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APPLICATION ARTICLE

A fuzzy-QFD approach to manufacturing strategy formulation

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Abstract

Modern firms adopt Advanced Manufacturing Technologies (AMTs) in the quest for their competitive success, but often end up in the huge capital investments in technology upgradations. The purpose of this work is to demonstrate firm-specific efforts to leverage AMTs through Manufacturing Strategy (MS) formulation utilizing Fuzzy-Quality Function Deployment (QFD) in selected three firms representing varying industrial context.

Fuzzy-QFD is operationalized using the quantitative inputs on MS formulation such as- (1) Relative strategic importance of competitive priorities ("what") (2) Linkage between Competitive priorities and MS elements ("what-how"). The results of Fuzzy-QFD model based MS formulation are then shared and validated on detailed discussions with the industry experts. These discussions reveal intricacies of MS formulation and its impact on business processes and operational plan.

This study shows two interesting findings- first, the competitive priorities sequence (*Quality-Flexibility-Delivery-Cost)* for select firms differs than the classical sand-cone sequence (i.e., *Quality-Delivery-Flexibility-Cost*). Second, even with common competitive priorities sequence, firms show the unique way of the realization of MS exhibiting the complex and idiosyncratic nature of strategic decisions. Manufacturing Managers can utilize The study provides analytically efficient and easy way to MS formulation. Further, the findings of the study can help firms to align their operational plans and AMTs as per competitive requirements.

Keywords Manufacturing strategy · Quality function deployment (QFD) · MS elements · Competitive priorities · Advanced manufacturing technology (AMT)

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1 Introduction

Modern firms rely on advanced manufacturing technologies (AMTs) (such as industry 4.0, flexible manufacturing systems, automation, computer integrated manufacturing, additive manufacturing) and advanced manufacturing systems (AMSS) (such as lean, just-in-time, toyota production system, total quality management, six-sigma, business process reengineering) in their quest for competitive success. Despite the endless attempts in implementing AMTs and AMSs de facto manufacturing strategy (MS), many firms often fail to develop competitive manufacturing capabilities. Such continuing failures and competitive pressure may result in the deformation of the strategic role of manufacturing in business strategy at the loss of competitive edge [10, 11, 32, 36]. The central question of this research is—"How modern firms need to formulate their MS, and align their AMTs and AMSs towards competitive requirement"?

Best practices of AMTs and AMSs perhaps are emerging as advanced manufacturing paradigms among practitioners [78, 79]. Managers of technology leading firms scout and adopt technological solutions and reap operational benefits. Imitating the industry leaders, the following firms prefer AMTs as an "enduring single time solution" to resolve technology and market constraints. [14, 29, 30]. The rise of operational improvement programs has overshadowed the traditional wisdom of Manufacturing Strategy (MS) formulation [38, 62].

The academic research in MS domain has been dominated by conceptual models and rigid frameworks considering empirical validations with international or opinion surveys following the legacy of logical empiricism focusing on development and testing of theoretical hypotheses [60, 61]. The analytical and firm-specific studies capturing MS formulation is relatively less addressed domain in MS research [28, 61].

Few exceptional studies like Bottani [7], Jia and Bai [33] and Vinodh and Chintha [76] considered MS formulation as the dichronous interactions between choice of competitive priorities and manufacturing decisions. Such model illustrations are generally conducted in hypothetical or illustrative model settings, but lack generalizable or even firm-specific insights to manage complexities of MS formulation. This work aims to contribute towards the void of firm-specific MS formulations building on findings of previous studies.

The purpose of this study is explore to firm-specific efforts in MS formulation and align applications of AMTs and AMSs towards competitive requirements of the firm. In this study, MS formulation is approached as the dichronous interactions between competitive priorities and MS elements representing strategic triad representing content, process and context dimension. Specifically, the research objectives of the study are:

*RO*1: To understand the sequence of competitive priorities across select representative firms representing strategic objectives of the firm.

*RO*2: To identify the critical MS elements, modelling interactions between competitive priorities and MS elements.

*RO*3: To explore the variations in MS formulation across select firms representing diverse industry backgrounds.

This study adopts Fuzzy-QFD based dichronous modelling approach to explore MS formulation. QFD is specifically adopted as the transformative device to convert the strategic directives of the competitive priorities into MS decisions and action plans. The fuzzy linguistic scale is used to capture the vagueness and imprecision in the competitive priorities and their relationship with MS elements.

The key findings of the study are as follows: (1) Despite the variations in the industrial context, firms show Quality-Flexibility-Delivery-Cost (*Q*-*F*-*D*-*C*) as the preferred sequence of competitive priorities. (2) Firms do follow similar competitive sequence, but show variations MS elements indicating differences in operational decision levels. (3) Implimentation of AMTs and AMSs vary with strategic requirement of the firm, in relation with the position of the firm with respect to performance frontiers as elaborated by Schemener and Swink [63].

2 Literature synthesis

MS formulation and its strategic significance in developing competitive manufacturing capabilities is undisputed in the academic literature of MS [10, 11, 30, 32]. Skinner [70] emphasized that manufacturing can be the source of competitive advantage, but the strategic approach in deploying MS needs to be dynamic, practical, and iterative.

2.1 MS triad: content, process and context

The classical MS research have approached MS formulation with content and process dimensions [8, 33, 47, 68]. MS content includes determination the sequence of competitive priorities and its alignment with manufacturing decisions specifying positioning of the firm in the market [28]. Competitive priorities define the strategic objectives that dictate manufacturing decisions at structural (capacity, facility, process technology, supply chain), and infrastructural (quality systems, production planning control, organization structure and resource management) to develop manufacturing capabilities of cost, quality, delivery and flexibility. MS process includes the way resources and existing capabilities are deployed and utilized with intended MS content [8, 72, 73]. The fit between the choice of competitive priorities and associated manufacturing decisions determine the strength of manufacturing capabilities. Bottani [7],Jia & Bai [33],Pooya & Tabrizi Moghadam [54] demonstrated modelling of interactions among MS dimensions through House of Manufacturing Strategy (HoMS).

