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ORIGINAL ARTICLE

An ISM based framework for structural relationship among various manufacturing flexibility dimensions

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Abstract In the present era, when manufacturing industry is facing competitive, unpredictable, and dynamic environment, with growing complexity, and high levels of customisation, industry leaders are striving hard to invent and adopt newer technologies. The unexpected events, so called disturbances invariably affect the overall performance of manufacturing system (MS) which can be handled by incorporating flexibility dimensions with respect to design, operation, and management of MS. In this paper, various manufacturing flexibility dimensions critical to flexible MS are identified from the literature review, and brain storming with academicians and practicing managers. Interpretive structural modeling approach is applied to develop a structural framework for 10 well accepted flexibility dimensions, which are further classified into three levels namely individual/resource, shop floor, and plant. The results indicates that flexibility dimensions performed at individual/resource level is most crucial followed by flexibility dimensions performed at level of shop floor, and level of plant in order, for MS performance.

Keywords Flexibility dimensions · ISM based framework · Manufacturing flexibility · Structural relationship

1 Introduction

In simple terms a manufacturing system (MS) is a combination of man, machines, material handling devices, and power source. In present era of manufacturing the effectiveness of any MS is not only based on cost, quality, and other performance measures but it is also shifting towards time based performance measures (Chan et al. 2006). A typical MS transforms raw material into a product of desired shape and size consistently. The MS is constantly exposed to the effects of unpredicted environmental influences better to say disturbances at the different stages of the transformation process. These disturbances make the transformation process more complex. These disturbances or unexpected events can be divided into two categories based on their source of origination in the literature (Valdez 2010) and illustrated as under:

- Disturbances originated within system boundary: such as resource unavailability, machine break down, etc.
- Disturbances originated from outside system boundary: such as variation in demand, product dimension, etc.

Despite increasing automation of MS, the human element is still an essential component (Hwang et al. 1984) in any MS. Chung (1996) demonstrated that success in the implementation of advanced manufacturing technology largely depends on human resource related issues like capability of man power in terms of skills, attitude, knowledge, etc. Therefore, disturbances originated due to human factor should be handled very carefully. Both categories of disturbances invariably affect the overall performance of any MS. To handle these unexpected disturbances the managers should consider/practice the concept of flexibility in design, operation, and management of MS (Sethi and Sethi 1990). Table 1 presents the details of disturbances and flexibility dimension required to handle these disturbances.

It is clear from the above that each type of disturbance requires a different and particular type of flexibility to

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Table 1 Disturbance and required flexibility dimension to handle it

Disturbances	Description	Required flexibility
Inside		
Human factor	Absenteeism, lack of training, etc.	Labour, program, automation
Others	Machine breakdown, information flow, etc.	Machine, material handling, routing, operations, process
Outside	Consumer, demand, competitor, society, government regulation and policies, etc.	Production, product mix, labour, delivery, volume, market, expansion, new design

accommodate it. Considerable amount of work has been reported on addressing the uncertainties/disturbances which may affect MS performance (Kara and Kayis 2004; Mishra et al. 2014; Sethi and Sethi 1990). Ample studies were undertaken by authors to establish relationship between manufacturing flexibility and other variables such as environmental uncertainty, strategy, organizational attributes, technology, innovation and product types, etc. but in literature the details regarding relationship among various types of flexibilities and effect of one type of flexibility on another type of flexibility is missing (Beach et al. 2000). Empirical studies of manufacturing flexibility reported by Upton (1995), documented the lack of correlation between various types of flexibility in a manufacturing environment (Saleh et al. 2009). In present study, authors performed an extent review of literature and identified various flexibility dimensions critical to system performance. Further, an interpretive structural modeling (ISM) model is developed to find the interrelationship among various manufacturing flexibility dimensions.

The brief outline of paper is as follows: the literature review presented in Sect. 2, describes manufacturing flexibility, and its various dimensions. In this section 10 manufacturing dimensions have been selected for development of model. They are also categorised according to the level at which they could be performed in a MS. Interrelationship among various manufacturing flexibility dimensions are identified in Sect. 2.1. Section 3 devoted to methodology and framework development. Particularly, ISM methodology is explained briefly in Sect. 3.1. Matrice d'Impacts Croisés Multiplication Appliquée á un Classeement (MICMAC) analysis is discussed in Sect. 3.2. All four ISM models are developed in Sects. 4.1–4.4. MICMAC analysis is carried out in Sect. 4.5. At last the conclusions and scope of future work are presented in Sect. 5.

