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Manufacturing Flexibility and its Effect on System Performance

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Abstract

In present time, manufacturing industries are facing a very competitive, unpredictable, and ever changing environment, with growing complexity and high levels of customization. In order to achieve the customer satisfaction without sacrificing profitability, one hand industry leaders are trying to invent and adopt newer technologies and on the other hand, top management of industry requires an assurance of early return on their investment from its technical people /managers prior to actual investment in any new technology. Flexibility is probably among the most sought after manufacturing technologies. To address the issue, a prior study of the effect of different flexibility levels on manufacturing process is required. In the present paper an attempt has been made to understand the various flexibility types and their effect on the performance of a Manufacturing System (MS). It is observed that beyond a certain level of flexibility manufacturing system performance starts deterioting. A theoretical frame work for manufacturing system, factors affecting its performance & Manufacturing Flexibility (MF) is laid down. Further, an effort has also been made to present simple probable measure of various flexibility types. Towards the end with the arrangement of various flexibility dimensions in different categories on a flexibility pyramid, the concept of flexibility pyramid is proposed. Some further probable research areas are also identified.

Keywords: *Manufacturing Flexibility, Types, Measures, Flexibility Pyramid, Manufacturing System Framework.*

1. Introduction

In present dynamic and ever-changing market scenario, uncertainty is one of main characteristics. Large product variety, and shorted product life cycle are the result of technological advancement which further leads to more demanding customers with uncertainty in demands [1]. Thus, poses challenges on the manufacturing firms.

In simple words, Manufacturing System (MS) transforms raw material into desired shape and size consistently and economically. There are number of unexpected events, like fluctuating demands, machine break down, government regulations, competitor's action, consumer's choice, absenteeism, etc., making this transformation process more complex [2]. These disturbances either originated within system boundary or outside system boundary, invariably affect the overall performance of any MS. The illustrative framework for the factors affecting the performance of a MS envisioned in figure 1.

To address these unexpected disturbances, the MS essentially needs to be under the umbrella of MF. That might be one of the reasons for the concept of MF (or flexibility, both the terms are invariably used in the present paper), being among the key considerations in the design, development, operation, and management [3] of a manufacturing system. A wide range of growing literature is available for definition and dimensions of manufacturing flexibility; however limited literature is available on the measures of MF. The present paper, on one hand, aims towards the study of the effect of various flexibility types on the performance of a MS, and, on the other, it develops a framework for a MS, factors affecting its performance, and flexibility. The various MF types are arranged at different levels of a flexibility pyramid. The organization of the rest of the present paper is as follows: MF, its various types, their definition and measures are discussed in section 2. Review of relevant literature; the point of view of effect of manufacturing flexibility is grouped in two subsections according to simulation and empirical work in section 3. A frame work for manufacturing system and flexibility as well as the concept of flexibility pyramid is proposed in section 4. Conclusions drawn and scope of future work are given in section 5.

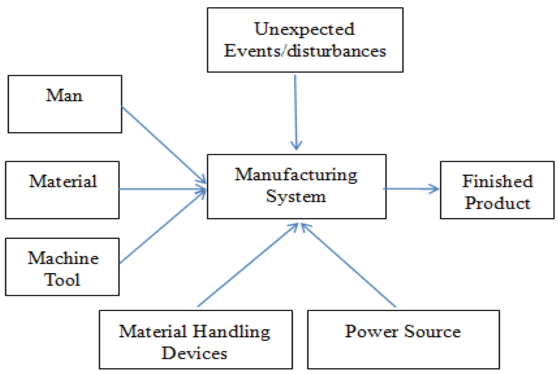

Figure 1. Framework for manufacturing system and factors affecting its performance

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2. Manufacturing Flexibility (MF)

Even though a number of authors have exerted much effort to capture the essence of flexibility and formulated number of definitions (for more details refer to [2-9]), there is a lack of general consensus on the definitions of flexibility [10]. Shewchuk & Moodie [10] found more than 70 terms on flexibility (types and measures) in the literature. Existence of at least 50 terms for the various types of MF is reported by Sethi and Sethi, in their popular survey of relevant literature [3]. Flexibility is a complex, multidimensional, and hard-to capture concept. In many cases several terms refer to the same flexibility type. Imprecise and conflicting definitions for flexibility types/ dimensions are there, even for identical terms [5]. A systematic review of vast literature available on manufacturing flexibility is recently published by Marta Pérez Pérez *et al.* [11]. Flexibility terms are studied from hierarchical and systematic perspectives. Wide terminological and conceptual ambiguity associated with the manufacturing flexibility has been addressed [11].

