficient 2000 and Modified merger coefficient 2003 shows that parts ANC-090 and ANC-101 have 100% similarity which in fact is not possible due to difference in number of operations with ANC-101 to be on greater side

Comparing the results of BMIM and BMIMS, it is evident that by utilizing tool changer performing multiple operations instead of single operation the results are more improved and optimized. However, the only diversion is prominent in CDV and ANC-090 parts in which the value is a bit low. This is due to the effect of setup formation as a difference exists in precedence matrix of both parts. Fig. 5 shows the comparison between different similarity coefficients. In order for four parts to have BMIMS value same as BMIM, all operation sequence of parts is assumed to be independent setup for each operation. For instance, in manufacturing two parts CAI and CDV can have the same value if there are one operation and one tool for each setup. For classification of parts based on BMIMS, average linkage clustering (ALC) is applied [20]. It is used to calculate higher similarity coefficients between parts; a methodology based on ALC. Fig. 6 show a BMIMS dendrogram. From the figure it can be seen that part ANC-090 and part ANC-101 have 85% similarity whereas parts CAI and part CDV have 77%. Similarity for all parts is 62%.

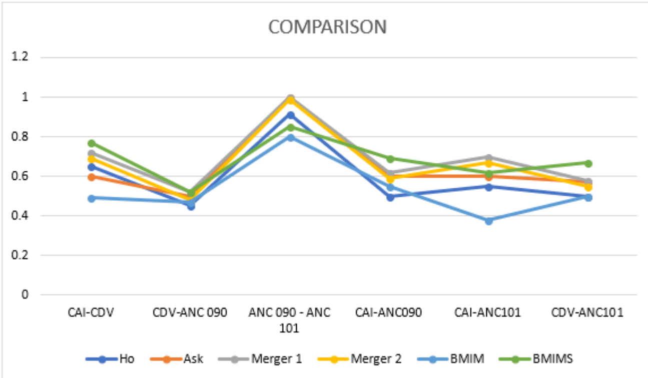


Fig. 5. Comparison Of different similarity coefficients

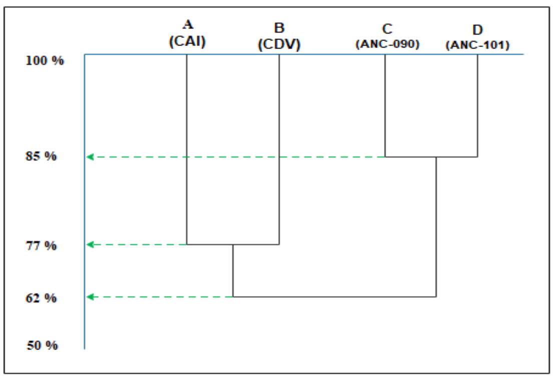


Fig. 6. Dendrogram for BMIMS

VI. Industrial Study

The proposed methodology is applied on a real case – an oil pump body family. This oil pump body family is a sub-assembly family of an oil pump family. In order to simplify this case, two-part variants of the oil pump body family are shown in Fig. 7. The aim of this experimental study is to show the similarity and the effectiveness of the proposed representation method as well as how they reconfigured in the proposed solution framework. The part analysis to machining features is performed according to STEP AP-224 (Mechanical Product Definition for Process Planning Using Machining Features) [17]. The analysis of the oil pump cover presented E1, E2, E3, E4, E5, E6, E7 and E8 as machining features (Fig.7 (a)), And the perusal of oil pump body variant presented P0100, CY110, CY120 and CH100 as machining features (Fig.7(b)). Where, the machining features have attributes enable to sufficiently describe the geometric and the topologic relations according to operational data present describing parameters in Table V.