2 Literature review

In context of manufacturing, both the terms 'flexibility' and 'manufacturing flexibility' are used implying same meaning in this article. Numerous authors tried to capture the essence of manufacturing flexibility and formulated number of definitions, some of them can be found in literature (De Toni and Tonchia 1998; Héctor Kaschel and Bernal 2006; Kara and Kayis 2004; Saleh et al. 2009; Sethi and Sethi 1990; Valdez 2010; Wadhwa and Browne 1989; Wadhwa et al. 2005). Still there is a lack of general agreement on definitions of flexibility (Shewchuk and Moodie 1998). Shewchuk and Moodie (1998) found over seventy terms on flexibility, its' types and measures in the literature. Measures of various flexibility dimensions can be found in Beach et al. (2000), Browne et al. (1984), Chang (2012), Chen and Adam Jr (1991), D'Souza and Williams (2000), Gupta and Goyal (1989), Koste and Malhotra (1999), Ramasesh and Jayakumar (1991), and Sethi and Sethi (1990). Sethi and Sethi (1990), in their popular survey of literature reported at least fifty terms exist for the various types of flexibilities studied. They also observed that flexibility is a complex, multidimensional, and hard-to capture concept, even several terms refer to the same flexibility type in many cases, and the definitions for flexibility types often are imprecise and conflicting, even for identical terms (Héctor Kaschel and Bernal 2006; Shewchuk and Moodie 1998). It is observed that researchers must agree that, in simplest terms:

> Flexibility is the ability to deal with change

In context to manufacturing,

> Manufacturing flexibility is the ability of any MS to deal with change.

In 1984, Browne et.al identified eight types of flexibility, while in 1990; Sethi and Sethi envisioned the concept of eleven flexibility types, while in 2000, Vokurka and O'Leary-Kelly observed four additional types of flexibility to be important in the context of MS. Earlier to Vokurka and O'Leary-Kelly (2000), in 1991, Ramasesh and Jayakumar (1991) came up with the theory that flexibility can be in several different forms e.g., machine, operation, routing, material handling, process, program, product, volume, expansion, labour, and material flexibilities. The definition for each of these 15 flexibility dimensions is presented in Table 2.

Based upon the critical review of relevant literature related to flexibility dimensions and further discussions with experts from academics and industry, 10 flexibility dimensions are taken for development of model. Further, taking inspiration from Peláez-Ibarrondo and Ruiz-Mercader (2001), and Koste and Malhotra (1999) these 10 flexibility types have been segregated as per the level

Table 2 Definitions of 15 flexibility types/dimensions

S. No.	Flexibility dimensions	Definitions
1	Machine (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	Machine's ability to perform a range of operations without incurring any major setup
2	Process (Beach et al. 2000; Chang 2012; Chen and Adam Jr 1991; D'Souza and Williams 2000; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	System's ability to produce a given set of part types in different ways possibly with different material
3	Operations (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Héctor Kaschel and Bernal 2006; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	Ability to produce a component/product by interchanging the order of processes
4	Product (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	System's ability to substitute, change over or add new (set of) part(s), efficiently
5	Routing (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	System's ability to have number of alternative paths within the system, by which a part could be made
6	Volume (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; D'Souza and Williams 2000; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	System's ability to operate at range of different output levels economically
7	Production/product mix (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	System's ability to produce a plethora of products without adding new equipment
8	Expansion (Browne et al. 1984; Chang 2012; Chen and Adam Jr 1991; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	Ease at which capacity and capability of the system may be enhanced
9	Material handling (Chang 2012; D'Souza and Williams 2000; Héctor Kaschel and Bernal 2006; Koste and Malhotra 1999; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	Capability of material handling system to move and position different parts throughout the MS
10	Program (Chan et al. 2006; Chang 2012; Vokurka and O'Leary-Kelly 2000)	Capability of system to operate/run unattended for a long period of time
11	Market (Chang 2012; Sethi and Sethi 1990; Vokurka and O'Leary-Kelly 2000)	Adaptability and responsiveness to the changing market environment
12	Automation (Sethi and Sethi 1990)	Level at which flexibility is incorporated in the automation/computerization of manufacturing technologies
13	New design (Sethi and Sethi 1990)	Ability to design and introduce new product into the system well before time
14	Delivery (Sethi and Sethi 1990)	Responsiveness of the system towards changes in delivery requests
15	Labour (Cesaní VI and Steudel 2005; Chang 2012; Héctor Kaschel and Bernal 2006; Koste and Malhotra 1999; Ramasesh and Jayakumar 1991; Sethi and Sethi 1990)	Multitasking ability of labour/man power i.e., within the MS without sacrificing the efficiency