Here, flexibility is considered as the ability to develop and select the alternatives for a particular situation. In context of manufacturing, "*ability of a manufacturing system to develop and select alternatives for a particular manufacturing situation is known as MF"*. Alternatives may be created and selected in various dimensions under a number of situations of a manufacturing system; hence MF may have several different types/ dimensions/ forms. Ramasesh and Jaykumar [12] rightly remarkd that MF can be in number of different forms, e.g. machine, material, material handling, routing, operation, process, product, program, volume, expansion, labour, etc.

2.1. Flexibility Types and Measures

Flexibility is crucial factor for any MS. If properly utilized, it has a positive effect on the performance of a MS [13]. A number of categories and types of MF can be found in the literature. In 1984, Browne *et al.* [14] identified eight dimensions of MF, while in 1990; Sethi and Sethi [3] proposed the widely accepted concept of eleven flexibility types. These eleven types of flexibilities have been segregated into three categories, namely basic, system, and aggregate. Machine, operation, and material handling flexibilities are categorized as component or basic flexibilities. Expansion, process, product, routing, volume, flexibilities are kept in the system flexibility group. Lastly Market, program, and production flexibilities are made the category of aggregate flexibilities [2]. Later, Vokurka and O'Leary-Kelly [15] proposed four more types of flexibility, namely automation, new design, delivery, and labour. The definition for each of the fifteen flexibility dimensions (at least there is a broad consensus on these) adapted from [2-3, 14-21], and tabulated in Table 1. Though, it is very difficult to measure flexibility type directly, a fuzzy based mathematical framework to measure/quantify nine flexibility types and overall flexibility is developed in [21]. A complex mathematics delays the decision process, to keep it simple, the handy measure of all flexibility types are presented in table 1. Recently Kumar and Sharma [2], arranged ten flexibility types at different levels at which they are performed. Machine, material, and labor are placed at the level of individual/resource. Process, operation, and routing flexibilities are functions at the level of shop floor. Product, volume, production, and expansion flexibilities are performed at plant level. It is also observed independent variables machine, material handling, and labor flexibilities are linked to dependent variables, namely production, volume, and product flexibilities through linked variables, namely operation, routing, process, and expansion flexibilities.

3. Literature Review

In the underwritten lines, a review, of the literature pertaining to effect of flexibility on the performance of a MS is carried out and presented in two categories, according to the approaches of work, viz Simulation & modeling, and Empirical.

3.1. Review of Simulation and Modeling Work on Effect of Flexibility Types on System's Performance

In a review of effect of flexibility on manufacturing performance, it is observed that Susumu Morito *et al.* [23] analyzed a real life Flexible Manufacturing System (FMS), using discrete event simulation, and found that just having two or three alternative machines, would greatly enhance both the flexibility and performance of the MS. Contributions towards flexibility and performance, from more than three alternative machines would be dismal. Morito *et al*. [23] noticed that, on one the hand, make-span performance is not affected by scheduling priorities, while, on the other hand, a carefully crafted machine assignment would be crucial to attain short make-span. The findings are further strengthened by Chan [24] by the use of the Taguchi's experimental design framework with simulation techniques (ANOVA) based methodology. In most situations optimum performance is observed at routing flexibility level 1 or 2. Deterioration is system performance starts beyond this flexibility level. This suggests that increase in routing flexibility and improvement of system performance could not go together endlessly. Optimal pallet requirement, routing, and sequencing rules for hypothetical FMS were also determined by Chan, [24]. The similar results are obtained by Chauhan [25], in his study of a hypothetical FMS with ARENA simulator. He observed that beyond a suitable flexibility, and pallet level, system performance starts deteriorating, as judged by the make-span measure of performance. Continuous reduction in make-span time with the increase in routing flexibility is observed at a fixed level of delay time. When routing flexibility is further increased, the variability in make-span time due to delay time reduces [25]. Albino & Garavelli [26] by their simulation study pointed that, with the decrease in resource dependability, productivity can be effectively increased by the use of routing flexibility, particularly in the limited flexibility configuration.