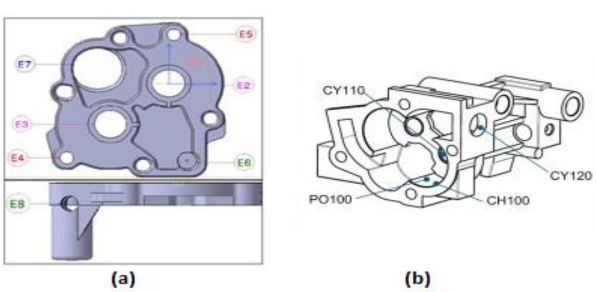


Fig. 7. (a) Oil Pump Cover (b) Oil pump Body Variant

TABLE V.
Operational Data Set for Oil Pump Family

Feature	Description	Operation			Machining Feature
Oil Pump Cover					
		ID	**No**	**TAD**	
E1	Plane Surface	1	1	-Z	**M**
E2	Hole	3	2	-Z, +Z	**D**
E3	Hole	3	3	-Z, +Z	**D**
E4	Through Hole	4	4	-Z	**R**
E5	Through Hole	4	5	-Z	**R**
E6	Through Hole	4	6	-Z	**R**
E7	Through Hole	4	7	-Z, +Z	**R**
E8	Through Hole	4	8	+Y	**R**
Oil Pump Body Variant					
Feature	**Description**	**Operation ID**	**No**	**TAD**	**Machining Feature**
P0100	Plane Surface	1	9	-X, +X	**M**
		2	10	-X, +X	**M**
CY110	Hole	3	11	+X	**D**
		3	12	+X	**D**
CY120	Through Hole	4	13	+Y	**R**
CH100	Threaded Hole	7	14	-X	**T**
		5	15	+X	**T**

In order to find out the similarity between these two parts, the developed methodology based on BMIMS is applied and the setup formation is based on machining features. Computational illustration of similarity coefficient i.e. BMIMS for Oil pump cover (taken as Part A) and Oil pump body variant (taken as Part B) is shown in Fig. 8.

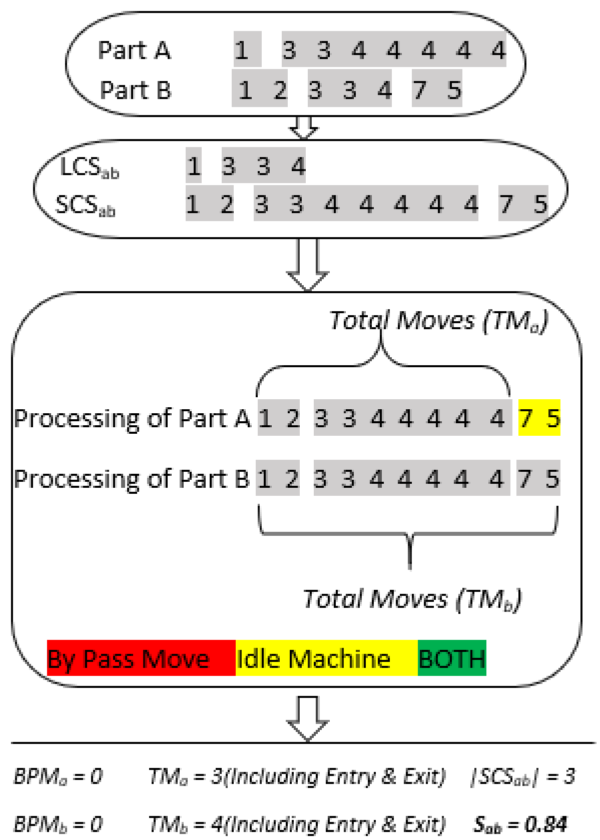


Fig. 8. Computation of BMIMS for Oil Pump Family

VII. Conclusion

The improved methodology presented in this research has shown that proper selection of part families in Reconfigurable Manufacturing Systems plays an important role in enhancing the production efficiency and economy. The selection translates into improved accuracy, tolerance and part similarity index; thus, resulting in less setups required for part production. Another outcome of the research is the calculation of setup sequence based BMIMS similarity coefficient derived by incorporating concepts of LCS and SCS. The results of improvement are shown to validate assumptions and proposed method is compared with previous researches to support the hypothesis. Quality of manufacturing can be improved further by incorporating the operational time and tolerances while developing the part family. This is the work recommended for future investigations to enhance the efficacy of systems under consideration.

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