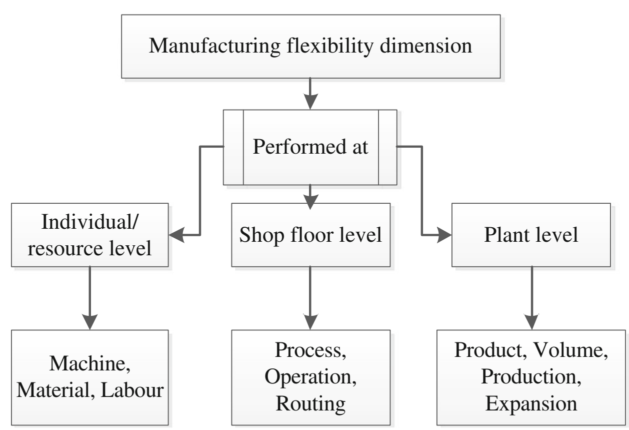


Fig. 1 Flexibility dimensions with it corresponding level of manufacturing system where it could be performed

where it is usually performed namely level of shop floor, plant, and individual/resource as shown in Fig. 1.

2.1 Identification of inter-relationship among various flexibility dimension

From the in-depth review of available literature on flexibility, their dimensions, and their effect on each other the following inter-dependencies has been identified and further used in the development of ISM model.

- Browne et al. (1984) said that machine flexibility is beneficial for attainment of process, product, and operation flexibilities, while Ranta (1989) improved it by saying that machine flexibility is necessary for other flexibilities (Sethi and Sethi 1990). According to Jaikumar (1984)' group technologies attempt to improve machine flexibility. A considerable attention of management is essential for machine flexibility. Training of workers for acquisition of programming, maintenance, and diagnostic skills is required. Quality circle activities can result in gradual increase in machine flexibility (Sethi and Sethi 1990).
- Production flexibility may be derived by machine (Browne et al. 1984; Sethi and Sethi 1990), process (Browne et al. 1984), product (Browne et al. 1984), operation (Browne et al. 1984), routing (Browne et al. 1984; Gupta and Goyal 1989), volume (Browne et al. 1984), expansion (Browne et al. 1984), labour (Sethi and Sethi 1990; Slack 1987), and material handling flexibility (Sethi and Sethi 1990). It minimizes the implementation time for new products or major modifications of existing products (Carter 1986; Sethi and Sethi 1990), which indicates that production flexibility also adds to product flexibility i.e., both way relationship.
- Routing flexibility is beneficial for attainment of volume flexibility (Browne et al. 1984), and expansion flexibility (Browne et al. 1984; Ranta and Alabian 1988; Sethi and Sethi 1990). Intimate knowledge of system to labour is beneficial to prevent damage and to reroute production (Gerwin and Tarondeau 1989; Sethi and Sethi 1990). It is inhibited by material handling flexibility (Gupta and Goyal 1989; Sethi and Sethi 1990).
- Reduction in batch size, and inventory costs are the purposes of process flexibility (Browne et al. 1984; Ranta and Alabian 1988; Sethi and Sethi 1990), which indicates that it adds to volume flexibility. Process flexibility of a system derives from the machine flexibility, operation flexibility, and the flexibility of the material handling system (Sethi and Sethi 1990). Multi skilled workers enhance process flexibility (Gerwin and Tarondeau 1989; Sethi and Sethi 1990).
- Operation flexibility of a process facilitates easier scheduling of parts in real time (Browne et al. 1984; Ranta and Alabian 1988; Sethi and Sethi 1990). Ability of material handling system to deliver parts to machines in different possible orders, and parts that are assembled from standardized components or parts that are modular are likely to exhibit operation flexibility (Sethi and Sethi 1990). Hence, product flexibility adds to operation flexibility. Sethi and Sethi (1990) said that product flexibility depends on operation flexibility. Further, here we can conclude that skilled labour would deliver parts in more efficient manner, which again adds to operation flexibility.
- Hall and Stecke (1986) suggest the use of automated guided vehicles as transportation devices to support expansion flexibility. According to Carter (1986), expansion flexibility helps in reduction of cost and implementation time for new products, variations of existing products or added capacity. Further, expansion flexibility makes it easier to replace or add machinery by providing for such possibilities in the original design (Sethi and Sethi 1990). It adds to process flexibility and in turn process flexibility would strengthen the possibility of expansion flexibility. Skilled labour would also add to expansion flexibility.
- According to Gerwin (1989) workers must be skilled enough to be used elsewhere when production volume decreases (Sethi and Sethi 1990). It reflects that labour flexibility adds to volume flexibility.
- Machine flexibility, material handling flexibility, operation flexibility, efficient use of similar part programming routines, rapid exchange of tool and dies, flexible fixtures, etc. needs for product flexibility (Sethi and Sethi 1990). Further for nourishment of product flexibility, Jaikumar (1984) suggests the incorporation of systematic learning obtained from the production of product in the current portfolio of the system. It means workers must be able and willing to learn new operating procedures continually (Gerwin and Tarondeau 1989; Sethi and Sethi 1990). Francas et al. (2011) demonstrated the positive impact of labour flexibility on machine performance.

