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Received July 2009
Revised February 2010
Accepted March 2010

The role of modularity and integration in enhancing manufacturing performance

An absorptive capacity perspective

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Abstract

Purpose – The purpose of this paper is to examine the impacts of modularity-based manufacturing practices (MBMP) and manufacturing system integration (MSI) on manufacturing performance (MP) using absorptive capacity as an important enabling factor.

Design/methodology/approach – Constructs were developed through a comprehensive literature review. Structural equation modeling was used to test the research model and hypotheses based on a large sample of 303 US manufacturing firms.

Findings – Both MBMP and MSI have significant impacts on MP. The positive effects of MBMP on MP are stronger than those of system integration. The absorptive capacity of a firm facilitates better use of modularity practices and system integration.

Practical implications – More attention should be given to modularity practices in resource allocation planning. Also, system integration together with modularity practices can generate significantly higher MP.

Originality/value – The paper is the first large-scale empirical study to examine the effects of absorptive capacity on MSI and MBMP, which in turn impacts MP. Furthermore, the findings empirically support that a combination strategy of modularity and system integration can help manufacturing firms to achieve higher performance.

Keywords Integrated manufacturing systems, Operations and production management

Paper type Research paper

Journal of Manufacturing Technology Management
Vol. 21 No. 7, 2010
pp. 818-838
© Emerald Group Publishing Limited
1741-038X
DOI 10.1108/17410381011077937

1. Introduction

Champlin and Olson (1994) summarized three revolutionary change forces in the post-industrial manufacturing era – global competition, technology advancement, and new managerial practices. Research indicates that the traditional managerial philosophy of control and stability is no longer sufficient in the post-industrial environment.

Instead, new managerial thinking should emphasize organizational learning capabilities and flexibility (Benner and Tushman, 2003; Yeh, 2008). Although new technologies offer firms new strategic options, a challenge exists in effectively managing both the technology itself and the people using it, in a manner that promotes organizational learning. This study attempts to explore the factors affecting manufacturing performance (MP) (i.e. cost, quality, delivery, flexibility, and innovation) when firms are faced with the above challenges.

High MP is made possible through the effective use of new technologies, such as integrated advanced manufacturing technologies (AMT) (e.g. computer-aided design and manufacturing (CAD/CAM), flexible manufacturing systems (FMS), and computer integrated manufacturing systems (CIMS)) and modularity-based manufacturing practices (MBMP). Although FMS make variety more economical and MBMP enhance manufacturing flexibility, many firms do not realize the full benefits offered by these new technologies (Nahm *et al.*, 2003; Binder *et al.*, 2008). Failed or partial implementation can result in some technologies being pulled from use.

An early study by Jaikumar (1986) showed that USA was not using AMTs as effectively as Japan. The US installed FMSs showed an astonishing lack of flexibility in terms of variety of parts produced per system and machine utilization. A later study by Mansfield (1993) also indicated that US firms have been slower in assimilating FMS technologies due to the actual rate of return being lower in the USA than elsewhere. Jaikumar (1986) indicates that:

> [. . .] the technology itself is not to blame; it is management that makes the difference [. . .] The technology was applied in a way that ignored its huge potential for flexibility and for generating organizational learning.

This ability to exploit and assimilate knowledge and technology, thus generating effective organizational learning is referred to as a firm's absorptive capacity (Cohen and Levinthal, 1990). Absorptive capacity results from the cumulative effect of continuous learning. Existing literature indicates that prior related knowledge and the effectiveness of organizational communication processes are major constituents of absorptive capacity (Malhotra *et al.*, 2005). Therefore, firms with higher absorptive capacity are more likely to succeed in implementing new technologies because they have more related experiences or have a more effective communications infrastructure.

Given the value of a firm's absorptive capacity, this study considers it as a primary determinant of the effective use of new manufacturing technologies and practices, as illustrated through modularity-based manufacturing practices and integrated AMT systems. Despite such antecedent positioning, however, scant empirical research has been completed to test this important relationship. To empirically assess the relationship of which modularity is used by a firm and its absorptive capacity, a research framework is first proposed in Section 2. Constructs and models are tested in Sections 3 and 4, followed by discussion of research findings and implications.

2. Theoretical research framework

Hayes and Pisano (1994) suggest that fragmented markets and fierce global competition demand greater strategic flexibility of manufacturing firms. Strategic flexibility is based on the notion of economies of scope that greater variety can be more economical due to the sharing of technology, knowledge, and learning experiences. Economies of scope have become the very foundation of an entirely new manufacturing strategic paradigm, "mass customization" (Pine, 1993), whose goal is to produce customized products at mass scale without sacrificing efficiency and increasing cost (Anderson and Pine, 1997). Existing literature indicates that a firm cannot achieve mass customization capability without meeting certain prerequisites, particularly technological requirements (Doll and Vonderembse, 1991).