The emerging strategic role of manufacturing has been updated from the functional strategy to the core of business strategy [37, 38]. Such enlightened ‘Manufacturing’, at the core business strategy demands the consideration MS context i.e. business competition, market environment and competitive conditions along with MS content and process [9–11, 18], A. [32].

With the lack of MS context, the mismatch between business environment and market (i.e. MS context), existing manufacturing capabilities (i.e. MS content) and firm resources and business process (i.e. MS process) is inevitable [34, 37, 58, 72]. The misalignment in MS triad may result not only into misguided daily operations but also needless investments in capacity, facility, and process-technologies [10, 12, 70]. Advanced Manufacturing Technologies (AMTs) and Advanced Manufacturing Systems (AMSs) are preferred as the de facto enduring solution to their competitive requirements. These technological breakthroughs may provide initial edge, but require the realignment and reconfigurations in manufacturing systems and business processes for the sustenance [10, 11, 30].

2.2 Modelling MS formulations through house of manufacturing strategy (HoMS)

The updated position at the nucleus of Business strategy implies that MS formulation requires a balanced consideration of strategic triad similar to the business strategy [37, 38]. The strategic triad of MS formulation remains incomplete due to lack of considerations of MS context dimensions. [39] systematically assessed MS definitions and presented the primary elements representing content, process, and context dimensions. Table 1 presents the summarization of MS elements.

In this study, HoMS is updated with consideration of strategic triad- content, process and context for MS formulation. MS formulation is operationalized and modelled using three integral parts HoMS: (1) Sequence of competitive priorities, (Wall) (2) MS elements defining MS across content, process and context dimensions (Roof) as tabulated in Table 1 (3) Ranking and prioritization of critical MS elements (Foundation) as shown in Fig. 1.

The systematic process of modelling HoMS and data collection procedure for the operationalization of Fuzzy-QFD is presented in Sect. 3.

3 Research methodology

Though MS formulation research is under dominance of empirical survey based research, a few analytical exploratory studies have contributed significantly. Such analytical research in modelling interactions is mainly influenced with the business strategy research such as Ganco & Hoetker [21],Ghemawat & Levinthal [22] and Levinthal [48]. Past studies have approached modelling interactions in two ways: (1) Synchronous and (2) Diachronous.

The synchronous modelling approach multidimensionality of the complex interactions among strategic triad [48, 55]. Diachronous modelling approach is aimed to understand the how the earlier choice has influence the later decisions and actions through multi-criteria decision making methods (MCDM). Dror & Barad [17] and Barad & Dror [5], developed the notion of house of MS utilizing quality function deployment (QFD). Bottani [7], Jia & Bai [33] and Pooya & Tabrizi Moghadam [54] demonstrated the application of QFD integrated with Fuzzy systems to model HoMS.

Table 1 MS elements representing MS Content, Process and Context

MS dimension	MS elements	Operational definition	Contributing authors
Content (C)	Competitive priorities **(CP)**	Competitive priorities are set of manufacturing objectives that represent the linkage with the market	[16, 50]
	Distinctive competence **(DC)**	Distinctive competence reflects competitive strengths and the ability to differentiate in the market. Importance and ability of the manufacturing function to achieve the competitiveness position	[23, 56, 65, 75]
	Linkage with business strategy **(LBS)**	A critical part of firms' strategy and consistent with well-coordinated business objectives designed within the context	[4, 16, 65]
	Structure and infrastructure decisions **(SID)**	Patterns of decision that company develop manufacturing capabilities with chosen competitive priorities	[4, 30, 31, 52]
Process (P)	Strategy formulation process **(SFP)**	Justification and alignment of structural and infrastructural decisions with chosen competitive priorities	[8, 59, 69, 71]
	Decision Patterns and Resource deployments **(RD)**	Development and implementation of plans which affect the choice, deployment, and utilization of firm resources to leverage competitive advantage	[20, 67]
	Operational plan and Improvement programs **(OIP)**	The set of structured, time-phased, and evaluated actions that are implemented to improve the manufacturing capability of the firm	[1, 51, 52]
Context (Cx)	Firm-specific emerging notions **(FSN)**	Vital linkage among the role of manufacturing strategy and all operation functions and the emergent paradigms to be proactive in developing future market opportunities by addressing the question of how firms can cope with changing environments	[2, 3, 27, 77]
	Market and competitors **(MC)**	The ability of the firm to integrate, build, and reconfigure manufacturing tasks and resources, aligning with changing the competitive structure, industrial competition, and global customers' expectations	[15, 53, 74]

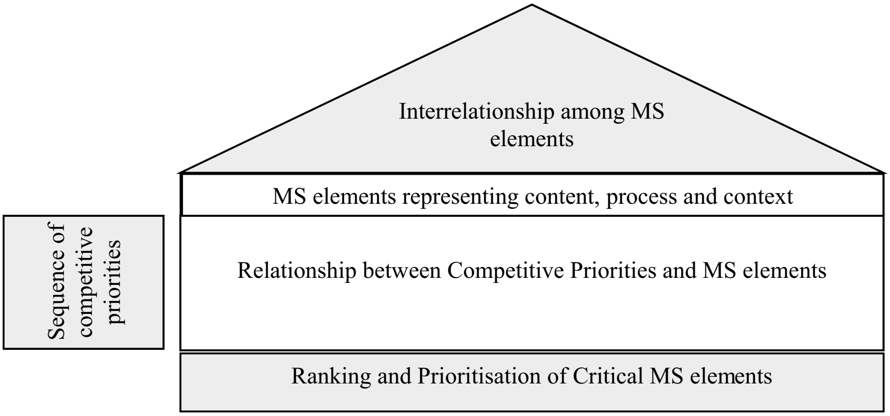

Fig. 1 House of Manufacturing Strategy (HoMS)

This work adopts Fuzzy-QFD to explore firm-specific MS formulation through diachronous modelling. Briefly, Quality Function Deployment (QFD) is utilized as the transformative device linking competitive priorities (“what”) with the MS elements (“how”), while the fuzzy set theory is integrated with QFD to capture inexact information, linguistic judgment inherent vagueness among MS elements.