3 Methodology

Multi-criterion decision making (MCDM) a well-known branch of decision making is widely used in ranking one or more alternatives from a set of available alternatives with multiple attributes. It presents an effective framework for decision making based on the evaluation of multiple conflicting criterions. In literature number of approaches have been reported for solving MCDM problems, such as analytical network process (ANP), analytical hierarchy process (AHP) and ISM. Warfield (1974) originally proposed ISM, which transforms the relationship among the criterion matrix into graphics through a two-dimensional matrix and Boolean algebra operations. Saaty (2004) offered ANP as an extension of the AHP. Comparative study of above three methods on the basis of Hsiao et al. (2013), Thakkar et al. (2008) and Yin et al. (2012) has been made and is

Table 3 Merits of ISM technique over AHP, and ANP techniques

Parameters	Analytic hierarchical process (AHP)	Analytic network process (ANP)	Interpretative structural modelling (ISM)
Discipline	Strict discipline of hierarchy	Loose networks	Set of interconnected criteria
Dynamic complexity	Moderate ability to capture	Lower ability to capture	Higher ability to capture
Interdependency	Elements of each level are independent of each other	The interdependencies and non-linearity is taken care	'Leads to' relationship among the criteria is established
Real life problem	Cannot handle complex real life problem	Useful in real life non-linear problem	Captures the complexities of real life problems and mimics human cognitive process
Simplicity	Moderate mathematics are there	Moderate mathematics are there	Hardly any mathematics involved

presented in Table 3. In the view of outstanding merits of ISM methodology over other techniques, it has been used in the study to develop the structural framework among various flexibility dimensions. Selection of measurement items, in this case flexibility dimension, is based on both critical review of relevant literature, and discussions with academicians and practicing managers. Lastly, autonomous, dependent, linkage, and independent variables are identified through MICMAC analysis.

3.1 ISM methodology

ISM is a qualitative tool, developed by Warfield (1974), with the objective of understanding the complex relationships among large number of elements related to a subject. In ISM technique, relationship among the variables depends on the judgment of the group which interprets (Borade and Bansod 2012). An overall hierarchical structure is obtained from the set of complex variables based on mutual relationships among them, and portrayed in a diagraph. Literature (Attri et al. 2013a–c; Borade and Bansod 2012; Hsiao et al. 2013; Mandal and Deshmukh 1994; Talib et al. 2011; Warfield 1974) can be referred for the comprehensive study of procedural steps of ISM, still a stepwise summary is presented as under:

- Step 1 Identification of variables to be related to each other and affecting the system,
- Step 2 Identification of contextual relationship among these variables by a pair-wise comparison, for generation of structural self-interaction (SSI) matrix,
- Step 3 Transformation of SSI matrix into reachability matrix,
- Step 4 Partitioning of reachability matrix,
- Step 5 Development of the structural model.