Modularity strategy has also become a viable way to achieve mass customization and its use brought certain advantages to the firm. The primary advantage is that firms are able to decompose a complex system into simpler subsystems by using modularity architecture. This decomposition results in concurrent product designs, concurrent production methods, and easier outsourcing. Second, firms are able to benefit because post-modularity, a change in one module does not require changes in other related modules, which results in faster product introduction. However, Ulrich (1995) suggests that modularity provides only local optimization of a product's performance while integration can achieve better global performance of a product. Therefore, it is better to strategically combine modularity and manufacturing system integration (MSI).

Some studies have explored the relationship between modularity and integration. Jacobs *et al.* (2007) proposed that integration strategies (such as supplier integration, design integration, and manufacturing integration) mediate the relationship between product modularity (PM) and competitive performance. Their study views modularity and integration as a synergy because modules often link together through interfaces, which are purposefully integrated.

Current research identifies two important categories of new technology and practice as enablers of MP:

(1) integrated AMT such as CAD/CAM, computer-aided process planning, computer numerically controlled machines, and FMS (Hill, 1994); and

(2) MBMP, such as PM, production process modularity (PRM), and dynamic teaming (DT) (Tu *et al.*, 2004).

Utilizing modularity applications in different aspects of manufacturing makes quick product-line changeovers economical and feasible.

However, mere possession of the newest technologies will not create sustainable advantage. Clemons and Row (1991) indicate that when the same equipment is available to all firms and most applications can be easily duplicated; sustaining technology advantage arrives from the effective use of technology. Therefore, in the knowledge intensive, highly uncertain post-industrial environment, firms must closely study the competitive environment and identify the primary factors that constitute a firm's ability to effectively implement and absorb the specific knowledge and technology that actually improves performance. This critical learning and knowledge absorption capability helps to establish a firm's strategic flexibility.

To capture these potential relationships, we propose the theoretical research framework shown in Figure 1. Although other construct may contribute to the proposed relationships shown, this study focuses only on these four constructs. The following sections will provide a literature review of each major model construct. Research hypotheses are then developed and presented based on the review. The numbered arrows correspond to the hypotheses to be developed.

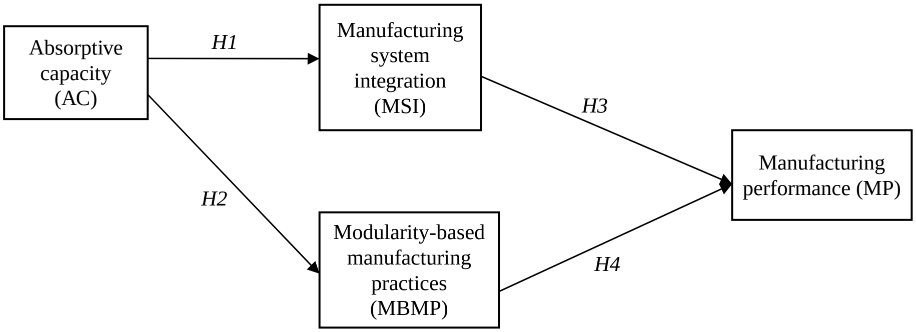

Figure 1.
Theoretical framework

2.1 Theory development

This study proposes significant relationships between four major manufacturing constructs: absorptive capacity, MSI, MBMP, and MP. Table I summarizes these constructs and their relevant literature basis.

2.2 Absorptive capacity of manufacturing firms

The concept of absorptive capacity originated from macro-economics, where it refers to the ability of an economy to utilize and absorb external information and resources. Although some researchers have recently applied absorptive capacity to the individual level (Chou, 2005), Cohen and Levinthal (1990) first adapted this concept to the organizational level and defined it as "the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends". They argued that absorptive capacity is largely an organizational learning concept and is therefore the cumulative effect of continuous learning. In the current study, absorptive capacity is a function of the firm's existing level of knowledge base, its knowledge scanning (KS) capability, and the efficacy of its communication processes.