Mountaz Khouja [27] reported if a system is more volume flexible, optimal production lot size will be higher; in turn, the optimal production rate would be lower. For MS having volume flexibility, the optimal production rate is smaller than the production rate required to minimize per unit production cost.

Table 1. Definitions of fifteen flexibility types / dimensions and their respective measures

S. No.	Flexibility	Definition	Measure	Remarks
1	Machine	Ability of machine to perform a range of operations without incurring any major setup	Average of different number of operations could be performed on a machine without any major setup change.	Measure in terms of time required to change tool/ set up are also observed in literature [17,21]
2	Process	Ability of system of producing variety parts without incurring any major setup	Number of different part types could be processed simultaneously.	Possibly using different material
3	Operations	Ability to produce a component / product by alternative processes or ways	Average number of alternate process orders / ways for each part type, which can be accommodated.	Without any effect on shape and size of final product
4	Product	System's ability to substitute /replace or add new part(s) for existing part	Number of substitute products could be produced quickly and economically.	Measure in terms of requisite time in switching from one part mix to another, are also observed in literature [17].
5	Routing	System's ability to have number of alternative paths within the system, by which a part could be made	Average number of alternative path by which a part could be processed.	It indicates the robustness of the system, to accommodate and break down.
6	Volume	System's ability to operate at range of different output levels economically	Number of different output levels could be produced economically	The smallest volume for all part types for profitable operation.
7	Production	System's ability to produce a plethora of products without adding new equipment	Number of products which could be made by the system	Product range; Similar to product flexibility of [22]which enables a manufacturing system to make a variety of part types with the same equipment
8	Expansion	Ease at which capacity and capability of the system may be enhanced	Capacity and capability which could be added without any major investment.	Magnitude of the MS
9	Material Handling	Material handling system's capability of moving and positioning various parts throughout the MS	Number of simultaneous components that can be moved and positioned by the system	Measure in terms of the quantity, diversity, and transportation time of parts.
10	Program	System's capability of unattended operation for a long period of time	Period for which MS could be operated/run without attention	Fraction of period for which system could be operated without attention
11	Market	Adaptability and responsiveness to the changing market environment	Response time of system to change in market	System should be proactive towards changing market
12	Automation	Level at which flexibility is incorporated in the computerization/automation of manufacturing technologies	Measure of the stage of flexible automation within the system	Proportion of plant having flexible automation
13	New Design	System's ability of designing and introducing newer products into the market well before time	Number of new design/product can be introduced from the existing facilities	Pro-activeness of the system to changing customer taste
14	Delivery	Responsiveness of the system towards changes in delivery requests	Number of simultaneous changes in delivery requests could be accommodated successfully	Ratio of number of successfully implemented changes in delivery requests to total request for change in delivery
15	Labour	Multitasking ability of labour/ operator/human resource i.e. within the MS without sacrificing the efficiency	Average number of different tasks that could be performed by an individual human resource	Ease in inter-departmental transfer of personals

The study of Chandra *et al.* [28] reflected that under the specific scenarios, the level of total demand at profitable production rate marginally affected by the increase in product mix flexibility. Meanwhile, profitability is improved by increasing product mix flexibility for a constant total demand, most significantly for total demand exceeding the system's capacity.

The study of Horng [29] observed that with limited labour resources, mixed labor assignments directly and indirectly improves the performance within a cell. This study indicates that when more than 70% of the skills are shared by all of the operators requiring higher training costs, and system performance do not improve significantly.

Deterioration in make-span performance with an increase in decision delays is reported by Wadhwa and Bhagwat [30]. This deterioration is higher at higher levels of flexibility, i.e. higher the number of available options to choose. They further observed that interaction between flexibility and decision delays results a certain level of decision delays beyond which, the performance of the system is reduced due to their cumulative effect.