Complete procedure is explained in Sect. 4.1 with the help of illustrative problem.

3.1.1 Pair wise comparison for implementation of ISM

For the implementation of ISM, a systematic pair wise subjective comparison between flexibility dimensions is made in the light of available literature and findings of expert brain storming session. From the in-depth review of relevant literature (Sect. 2.1) and brain storming sessions with the academicians and practicing managers, dependencies among different flexibility dimensions has been investigated and the same are used for pair wise comparison of various flexibility dimensions for the development of ISM model.

In the discussion it is also pointed out that an efficient material handling system would be an added advantage for volume flexibility. Operations flexibility will be beneficial in attainment of expansion flexibility. Volume flexibility could be nourished by product, and routing flexibility. Routing flexibility could be helpful in achieving the process flexibility, which in turn could be beneficial in attainment of product flexibility. An efficient manpower will improve the utilization of all other flexibility types including machine flexibility.

3.2 MICMAC analysis

It is called the Matrice d'Impacts Croisés Multiplication Appliquée á un Classeement (cross impact analysis) or MICMAC analysis, developed by Michel Godet and JC Duperrin in 1973 with the objective to analyze the driver power and the dependence power of the variables in order to find the most important variable within the system. MICMAC principle is based on multiplication properties of matrices for identification the key enablers that drive the system in various categories. On the basis of their drive power and dependence power, the enablers, have been classified into four categories as follows: autonomous variables, dependent variables, linkage variable, and independent variables. For further details of MICMAC analysis

Attri et al. (2013a–c), Mandal and Deshmukh (1994) and Talib et al. (2011) can be referred.

- *Autonomous variables* variables having weak driving power and weak dependence, variables are relatively disconnected from the system, as they possess few weak links with other variables.
- *Dependent variables* variables having weak driving power but strong dependence.
- *Linkage variables* variables having strong driving power and strong dependence. These variables are unstable due to the fact that any action on these variables will affect other variables and also feedback on themselves.
- *Independent variables* (*drivers*) variables having strong driving power but weak dependence.

4 Case study

On the basis of extent review of literature, authors have identified various dimensions related to manufacturing flexibility. Further these dimensions are grouped in three categories i.e., individual/resource level, shop floor level and plant level, respectively (shown in Fig. 1) and are modelled with the help of ISM technique to examine the structural relationships between them. Further MICMAC analysis, has been done to find the key enablers that drive the system in various categories, i.e., autonomous variables, dependent variables, linkage variable, and independent variables.

Following codes are used in development of SSI matrix (quantity written in column as "i" and in row as "j"):

V → if flexibility dimension j depends on flexibility dimension i,
A → if flexibility dimension i depends on flexibility dimension j,
X → if both flexibility dimension i and j depends on each other,
O → no relation between flexibility dimension i and j.

For development of reachability matrix, required substitution are arranged in Table 4.

Table 4 Substitution required for transformation of SSI matrix into reachability matrix

(i, j) entry in SSI matrix	(i, j) entry in Reachability matrix	(j, i) entry in
V	1	0
A	0	1
X	1	1
O	0	0

4.1 ISM model for flexibility dimensions at individual/resource level

First of all flexibility dimensions at individual/resource level are identified as machine, labour, and material handling flexibility. For identification of contextual relationship among these flexibility dimensions, pair wise comparisons of these are performed. So developed SSI matrix is represented in Table 5.

In order to get initial reachability matrix (as shown in Table 6), replace X, V, A, and O in Table 5, according to the substitution given in Table 4. Sum of entries in corresponding rows and columns are labeled as driving power and dependence power, respectively. Lowest ranking number is assigned to variable having highest value of driving power. Same ranking numbers are assigned to variables having same driving power.

Now for partitions of reachability matrix, reachability set and antecedent sets for each of the variables, are identified. For example reachability set of machine contains the variables having entry as '1' in corresponding cells of row containing machine. Similarly, antecedent set of machine are the variables having entry as '1' in corresponding cells of column containing machine. In the same way, reachability and antecedent sets for all variables are identified. Intersection column contains the variables common in both reachability set and antecedent set for

Table 5 Structural self-interaction (SSI) matrix

	Labour	Material handing	Machine
Machine	X	V	
Material handling	A		
Labour			

Table 6 Initial reachability matrix

	Machine (1)	Material handling (2)	Labour (3)	Driving power	Ranks
Machine (1)	1	1	1	3	I
Material handling (2)	0	1	0	1	II
Labour (3)	1	1	1	3	I
Dependence power	2	3	2		
Ranks	II	I	II		

corresponding row. Thus obtained matrix is given in Table 7. Variable having largest portion of reachability in its intersection set is assigned level I, and so on.