Fuzzy set theory was introduced by Zadeh [80] and developed as complimenting set theory into multivariate form. Since then fuzzy theory has been advancing significantly towards real life problem solving [40, 42, 45]. Recently, Advanced Fuzzy set theory has been updated with PSK approach towards developing optimal solutions of complex situations [41, 43]. Considering the potential of fuzzy theory to capture vagueness in linguistic judgements, fuzzy set theory is preferred to compliment QFD modelling of HoMS. Thus, Fuzzy-QFD can provide a structured way to capture imprecise inputs (whats) and analysis associated manufacturing decisions (hows) [7, 76].

Vinodh & Chintha [76] highlighted two specific issues in QFD applications. First, there is a lack of formal mechanisms to translate “Whats” (Usually Qualitative) into “Hows” (usually Quantitative). Second, there are very few demonstrations on linking QFD to business process implications. Past studies on modelling content-process interactions are generally conducted in hypothetical or illustrative model settings, but lack generalizable or even firm-specific insights to manage complexities in MS formulation are underexplored.

In this study, Fuzzy-QFD approach to modelling HoMS is updated beyond Jia & Bai [33] and Pooya & Tabrizi Moghadam [54]. Specifically, this work demonstrates inclusion of complete strategic triad. Further, the variations in MS formulations across three case studies with diverse industry backgrounds are presented. Business process deployment as the operational response to MS formulation is recorded through detailed discussions with industry representatives. The modelling of HoMS through Fuzzy-QFD is considered with the four-staged process as shown in Fig. 2.

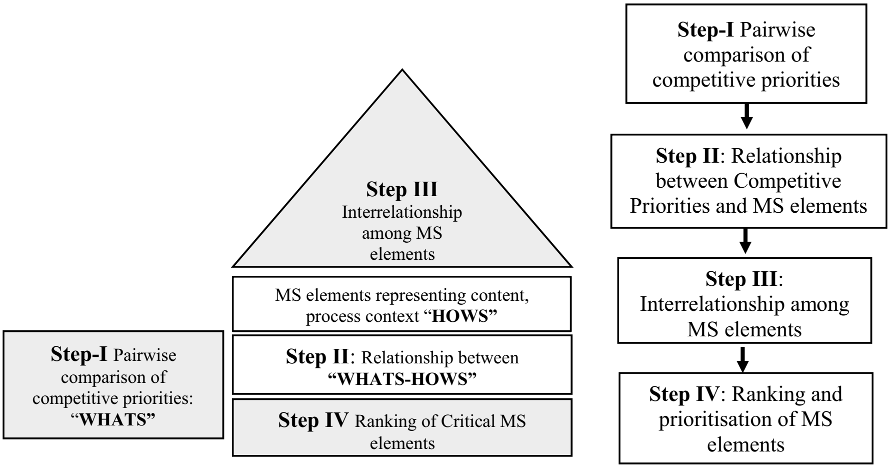

Fig. 2 Fuzzy-QFD approach to MS formulation

1. Determining the relative strategic importance of competitive priorities ("what")
2. Exploring linkage among competitive priorities and MS elements ("what-how")
3. Interrelationship among MS elements (correlation among "Hows")
4. Ranking and prioritization of critical MS elements

Step 1 Pairwise comparison of competitive priorities.

Competitive priorities are used as the "whats" in the QFD matrix, and their relative importance is captured. Table 2 presents scale for capturing competitive priorities-cost, quality, delivery and flexibility is adopted based on previous studies [8, 13, 31, 58].

The fuzzy scale is adopted to capture vagueness and judgment in the industry perspectives of competitive priorities. The linguistic set (Z) was developed to express opinions on the group of attributes adopting similar as an earlier study Vinodh & Chintha [76] as illustrated in Table 3.

$$Z = \{VH; H; L; VL\}$$

Table 2 Scale of competitive priorities

For your manufacturing firm, the strategic importance of ability: (rated on- Very High (Vh), High (H), Low (L), Very Low (VL))	
Cost	To differentiate on lower product cost through increasing labor productivity capacity utilization, production cost reductions
Quality	To differentiate with higher product quality and performance
Delivery	To differentiate with faster and reliable deliveries through production lead time reduction
Flexibility	To differentiate with product flexibility through quick product changeover, design, volume changes

Table 3 Importance weight and corresponding fuzzy number

Importance weight (Wi)	Fuzzy number
Very high (VH)	(0.7,1,1)
High (h)	(0.5,0.7,1)
Low (l)	(0,0.3,0.5)
Very low (VL)	(0,0,0.3)

The importance assigned by the respondents was aggregated using the average operator as described by the following Eq. 1:

$$\text{Importance what} = \left\{ W_i; \quad \text{where } i = 1, 2, 3, \dots, k \right\}$$

$$W_i = \frac{1}{n} \otimes \left(w_{i1} \oplus w_{i2} \oplus w_{i3} \oplus \cdots \oplus w_{in} \right) \tag{1}$$

where, k is a number of "whats" and n is the number of respondents. (k = 4 and n = 4 for each select case). Each element on the importance of what vector is a triangular fuzzy number defined by the triplet,

$$W_i = \left\{ w_{i\alpha}, w_{i\beta}, w_{i\gamma} \right\}$$

Step 2 Relationship between competitive priorities and MS elements.