Chan [31] in his study of impact of dispatching rules, operation flexibility, and the combination of these two on the performance of a FMS, observed that performance of his FMS model improved more significantly by alteration in the dispatching rules as compared to changing the levels of operation flexibility. Increasing the operation flexibility should not be taken as the key direction for performance improvement of the FMS. Among the six dispatching rules considered in the study, the shortest remaining processing time rule is found to be the best. However, none of the six levels of operation flexibility considered, can claim to be the best among the six levels. In another study of effects of routing flexibility, sequencing flexibility, and scheduling decisions on the performance of a FMS, Joseph and Sridharan [32] observed that all the performance measures of the system is improved with the introduction of sequencing flexibility, in the absence of routing flexibility. Deterioration in system performance could be minimized by the inclusion of sequencing flexibility or routing flexibility or both. However, the diminishing rate of benefits at higher flexibility levels of each of these flexibilities is observed.

In a comparative study regarding to the influence of product, transformation, and sequencing flexibility, Wadhwa *et al.* [33] found that the influence decreases from product flexibility, to transformation flexibility, to the sequencing flexibility [8]. Baykasoglu and Ozkabir [13] reported that machine flexibility effects job shop performance more in comparison to process plan flexibility. A considerable decrease in the rate of scheduling performance improvement is also observed beyond a certain level of machine flexibility.

By giving a close observation to the findings of various researchers discussed above, it is observed that increase in flexibility levels up to a particular level, it will benefits towards performance of MS. Additional increase in flexibility beyond this particular level deteriorates the performance of manufacturing system. Combination of flexibility levels of different flexibility types may be system specific and depends on the constraints and priorities of the management. Garavelli [34] compared the system performance under three different degree of flexibility total flexibility (as in a job-shop), no flexibility (as in a cellular system with no inter cell move) and limited flexibility (a particular inter cell routing flexibility), and found that the system performance under limited flexibility is optimum, while the system performance under zero flexibility is worse. The similar results were reported by the study of the impact of different routing flexibility levels on make-span of a FMS, carried out by Ali and Wadhwa [35]. The results further strengthen by Muriel *et al.* [36] in their study which indicates that the production variability is significantly increased with the introduction of partial flexibility. Further, even allocation of demand (distributed tactical capacity allocation) to the plants, leads to better performance of the flexible system. Nagarur [37] coined a framework called producibility, with the integration of both flexibility and reliability. It is a direct measure of the ability of system to accomplish the given task(s).

3.2. Review of Empirical Work on Effect of Various Flexibility Types on the Performance of a MS

In recent years much has been written about flexibility, FMS, and Flexible factories, but the literature has been largely theoretical, a little practical work has been observed.

Vokurka and Kelly [15] reviewed the empirical studies and revealed four general areas having dominant factors influencing MF, namely organizational attributes, strategy, technology, and environmental factors. The previous models, [38-41] addressed the vital relationship between MF and environmental uncertainty, but do not address relationships involving MF, organizational attributes, business strategy, and technology. Limited relationships are addressed by these models [15]. Finally, they proposed their own framework. These all frameworks incorporate the effect of all flexibility type under a single variable "MF".

Suarez *et al.* [41] divided flexibility types into two major categories, namely, "First order" flexibilities and "lower order" flexibilities. Flexibility types segregated as first order flexibility directly affects the firm's competitive position in the market, and lower order flexibility types communicate their final effect through one of four first order (Mix, Delivery Time, New Product, and Volume) flexibility types. Some of Their major findings are as: (a) more automation leads to less flexible (b) Worker involvement, supplier relationship, flexible wage system, etc. appear to increase new-product, mix, and volume flexibility (c) Both mix and new product flexibility seem to be raised by component reusability (d) A mutual reinforcement between new-product and mix flexibility is observed, and likely to be further supported by similar other factors (e) Volume fluctuations may be reduced by Mix flexibility. Hence a theoretical reduction is "in the need of volume flexibility". In their study, Jack and Raturi [42] used empirical research methodologies to test and validate their hypotheses. They reported a positive impact of volume flexibility on performance.