For next iteration, row corresponding the level I, is eliminated, and the variable(s) in intersection cell of this row is eliminated from all entries of matrix. Iterations are repeated until the assignment of levels to all variables. Thus, obtained final reachability matrix is given in Table 8.

On the basis of final reachability matrix diagraph is drawn (Fig. 2) having higher level at bottom to lowest level at top.

Table 7 Iteration 1 for reachability matrix of Table 6

Variables	Reachability set	Antecedent set	Intersection set	Level
Machine	1,2,3	1,3	1,3	
Material handling	2	1,2,3	2	I
Labour	1,2,3	1,3	1,3	

Table 8 Final reachability matrix

Variables	Reachability set	Antecedent set	Intersection set	Levels
Machine (1)	1,3	1,3	1,3	II
Material handling (2)	2	1,2,3	2	I
Labour (3)	1,3	1,3	1,3	II

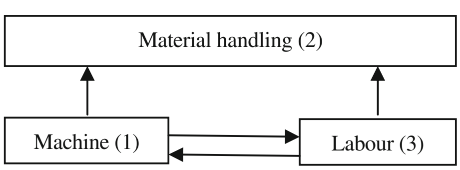
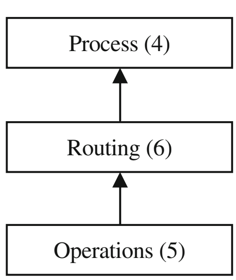


Fig. 2 ISM model for flexibility dimensions at individual/resource level

Fig. 3 ISM model for flexibility dimensions at shop floor level



4.2 ISM model for flexibility dimensions at shop floor level

ISM model (Fig. 3) for flexibility dimensions performed at shop floor level viz., routing, operation, and process flexibility, with relevant matrices i.e., SSI matrix (Table 9), initial reachability matrix (Table 10), and final reachability matrix (Table 11) are presented in this section.

4.3 ISM model for flexibility dimensions at plant level

ISM model (Fig. 4) for flexibility dimensions performed at plant level viz., expansion, production, volume, and product flexibility, with relevant matrices i.e., SSI matrix (Table 12), initial reachability matrix (Table 13), and final reachability matrix (Table 14) are presented in this section.

4.4 ISM based framework for all flexibility dimensions under consideration

SSI matrix, initial reachability matrix, and final reachability matrix for all flexibility dimensions under consideration are prepared and shown in Tables 15, 16, and 17, respectively. ISM model for the same is presented in Fig. 5.

4.5 MICMAC analysis for ISM based framework for all flexibility dimensions under consideration

MICMAC analysis, the driving power and dependence power of each of the flexibility dimension are taken from Table 16. It classifies the flexibility dimensions described earlier into four clusters (refer Fig. 6; Table 18).

Table 9 Structural self-interaction (SSI) Matrix

	Routing	Operations	Process
Process (4)	A	A	
Operations (5)	V		
Routing (6)			

Table 10 Initial reachability matrix

	Process (4)	Operations (5)	Routing (6)	Driving power	Ranks
Process (4)	1	0	0	1	III
Operations (5)	1	1	1	3	I
Routing (6)	1	0	1	2	II
Dependence power	3	1	2		
Ranks	I	III	II		

Table 11 Final reachability matrix

Variables	Reachability set	Antecedent set	Intersection set	Levels
Process (4)	4	4,5,6	4	I
Operations (5)	5	5	5	III
Routing (6)	6	5,6	6	II

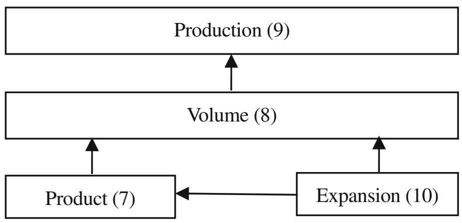


Fig. 4 ISM model for flexibility dimensions at plant level

Table 12 Structural self-interaction (SSI) matrix

	Expansion (10)	Production (9)	Volume (8)	Product (7)
Product (7)	A	X	V	
Volume (8)	A	V		
Production (9)	A			
Expansion (10)				