In this phase, the linkage of competitive priorities and MS elements is explored. Each member from three select firms analyzed the match between the competitive priorities and MS elements. ("what"–"how"). The operational description of MS elements was shared (Table 1) and explained to the participating respondent.

Further, the respondents were requested to express their opinions on correlation scores on competitive priorities and MS elements. We use the linguistic set (U) to express opinions on the group of attributes adopting similar to Vinodh & Chintha [76]. The correlation between competitive priorities and MS elements were rated on the scale: strong, medium and weak.

$$U = \{S; M; W\}$$

Triangular fuzzy numbers (Table 4) are used to quantify the linguistic variables.

The fuzzy numbers obtained for each member were aggregated using the following Eq. 2:

Table 4 Degree of the relationship between "what-how" and corresponding fuzzy number

Degree of relationship	Fuzzy number
Strong (S)	(0.7,1,1)
Medium (M)	(0.3,0.5,0.7)
weak (W)	(0,0,0.3)

$$\text{Score} = \{S_{ij}; \quad \text{where } i = 1, 2, 3, \dots, k; \quad j = 1, 2, 3, \dots, m\}$$

$$S_{ij} = \frac{1}{n} \otimes (S_{ij1} \oplus S_{ij2} \oplus S_{ij3} \dots \oplus S_{ijn}) \tag{2}$$

where k = number of competitive priorities ("whats"); m = number of MS elements ("Hows") and n = number of respondents for each firm type. (here, $k=4$; $m=8$; $n=4$). With the above equation, the matrix of correlation scores between competitive priorities and MS elements ("whats"- "hows") is determined, in which S_{ij} represents an aggregate correlation between i^{th} "what" and j^{th} "how". The S_{ij} is the relative importance score and can be defined by fuzzy a triplet.

$$S_{ij} = \{S_{ij\alpha}, S_{ij\beta}, S_{ij\gamma}\}$$

We can now calculate the weight of MS element ("hows"), averaging the aggregate weighted S_{ij} correlation scores with the aggregate weights of the ''competitive priorities (whats)" w_i, according to Eq. 3:

$$\text{Weight} = \{W_j; \quad \text{where } j = 1, 2, 3, \dots, m\}$$

$$W_j = \frac{1}{k} \otimes [(S_{j1} \otimes w_1) \oplus (S_{j2} \otimes w_2) \dots \oplus (S_{jk} \otimes w_k)] \tag{3}$$

Step 3 Interrelationship among MS elements.

This step is followed by the development of a correlation matrix, which expresses the correlation between jth and j'th ($j, j\prime = 1, 2, 3, \dots m, j \neq j\prime$) MS element. The correlation entry is defined as $T_{jj\prime}$.

We use the linguistic set (C) to express opinions on the group of attributes adopting similar to Vinodh & Chintha [76]. The correlation between competitive priorities and MS elements were rated on the scale: *Strong positive (SP), Positive (P), Negative (N), strong Negative (SN).* Table 5 shows the degree of correlation among MS elements and corresponding fuzzy numbers

$$C = \{SP; P; N; SN\}$$

Step 4 Ranking and prioritisation of critical MS elements.

The total score is evaluated for the jth MS elements can be computed using the following Eq. 4 based on previous studies such as Bottani [7] and Vinodh & Chintha [76],

Table 5 Degree of correlation among MS elements and corresponding fuzzy numbers

Degree of relationship	Fuzzy number
Strong positive (SP)	(0.3,0.5,0.7)
Positive (P)	(0,0.3,0.5)
Negative (N)	(−0.5, −0.3,0)
Strong negative (SN)	(−0.7, −0.5, −0.3)

$$\text{Score}_j = W_j \oplus \sum_{j=j'}^{n} T_{jj'} \otimes W_j, \quad j = 1, 2 \ldots, m \tag{4}$$

The $score_j$ are the triangular fuzzy values defined by the fuzzy triplet.

$\text{Score}_j = \{\text{Score}_{j\alpha}, \text{Score}_{j\beta}, \text{Score}_{j\gamma}\}$.

It should be noted that $Score_j$ describes a computation between fuzzy numbers; thus the resulting score of MS elements is a fuzzy number too. To rank the critical MS elements, the scores need to be defuzzified. Jia & Bai [33] suggested the crisp value for the triangular fuzzy number a (α, β, γ) can be described as shown in the following Eq. 5.

$$\text{crisp score} = \frac{\alpha + \beta + \gamma}{3} \tag{5}$$

3.1 Data collection

The data collection is carried out using- a) Selection of target firms b) Selection of industry experts at strategic and managerial levels affiliated with target firms.

3.1.1 Selection of firms

Firms are selected representing the different industry contexts such as automobiles, machine tools manufacturing, heavy engineering, plastic molding, consumer goods, chemical industry, furniture manufacturing, additive manufacturing and sampled 8 manufacturing firms present in India with proven records of manufacturing process mastery with Quality Management Systems (QMS) certification. Out of 8 contacted firms, 3 firms agreed to participate in the research. The company profile, firm size, and sector information are summarised in Table 6.

3.1.2 Selection of industry experts affiliated to select firms

The selection of industry representatives was carried out at two levels: (1) Strategic level and (2) Operational levels. A Manufacturing leader representing the select firm and spearheading the strategic formulation at the firm level with more than 20 years of industrial experience is selected to represent the strategic level of the firm. Three divisional managers from each of the select firms with at least 5 years of industrial experience are chosen as operational level representatives to explore tactical perspectives on MS formulation.