In general, Hallgren and Olhager [43] observed plants having high flexibility levels performs better in all four operational performance measures, namely cost, conformance to quality standards, speedy and on-time of delivery, as compared to plants having low flexibility levels. On the front of on-time delivery, the volume flexible plants demonstrate better performance than mix flexible plants however; on other fronts the performance of multi flexibility plants is significantly higher as compared to only volume flexible plants. It is more important to have both mix and volume flexible [43]. Salvador *et al.* [44] found that mix flexibility is negatively affected by the few approaches used to increase volume flexibility and vice versa.

Findings of an empirical study, named the effect of manufacturing flexibility on export performance in China by Ogunmokun and Li, relates manufacturing flexibility to export performance, with a major implication that organizations that are not flexible in their manufacturing may be hindering the performance of their export ventures, necessary for sustaining the survival of their operations [45].

Luan *et al.* [46] in their empirical research and survey of about 381 manufacturing enterprises found that flexible manufacturing competence has positive, significant and direct impacts on firm's competitive advantage. The similar results are reported by Lee and Chen [47] in their empirical study of organizational Performance of Taiwan-listed photovoltaic companies. In 2015, a survey on competitiveness of small and medium enterprise of north India, Kaur *et al.* [48] found that labor flexibility has the highest impact on competitiveness of the firm followed by the machine flexibility and material handling flexibility. In another empirical study of a food industry, Chang [16] priorities the effect of eight flexibility types in the following order (highest first) production flexibility, product flexibility, market flexibility, labor flexibility, machine flexibility, volume flexibility, material handling flexibility, expansion flexibility. Zainol *et al.* [49] reported a good positive impact of MF on product modularity also.

In 2016, a study of relationship between Manufacturing Flexibility Competency (MFC), Innovation Capability (IC) and Operation Performance (OP) of Indonesian manufacturing firms is published and reported a positive association among the three. Further it inferred that IC mediates between MFC and OP [50].

Recently, Brettel *et al.* identified the relationships between flexibility and performance by systematically charting empirical findings from the literature and linked this development to the advancements of manufacturing schemes of industries 4 [51].

4. The Frame Work

From the above literature review, it is evident that some flexibility types have direct and significant effect on the performance of a MS. Whilst, few flexibility types are hardly make any major impact on the performance of the MS. Few flexibility types, which could affect the magnitude of impact of other flexibility types on the performance of a MS, are also observed.

4.1. Framework for Manufacturing System and Flexibility

In order to develop a theoretical frame work for manufacturing system and flexibility, flexibility is considered as a panacea to all practical problems of any manufacturing system. It is evident that Flexibility is a stronger predictor of performance in more dynamic environments [52]. The framework envisioned in figure 1 can be modified by encircling manufacturing process with the MF. As flexibility is the ability of system to deal with change, hence all changes as well as prospective changes must be handled by MF prior to affecting the MS, for the sake of pro-activeness of the system. Hence, all unexpected events can be removed as they are the by-product of other factors and parameters. Organizational attributes, strategy, and environmental factors must be added to get a fairer and complete picture. Literature [15] has the strong evidences regarding the influence of organizational attribute, strategy and environmental factors on manufacturing system performance similar to the common belief. The technological aspects may be covered by machine tool, material handling devices and skilled manpower etc. The modified frame work is depicted in figure 2.

For the simplest analysis of frame work, if the material handling system of MS can handle any component in two different ways, it could be said that MS has two units of material handling flexibility. It gives the leverage to the MS to handle a component and raw material. But if the material handling system is of the same material it can handle a component in 10 ways. Above this if the same MS has such large level of flexibility in number of flexibility types, in most of the cases, the total number of choices is the product of all such flexibility level. It makes a very large number of choices to select, selection from a large number of choices introduce delay in decision. Further a major portion of capability remains unutilized. Further IT implementation has direct and significant impact positive operations performance on Machine, Labor, Material handling and Volume flexibility dimensions Mix and Routing flexibility dimensions [53]. IT implementation could be used for enhancement of effectiveness of the system.