Table 13 Initial reachability matrix

	Product (7)	Volume (8)	Production (9)	Expansion (10)	Driving power	Ranks
Product (7)	1	1	1	0	3	II
Volume (8)	0	1	1	0	2	III
Production (9)	1	0	1	0	2	III
Expansion (10)	1	1	1	1	4	I
Driving power	3	3	4	1		
Ranks	II	II	I	III		

Table 14 Final reachability matrix

Variables	Reachability set	Antecedent set	Intersection set	Levels
Product (7)	7	7,10	7	III
Volume (8)	8	1,8,10	8	II
Production (9)	7,9	7,8,9,10	7,9	I
Expansion (10)	7,10	7,10	7,10	III

Table 15 Structural self-interaction (SSI) matrix for all flexibility dimensions under consideration

	Expansion (10)	Production (9)	Volume (8)	Product (7)	Routing (6)	Operations (5)	Process (4)	Labour (3)	Material handling (2)	Machine (1)
Machine (1)	V	V	V	V	V	V	V	X	V	
Material handling (2)	V	V	V	V	V	V	V	A		
Labour (3)	V	V	V	V	V	V	V			
Process (4)	X	V	V	V	A	A				
Operations (5)	V	X	V	X	V					
Routing (6)	V	X	V	V						
Product (7)	A	X	V							
Volume (8)	A	V								
Production (9)	A									
Expansion (10)										

Table 16 Initial reachability matrix for all flexibility dimensions under consideration

	Machine (1)	Material handling (2)	Labour (3)	Process (4)	Operations (5)	Routing (6)	Product (7)	Volume (8)	Production (9)	Expansion (10)	Driving power	Ranks
Machine (1)	1	1	1	1	1	1	1	1	1	1	10	I
Material handling (2)	0	1	0	1	1	1	1	1	1	1	8	II
Labour (3)	1	1	1	1	1	1	1	1	1	1	10	I
Process (4)	0	0	0	1	0	0	1	1	1	1	5	V
Operations (5)	0	0	0	1	1	1	1	1	1	1	7	III
Routing (6)	0	0	0	1	0	1	1	1	1	1	6	IV
Product (7)	0	0	0	0	1	0	1	1	1	0	4	VI
Volume (8)	0	0	0	0	0	0	0	1	1	0	2	VII
Production (9)	0	0	0	0	1	1	1	0	1	0	4	VI
Expansion (10)	0	0	0	1	0	0	1	1	1	1	5	V
Dependence power	2	3	2	7	6	6	9	9	10	7		
Ranks	VI	V	VI	III	IV	IV	II	II	I	III		

Table 17 Final reachability matrix

Variables	Reachability set	Antecedent set	Intersection set	Levels
Machine (1)	1,2,3	1,3	1,3	VIII
Material handling (2)	2	1,2,3	2	VII
Labour (3)	1,2,3	1,3	1,3	VIII
Process (4)	4,10	1,2,3,4,5,6,10	4,10	IV
Operations (5)	5	1,2,3,5	5	VI
Routing (6)	6	1,2,3,5,6	6	V
Product (7)	5,7	1,2,3,4,5,6,7,10	5,7	III
Volume (8)	8	1,2,3,4,5,6,7,8,10	8	II
Production (9)	5,6,7,9	1,2,3,4,5,6,7,8,9,10	5,6,7,9	I
Expansion (10)	4,10	1,2,3,4,5,6,10	4,10	IV