In this way, we engaged 3 strategic level and 9 operational level experts from select three firms for the data collection purpose. Table 7 shows the industry experts representing strategic and managerial levels select firms. We now explain data collection from representing select firms- Company A (GRAO, M1,

Table 6 Summary profile of participating firms

Company	A	B	C
Product range	Rapid prototyping and manufacturing of assortments jewelry, engineering, automotive, architecture, consumer goods	Manufacturing molds and plastic components, utensils and toys. Tier II supplier of leading automotive industries	Design, development, and manufacturing of Special Purpose Machine (SPMs), machine tools manufacturing
Firm size	Medium	Small	Large
Firm type	Private limited	Partnership	Private limited
Sector	Jewelry manufacturing, engineering services	Auto-component industry, plastic molding industry	Machine tool manufacturing
Market	Domestic and international	Domestic and international	Domestic and International
Divisions/FWFs	Jewelry	Plastic molding	Special purpose machine division
	Engineering services	Auto component division	Foundry
	Medical division	Toolroom	Spindle manufacturing division

Table 7 Industry experts representing strategic and operational levels of select firms

Affiliation		Position	Division	Experience (years)	Key Responsibilities
Company A	GRAO	Director and mentor	Firm-level	30	Being the motive force as a mentor for the team that engages in capturing the voice of the customer and convert practically feasible products
	M1	Manager and production head	Jewelry	7	Production planning and control, performance monitoring for jewellery division
	M2	Manager and head quality-dept	Engineering services	9	Design, development and rapid prototypes and rapid tooling with direct customer involvement. Also heading quality and process control dept for the firm
	M3	Manager, head- new product development	Medical division	8	Design, development with medical implants with direct associations with patients, orthopedic doctors, and dental surgeons
Company B	VSUBBA	Partner and owner	Firm-level	22	In charge of the entire organization as an owner looking after manufacturing, PPC, quality, purchasing, financial functions
	S1	Production head-	Plastic molding	6	Manufacturing and quality control of plastic molds, injection molds
	S2	Manager- auto component division	Auto component division	6	Production, planning, and scheduling for auto-component supply. Also, in charge of continuous improvement (CI) initiatives
	S3	Design- manager	Toolroom activities	8	In charge of tool room activities involved in the design, development of jig, fixtures, and molds

Table 7 (continued)

Affiliation		Position	Division	Experience (years)	Key Responsibilities
Company C	SRSETH	Director, independent strategic consultant	Firm-level	35	Strategic planning, manufacturing strategy development, managing and coordinating operations of all SBUs and manufacturing component divisions
	N1	Head-special purpose machines	Special purpose machine division	29	Machine tool design & development with setting up a manufacturing line
	N2	Foundry-plant manager	Foundry	28	Responsible for production, planning, process control of foundry division
	N3	Spindle manufacturing- Plant head	Spindle manufacturing division	25	Fulfilling the internal and external customer requirements for the spindle. Also, heading process planning, continuous improvement for the firm

M2, M3); Company B (VSUBBA, S1, S2, S3) and Company C (SRSETH, N1, N2, and N3).

3.2 Application of fuzzy-QFD model

The fuzzy-QFD approach is applied in the select three firms following through with four-staged process: (1) Plant visit and Gemba walk, (2) Semi-structured interviews with industry experts representing strategic levels. (3) Quantitative measures on the desired sequence of competitive priorities, MS element linkage at strategic and managerial level. (4) Discussions on the validations of the results at the firm level decoding business processes and operational plans.

The daily operations and ongoing plant activities reflect the implementation of MS formulation. Thus, Gemba walk and plant visits are preferred to observe the actual manufacturing process and explore the day-to-day operations [49, 51]. Semi-structured interviews with industry experts representing the strategic level of the select firm to explore MS formulation. Such interactions enabled the opportunity for the interviewees to think about topics, themes, and core content in a new way and to reflect upon and link their experiences and perceptions.

The quantitative inputs on- Relative strategic importance of competitive priorities (step 1), Linkage among competitive priorities and MS elements (step 2) and Interrelationship among MS elements (step 3) are used as the inputs to Fuzzy-QFD framework. The details of the collected data are summarised in Annexure 1.

Using Eq. 1–5, Fuzzy-QFD model is operationalized to evaluate the crisp scores to assess the ranking of MS elements. Table 8 summarises the results depicting the preferred sequence of competitive priorities and critical MS elements for companies A, B and C. The detailed quantification of crisp scores is presented in Annexure 2.

Table 8 Summarised HoMS for company A, B, and C

DC
LBS
SID
SFP
RD
OIP
FSN
MC

Competitive Priorities				Content			Process			Context	
				Distinctive competence (DC)	Linkage with BS (LBS)	structural and infrastructural decisions (SID)	Strategy formulation process (SFP)	Resource deployment decisions (RDD)	Operational improvement programs (OIP)	Firm specific notions (FSN)	Market competitors (MC)
	A	B	C	A B C	A B C	A B C	A B C	A B C	A B C	A B C	A B C
Quality	0.86	0.90	0.90								
Delivery	0.73	0.78	0.66								
Flexibility	0.82	0.78	0.90								
Cost	0.46	0.62	0.23								
Prioritization of critical MS elements											
Company A				**1.82**	1.55	**1.91**	1.59	1.61	1.59	**1.95**	**1.89**
Company B				**1.98**	1.81	**2.02**	1.93	**2.11**	**2.02**	1.94	1.96
Company C				**2.04**	1.91	**2.03**	1.78	**1.97**	1.87	**2.06**	1.90

We discussed the shared sequence of competitive priorities and the ranking of MS elements to validate the results with participating experts. Managers generally agreed upon their MS formulation and their firm-specific understanding of the approach adopted.