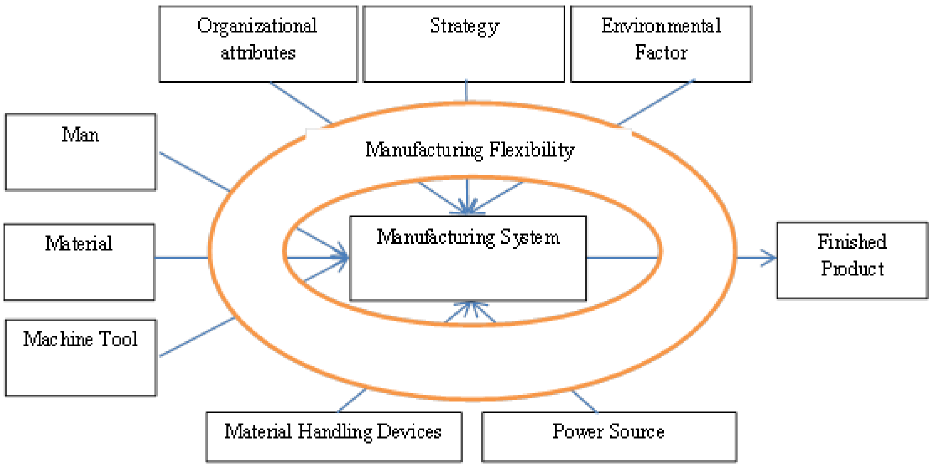

Figure 2: Framework for manufacturing system, factors affecting its performance, and Manufacturing Flexibility

4.2. Various Categories of Flexibility Types

Saurez *et al.* [41] divided flexibility types into two main orders, namely order 1 and lower orders, by using firm to market approach. In their model lower order flexibility types are wide side of funnel, i.e. firm side and first order flexibility types are narrow side of funnel, i.e. market side. Competitive position of the firm into the market is directly affected by the flexibility types grouped as Order 1 viz: Volume, New Product, Delivery, Production (Product mix), and effect of order 1 flexibility types is easily perceived by the customers. Lower Order contains all other flexibility types. Kumar and Sharma [2] divided 10 flexibility types into three levels, namely flexibility types performed at plant level, shop floor level, and individual/ resource level. Kumar and Sharma [2], further segregated these 10 flexibility types as independent variables, linkage variables, and dependent variables.

Here, four different categories of flexibility types are suggested. All 15 flexibilities types, discussed here are segregated into four different categories by a careful study of both analytical and empirical research analyzing the impact of various flexibility types on the performance of a MS available to us so far. Category 2 is kept same as order 1 of [41] because all exercise is done to retain and improve the competitive position at the market, and these four are critical for market position. Remaining flexibility types are divided into three categories (category 1, category 3, and category 4) as per the flow of firm's response towards market changes.

It is not necessary, for a certain firm, to infuse all kind of flexibility dimensions in its system to remain in competition. The flexibility types and level of each flexibility type requirement may be different for different industries. Further the optimum level of all required flexibility types may also be different from the optimum level of each other.

- Category **1:** Flexibility types for efficient adoption of customer demand and innovation, pro-activeness of the firm to adapt in the changing market scenario, generally performed by top level management not only to sustain but to capture the larger market share: new design, and market
- Category **2:** Flexibility types which directly affect the Firm's competitive position in the market: decision in taken at the plant level management: volume, product, delivery, and production (product mix)
- Category **3:** Flexibilities generally performed at shop floor personals in order to meet the plant production objectives: program, expansion, automation, operations, routing (Sequencing), and process
- Category **4:** Flexibility types which would be performed mainly at individuals in order to meet the shop floor production targets: machine flexibility, material handling, and labour (human resource).

4.3. Flexibility Pyramid

After defining the levels of flexibilities a flexibility pyramid can be developed. Flexibilities of category 1 to category 4 are positioned from apex to bottom of pyramid as illustrated in figure 3. As move from bottom to top of pyramid number of people involved decreases. In tune to [2], bottom variables are independent to other flexibility dimensions. They are most crucial for system performance. While variables are at apex of pyramid are dependent variables. These are crucial for pro-activeness of the system. Linkages variables are in middle of pyramid. Importance of flexibility type in order to response to market decreases from apex to bottom of pyramid. For manufacturing performance, importance of parameter from bottom to top decreases. Flexibility types at bottom sharply and immediate affect the manufacturing performance, while effect of flexibility types at apex are visible in long term. The effect of flexibility types at lower order may be transformed into the one of flexibility types at higher order.