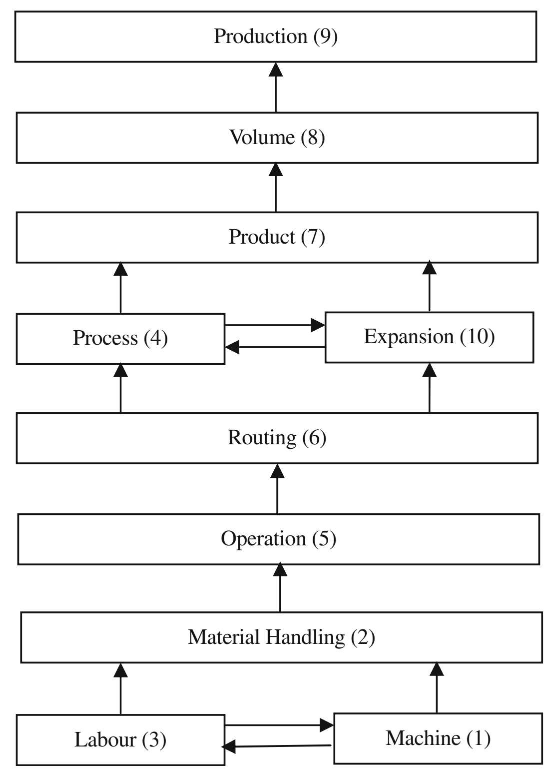


Fig. 5 ISM based framework for all flexibility dimensions under consideration

5 Conclusions

In the light of recently developed ISM model along with a critical review of literature the following conclusions can be made:

- For flexibility dimensions considered, authors observed that flexibility dimension at lower level may be derived from the dimensions at higher level.
- Though, labour flexibility finds a very little role in FMS. But importance of human resource/labour

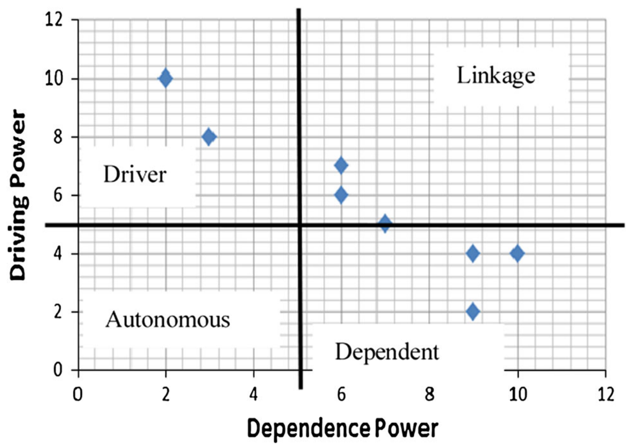


Fig. 6 Clusters of enablers among flexibility dimensions

Table 18 Clusters of various flexibility dimensions

S. No.	Cluster names	Flexibility dimensions
1	Autonomous variables	Nil
2	Dependent variables	Production, volume, product
3	Linkage variables	Operation, routing, process, expansion
4	Independent variables (drivers)	Machine, labour, material handling

flexibility is vital and in tune with studies of Cesaní VI and Steudel (2005), Chung (1996) and Sawhney (2013). Further a well-mixed labour and machine flexibility may produce better results.

- After observing all four ISM models, it is interesting to note that overall ISM framework has ISM model for flexibilities performed at individual/resource level at its bottom, ISM model for flexibilities performed at shop floor level at its middle, and ISM model for flexibilities performed at plant level at its top.
- Another interesting fact is that flexibility dimensions performed at individual/resource level act as independent variables (drivers). Flexibilities performed at shop floor level act as linkage variable, while flexibilities performed at plant level act as dependent variables in general. Here, it can be implicated that flexibility dimensions performed at individual/resource level is most crucial followed by flexibilities dimensions performed at level of shop floor, and level of plant in order, for MS performance.
- It is also observed that no flexibility dimension could work in isolation. It has an impact on other flexibility dimension(s) too. A firm may benefit more from a good mix of various flexibility dimensions rather an exclusive use of a single type of flexibility. From the literature (Baykasoğlu and Özbakır 2008; Chan et al. 2006, Chan 2001; Joseph and Sridharan 2011a, b; Morito et al. 1991), it is clear that up to a particular level of flexibility, the system performance increases with the increase in degree of flexibility. Increase in degree of flexibility beyond this threshold value, deterioration in system performance starts and makes it even worse. It would be beneficial to study the impact of different degrees of a particular flexibility dimension on the system performance in isolation as well as in a group of all/major flexibility dimension(s).

Estimation of the impact a given flexibility dimension on system performance as well as on other flexibility dimensions will be useful for both the design and operation of FMS. Return on investment is one of the basic and foremost criteria for adoption of any newer technology. Structural relationship among various flexibility dimensions developed in the study would be an effective tool for economic justification for adoption of certain flexibility dimension(s), and may be used strategically in identifying conditions and opportunities, for which, what kind of flexibility can drive the maximum benefits.

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