4 Results and discussions

The results of fuzzy-QFD based MS formulation are discussed at two distinct levels- within firm-level and across firm levels. The within-firm analysis helps in the understanding of firm-specific investigations on MS formulation. MS formulation at the firm level is discussed considering: (1) Firm-specific sequence of competitive priorities reflecting strategic emphasis, (2) Critical MS elements based on crisp values for MS elements (3) Supporting industry experts' interview quotes to state implications of MS formulation across business processes and operational plan. Further, the across firm analysis provides an opportunity to look beyond initial firm-specific impressions and explore the variations across multiple firms.

4.1 Competitive priorities and MS elements

Table 8 shows the crisp values on the relative strategic emphasis of manufacturing capabilities and MS elements. Such preference can be referred to as the competitive priorities representing the competitive requirements of the firm [8]. The crisp values for manufacturing capabilities of company A are 0.86, 0.82, 0.73 and 0.46 for Quality, Flexibility, Delivery and Cost dimensions respectively. That is, Company A emphasizes *Q-F-D-C* as a firm-specific sequence of developing manufacturing capabilities.

The computational procedure Fuzzy-QFD is utilized to obtain the crisp values for MS elements. The higher crisp values represent the criticality of the MS element to achieve the expected competitive positioning of the firm. The computation of the crisp scores for company A shows firm-specific notion (FSN) and market competitors (MC) have higher crisp values 1.95 and 1.89 as presented in Table 8. Interestingly, the crisp values for MS content dimensions (structural and infrastructural decision (SID) and Distinctive competence (DC) are higher than the MS process. This suggests that developing distinctive competence with higher investments in new processes and technology needs the implementation priority for company A.

The critical MS elements provide the empirical support for the MS definitions shared by the strategic designer of the firm in the interview. He defines MS definition for his firm as- *"Our manufacturing strategy can be defined as the Customer-driven agile product creation, which is in synchronization with demand reservoir. The demand reservoir is the funnelled opportunities, which need customization or highly complex in batch quantity up to a single product. This is driven by a core think tank of experts & leaders bolstered by the state of the art lean infrastructure."* The crisp scores for the competitive priorities of company B are 0.90, 0.78,0.78 and

0.63 across Quality, Flexibility, Delivery, and Cost respectively. This represents the strategic emphasis of company B as *Q-F-D-C*.

The computation of fuzzy-QFD based crisp values shows MS process elements such as Decision patterns and resource deployments (RD) and Operational improvement programs (OIP) have the greater crisp scores (RD-1.98 and OIP-2.02) followed by DC and SID. This implies that RD and OIP with higher crisp scores are critical towards competitive requirements. The operational decision such as quality management, production planning, and control (PPC), process control and operational improvement through best practices form the core of MS formulation for company B.

The views on MS of shared by the owner as the strategic leader of company B reflect with the crisp scores and criticalities among MS elements. He quotes in the detailed interview on MS as- *"Winning plan for customers by exceeding the competitors' performance with a complete solution of quality and technological requirements. Being a quality driven company, I want to develop a system that can proactively work for quality, safety as the environment. For that, we will be concentrating on process-related improvement. However, for the long-term, I want to develop, my organization as a solution for all activities under one roof like we say-one stop solution."*

The crisp values on the competitive priorities show *Q-F-D-C* as the preferred strategic emphasis of company C. Fuzzy-QFD computation based crisp values rank FSN and SID, followed by DC and RD as the critical. The developing the distinct vital, rare and inimitable resources [6, 20, 67] is the central thread for MS in company C.

The critical MS elements also align with the industry definition of MS shared by the strategic management of the company C. He defines MS definition for the company C as- *"Manufacturing Strategy is at the core of any business strategy that aims to achieve global competitiveness, create value for all stakeholders, transform and be future-ready and continuously raise the bar on sustainability through the innovative and collaborative pursuit of manufacturing excellence."*

4.2 MS formulations across select firms

We select the unit of analysis for this study as companies A, B, and C, representing diverse industrial contexts. Despite their contextual variations, all the participating firms regard "*Quality*" capability as the fundamental enabler for the manufacturing capabilities development. The crisp score for quality dimensions (A- 0.86, B- 0.90 and C- 0.90) are greater than rest other dimensions of manufacturing capabilities. One of the industry experts we interviewed reciprocated the significance of Quality dimensions and we quote- "*Quality is the trust-bridge that connects our products with the customer. We prioritize Quality development at the core of strategy as our operational excellence relies on that foundation.*

Further, the crisp values for DC and SID are significantly higher (For instance—A: 1.82, 1.91; B: 1.98, 2.02 and C: 2.04, 2.03). The agreement of higher values of DC and SID shows the importance of manufacturing function as the enabler of competitive advantage. The higher values of DC and SIP also provides the empirical support to the classical functional view of MS as- "*A pattern of decisions both structural and infrastructural, which determine the capability of the manufacturing system and specify how it operates to meet set manufacturing objectives which are consistent with business objectives*".

4.3 Strategic response to develop distinctive competence

We share initial results of the crisp values and operational priorities of the company with responding representative teams. The purpose of this validation is to understand the process of developing distinctive competence with manufacturing choices at structural and infrastructural levels similar to previous studies such as [24, 25]. These discussions cover several aspects such as: (1) Recent technology jumps and reasons, (2) Strategic response to develop distinctive competence (3) Time-lapse between two successive technology jumps (4) Business process implications of technology leap (5) Operations improvement programs (if any). Considering these discussions, we derive the position of the firm with respect to the performance frontier. Table 9 presents a summary of these discussions demonstrating variations in the strategic response across firms.