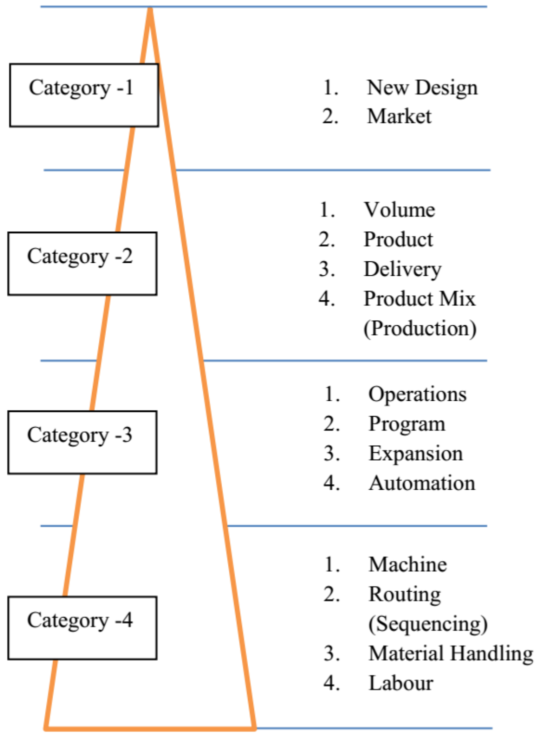

Fig. 3: Pyramid for Flexibility Types

5. Conclusion

From the above discussion it is evident that a certain degree of flexibility is not only beneficial but essential for modern manufacturing industry in present dynamic environment. Every firm has to estimate the flexibility types and its degree required for its sustainable growth. Flexibility is required at different level of organization and each one has its own importance, and most of them are inter-linked. Further flexibility pyramid would be a handy tool to make an understanding of the essence of flexibility. In spite of the development of a theoretical frame work, and flexibility pyramid, and above concluding remarks, following Observations and future scope of work might be helpful for a broader insight of the topic.

5.1. Observations

From the discussion in the article, following observations can be made:

- Major thrust area of researchers is on routing / scheduling flexibility, machine flexibility and labor flexibility, volume flexibility in order, and a little work is carried out on other types of flexibility.
- Up to a certain level of flexibility, the performance of MS increases with the rise in flexibility level
- Rise in flexibility level beyond this threshold value, deterioration in system performance starts and makes it even worse. The reason of this may be the increase in choices, as increase in choices leads to larger in decision delay.
- From empirical research, it is evident that every manufacturing unit has its different needs and requirement of flexibility type(s). That's why managers are advised to choose the required flexibility type(s) and their respective level(s) carefully.

Prior estimation of the impact a given type and level of flexibility on the performance of MS will be beneficial for both the operation and design of manufacturing systems. Every increment in any flexibility type or its level into the system adds to cost. Return on investment is one of the basic and foremost criteria for adoption of any newer technology. Rate of return method is a widely accepted powerful tool in accepting /rejecting decisions [54]. Flexibility analysis would be an effective tool for economic justification of adoption of certain flexibility types and their respective levels, and may be used tactically in finding conditions & opportunities for which flexibility can drive the maximum benefits. That is why a prior study of the effect flexibility on performance and optimum level of various flexibility types for a manufacturing system is inevitable.

5.2. Scope of Further Work

From the study the scope of further work could be identified as follows:

- Priorities the effect of various flexibility types and their respective levels separately on the MS's performance.
- Ordering of flexibility types according to their impact on manufacturing system performance.
- Knowledge management and IT implementation are also handy and vital tools to handle the change; there is also a scope of study of effect of knowledge management in combination with flexibility and reliability in manufacturing system.
- Effect of a particular flexibility type on other flexibility type(s) for a particular MS and in general too.
- Research studies are more focused towards modeling and simulation approach, a wide scope of empirical research is there.

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