Specifically, Company A adopts various 3D printing technologies, as their way to cater to unique and complex customer requirements from jewelry, engineering services, and medical aid sectors. The firm quests for technological superiority through continually scanning and scouting for advances in 3D printing technologies, and thus compete on the manufacturing and design flexibility in their manufacturing systems. One of the managerial representatives expressed, "*Our Focus is not restricted to 'how good the organization is', but 'how fast we are getting better'. In our 3D printing domain, much smaller but the potential players (maybe more constrained today) able to leapfrog us by radically new technology and able to surmount the technological and value chain challenges"*. Further discussions with managerial teams also reveal that agility in accommodating customer demands, economies of scope, the responsiveness of manufacturing systems and reconfigurations of manufacturing systems are the pillars of operations strategy. The scope of work standardization, operational improvements through efficiency improvement measures and economies of scale is minuscule.

The frequent technology leaps through 3D printing technologies adoptions, the number of new products engineered indicate the position of company A is on the performance frontier. There is hardly any scope for operational improvements as both aspects-operating and asset frontier of the performance frontier are coinciding with each other, in concurrence with findings of Schmenner and Swink [63] as illustrated in Table 9.

Our discussions with managers of company B reveal that the strategic thrust of the company is to enhance the customer-centric approach in both domestic as well international markets leveraging options developed via advanced molding and plastic technologies through operational excellence. The plastic manufacturing sector

Table 9 Variations in strategic response for developing distinctive competence

Company	Advanced technology implementation	Strategic response	Time-lapse between successive technology leaps	Scope for the operational excellence	Firm position with respect to performance frontier
A	3D printing	Scouting and adopting technology solutions faster than competitors	Too short	Least	Operating frontier overlaps with the Asset frontier. Technology leaps enable the movement of both asset and operating frontier
B	Computer-aided design (CAD) for dies and molds, and computer integrated manufacturing systems (CIMS)	Proactive technology jumps and followed by a focus on operational excellence to leverage the customer-centric approach in both domestic and international markets	Too long impermeable due to competitive/innovation gridlock	Higher	Operating frontier approaching the asset frontier
C	Strategic split to develop multiple focused factories-broad range unit and specialist unit	Broad range unit: competing on new product and flexibility through product innovation	Short	Moderate/less	Moving upward
		Specialist unit: competing on cost efficiencies through process innovation	Moderate-to-short	Higher	Moving downward

experiences the cutthroat competition and many small start-ups emerge daily. But these start-ups perhaps end up simply being unable to keep up the pace of operating improvements established as industry benchmarks.

The discussions with company officials signified two challenges- First, with plastic molding and dies technologies, product differentiation has become the order qualifying criterion in plastic manufacturing. Additionally, the plastic sector is under critical innovation gridlock as not many disruptive technologies are emerging up. One of the company B managers reflected, "*The focus is concentrated on the subtle adaptations in our operations, though apparently simpler and straight forward, but towards the competitive excellence. Plastic molding is the game of newer design/variety at the same time the lowest possible cost. We are working on product innovations with the integration of Computer Aided Design for dies and molds, product simulations. On the other side, environmental norms are very stringent in our industry, we are working on the optimization of our processes through the design of experiments, Six Sigma to reduce of defects, manufacturing lead time, single minute exchange of dies (SMED) to reduce the cost of production and enjoy more margins in both domestic and international markets*."

Cost improvisation and Delivery oriented initiatives such as scheduling, manufacturing lead time reduction, manufacturing velocity improvisation, global dispatch scheduling are practiced as part of continual improvement initiatives to reach out to domestic and overseas customers. However, Cost efficiency and operational improvement initiatives cannot be the long term enduring tactics for the plastic manufacturing sector. Further probing on this point, the responding team reveals that composite plastics fabrication is one of the forward-looking technological leaps, however, it is a relatively unexplored area, associated market economics, technology commercialization is yet to be developed.

Company B is approaching its performance frontier with the operational improvement tactics and economies of scale. The operational benefits with such initiatives would be seized off as the firm reaches its performance frontier limits. Researchers shared the innovation gridlock in the plastic manufacturing sector while performance gridlock due to approaching frontier may adversely affect the businesses of company B as explained in Table 9.

The adoption of advanced technology in the machine tool manufacturing sector is reactive and slower, despite a higher rate of advancing manufacturing technologies. Firms often prefer to limit with their existing powerful customers and neglect modern technologies as these technological disruptions have little differentiating appeal to their existing customer base. Understanding these contextual dynamics, company C has strategically split its operations into different manufacturing focus- Broad range unit and Specialist unit. The broad range unit focuses on process innovations and improvise on the cost efficiencies. The specialist unit is engaged in introducing new product variants to execute the technology push. Company C representative expressed on the strategic thrust, "*New wars cannot be won with older and obsolete weapons. We are experiencing the* *business cusp, one side we have to have economies of scale for our customers, but need to innovate for the future. Bifurcating manufacturing focus may enable us to respond to this unique and unprecedented strategic challenge."*

Separating the manufacturing focus has enabled company C to reposition along the performance frontier. The broad range unit is expected to reconfigure product differentiation through technology innovations while a specialist unit to cater the routing customers with cost and delivery efficient manufacturing systems.

4.4 MS formulation as an enabler to manufacturing competitiveness

The results of this study show two novel findings- first, the competitive priorities sequence (*Quality-Flexibility-Delivery-Cost)* for select firms differ from the classical sand cone sequence (i.e., *Q-D-F–C* by [19, 66]. Second, even with a common cumulative capabilities sequence, select three firms show the unique way of the realization of MS and developing their distinct competence through varying prioritization of MS elements. Subsequent discussions with company representatives show the approach to MS formulation and the stress given to critical MS elements exhibit the idiosyncratic and complex nature of strategy, as suggested by Rivkin [57].

The emphasis on "Flexibility" in the updated sequence configuration- *Q-F-D-C* than the traditional sand cone sequence is more vivid. This difference in the updated sequence may be attributed to specific reasons: (1) Changes in market requirements due to shorter product and market life cycles, and (2) Recognition to "Flexibility" as "Order-Qualifying" criteria in emerging manufacturing sectors.

The contextual incorporation of *Flexibility* reflects the dynamic capabilities of the participating firms. The firms strategize their manufacturing with the flexibility as a dynamic capability dimension to reduce vulnerabilities against internal as well as contextual changes with a little compromise on cost and delivery. Externally, firms are seeking to adopt advancing technologies to address rapidly changing business environments. Internally, firms opt to shift upward in north-west directions of the volume-variety matrix with adopting mass customization, flexible manufacturing systems, additive manufacturing systems, JIT systems.

Despite common sequence (*Q-F-D-C*), select three firms show the unique way of the realization of MS through varying prioritization of MS elements. The emphasis given on a MS element differs significantly. Our discussions with industry managers reveal that, firms do make the conscious choices of manufacturing decisions and implement their MS elements These MS elements are broad and the shades of multiple dimensions of structural and infrastructural choices are imbibed into the MS elements. Thus, MS implementation will naturally be idiosyncratic to the firm's competitive requirements, and mere imitation or copying of MS elements or terms associated are inadequate to provide a competitive edge to the firm.

One of the industry experts shared an interesting argument on the complexity of manufacturing as- "*Manufacturing is all about user experience and not with mere production of finished goods. All you are delivering in manufacturing is user experience and not mere products. Products are incidental. Manufacturing processes are* *not only converting raw materials but are creating or enabling the user experience. Manufacturing can influence how customer selects, purchases or evaluates. Or customer can influence the design, manufacturing. Or external context like environmental policies can influence both customers as well as manufacturing. All of this put together into a complex network is called as the manufacturing, and your strategic success lies in that complexity.*"

This study contributes to MS theory in following ways: (1) Firm-specific exploration of MS formulation to leverage AMTs is relatively under-researched domain, study contributes to MS formulation building on previous studies such as Jia & Bai [33] and Vinodh & Chintha [76]. (2)Traditionally, dichrounous modelling consider content, and process dimensions only. However, this research adopts MS elements representing strategic triad- Content, Process and Context. (3) The results show the sequence of competitive priorties as *Q-F-D-C*, that is different than traditional sandcone sequence- *Q-D-F–C*, representing Flexibility as critical performance dimensions. (4) Exisiting F-QFD model illustrations are generally conducted in hypothetical or illustrative model settings, this work demonstrates variations in MS formulations across three case studies with diverse industry backgrounds. Further, business process deployment as the operational response to MS formulation is recorded through detailed discussions with industry representatives.

The proposed model helps to deploy MS formulations considering inclusive MS triad. The diachronous linkage between competitive priorities and MS elements can avoid the risk of misalignment or the internal fit with the strategic requirements of the firm. Such linkage can help in streamlining cross-functional efforts in deployments of business processes and operational plans according to competitive requirements. The ranking of critical MS elements can be utilized to prioritize and devise improvement plans for leveraging AMTs and AMSs.

The firm-specific exploration of MS formulation in synchronization with technological breakthroughs can provide crucial insights into the effective management of AMTs. Additionally, the idiosynchronous characteristics of MS formulation signify the resource-based and dynamic capabilities views in developing manufacturing competitiveness. Further studies may be designed explicitly considering strategy theories highlighting the position of manufacturing at the nucleus of business strategy.

5 Conclusion

MS is advocated as the fundamental enabler of manufacturing competitiveness. Little research, however, exists on the industry perspectives to be practically adapted to formulate MS [35, 36, 64, 70]. This study is conducted to explore MS formulation to leverage AMTs with an integrated approach of Fuzzy-QFD. Fuzzy-QFD approach provides a scientific way to prioritize critical MS elements and exploit strategic and operational choices The study provides evidence to the idiosynchronous characteristics of MS and highlight importance of unique interactions among strategic triad- Content, Process, and Context. Despite common sequence (*Q-F-D-C*), firms show the unique and idosynchronous way of the realization of MS through varying prioritization of MS elements. The variations in approaches to MS implementation through different critical MS elements can help to explain why some firms have winning and unmatchable strategies even though they are open to public scrutiny. Firm-specific response to strategic elements and inter-elemental interactions (variations in critical MS elements) can be both- unique and the source of competitive edge.

A few limitations and future directives of the study can be summarized as follows. It should be noted that the finding presented are case-based, exploratory, and indicative, thus have limited scalability. Golpîra [26] stated fuzzy set theory has limited applications for larger-scale problems. Therefore, the complementary methods to capture the vagueness in MS formulation need to be developed to excel in the scalability of further studies similar to previous studies such as [44, 46]. Another limitation of this study is, MS formulation is considered with dichronous modelling to HoMS. The synchronous modelling of HoMS may be explored in the future research.

Present study findings reveal that modern firms do rely on periodic breakthroughs in the form of AMTs. Such periodic jumps may have two essential challenges. First, the firms need to invest its capital frequently in the technology disruptions as the solution to operating challenges. Second, the periodic technology adoptions may create confusion and chaos in the manufacturing systems and formulating MS. The future research need to be directed to explore firm-specific investigations on advanced technology enablement focusing on- "*How technology-based firms achieve strategic focus, manage their operations strategic transitions, and sustained in turbulent times*?" The strategic response to leverage AMTs through MS formulation can be modelled using tangible inputs and outputs. Such inputs may include manufacturing resources, capital. The output parameters may consist of operational capabilities (*Cost, Quality, Delivery, and Flexibility*) and business performance parameters (*Market share, profitability, Return on investments*).

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Declarations

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