Construct	Definition	Literature
Absorptive capacity	Organizational mechanisms to identify, communicate, and assimilate relevant external and internal knowledge	Cohen and Levinthal (1990), Zahra and George (2002), Tu *et al.* (2006)
Manufacturing system integration	Physical connections and information flows among the manufacturing system components	Vonderembse *et al.* (1997), Frohlich and Westbrook (2001), Chikan (2001), Gimenez and Ventura (2005)
Modularity-based manufacturing practices	A set of actions that enables firms to achieve modularity in product design, production process design, and organizational design	Ulrich and Tung (1991), Baldwin and Clark (1997), Feizinger and Lee (1997), Tu *et al.* (2004)
Manufacturing performance	The level of attainment of various manufacturing objectives, which are commonly considered to include cost, quality, delivery, flexibility, and innovation	Hayes and Pisano (1994), Boyer and Lewis (2002), Rosenzweig *et al.* (2003), Swink and Nair (2007), Liao and Tu (2008)

Table I.
Construct, definitions and literature

Academic research on absorptive capacity is relatively recent (Malhotra *et al.*, 2005; Tu *et al.*, 2006). A recent study by Tu *et al.* (2006) proposes that a firm's absorptive capacity should have four major components: existing knowledge base, communication network, communication climate, and the firm's KS mechanism to explore knowledge unknown but useful to the firm.

The existing knowledge base is defined as the existing facts and ideas of individuals in the organization that can influence the process of implementing organizational innovations. The knowledge base includes both general employee and managerial knowledge. Cohen and Levinthal (1990) suggest that prior related knowledge is a major determinant of absorptive capacity, just as an individual will learn subjects faster with prior knowledge. Technological knowledge is essential to a firm's knowledge base and to developing its absorptive capacity.

A communications network (CN) is defined as the scope and strength of structural connections that can bring flows of information and knowledge across different organizational departments. This flow process is frequently referred to as functional integration. Effective communication and knowledge diversity are considered as key generators of a firm's absorptive capacity (Cohen and Levinthal, 1990).

The communications climate (CC) is defined as the cultural factors that form the organizational atmosphere towards accepted communication behavior, which may facilitate or hinder the communication processes. These factors may include openness, value orientation, support, trust, experimental mindset, and willingness to change. There is a general agreement that organizational learning is based on the learning of each individual member (Nicolini and Meznar, 1995). Thus, a firm's absorptive capacity is ultimately realized through each individual's learning performance.

KS is defined as the examination mechanisms that enable a firm to effectively identify and exploit relevant external and internal knowledge and technology, and then apply them to specific needs of the organization. Many activities signify the existence of such a mechanism in an organization. Employee training (Cohen and Levinthal, 1994) and inter-organizational learning activities may serve as effective KS activities (Levinson and Asahi, 1995).

2.3 Manufacturing system integration

The definition of MSI particularly emphasizes the degree of AMT unit integration in the system (Small and Chen, 1997). Extensive use of AMTs may result in a highly automated manufacturing system, but this does not necessarily mean that the technologies are being used effectively and working harmoniously together. The level of technology integration could be a much more important issue (Burcher *et al.*, 1999).

According to Cooper and Zmud's (1990) technology implementation stage model, routine technology use is not the final stage of integration. In the infusion stage, technology is used to its fullest potential and increased organizational effectiveness is obtained by using the technology in a more comprehensive and integrated manner. Vonderembse *et al.* (1997) found that firms tended to automate specific tasks to solve local problems which often resulted in "islands of automation", which were incapable of responding quickly to rapidly changing customer needs. Thus, firms should first focus on integration across the value chain, and then focus on automating activities that add value to customers.

The current study identifies ten categories of AMTs, which were divided into two groups based on their primary purpose:

(1) manufacturing planning and control technologies; and

(2) manufacturing equipment and process technologies.

2.4 Modularity-based manufacturing practices

Although the concept of modularity is not new to manufacturing practitioners, it has drawn much greater research attention recently due to its definitive advantage in coping with an increasingly turbulent manufacturing environment. Baldwin and Clark (1997) are among the many proponents of modularity and regard modularity as an efficient strategy for organizing complex products and processes. In fact, modularity elicits benefits for both customers and manufacturers. For customers, modular products are much easier to customize, upgrade, and repair, thus have greater usability and serviceability (Bowen *et al.*, 1989). For manufacturers, modularity enables them to handle increasingly complex technology. By breaking up a product into modules, designers and producers have gained enormous flexibility (Baldwin and Clark, 1997). In this study, three categories of MBMP were identified; PM, PRM, and DT.

2.4.1 Product modularity. PM involves modularizing products so that the components can be easily re-assembled or re-arranged into different forms, or shared across different product lines. With its benefits, product modularization has become an inevitable trend in manufacturing. For example, NeoSystems launched an innovative computer architecture – modular digital architecture (MDA). Modules of accessories are simply stacked on a base MDA module for easy hardware installation and upgrade, similar to stacking a home stereo system. In describing this innovation, Baldwin and Clark (1997) commented, "At the heart of their remarkable advance is modularity – building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole".

2.4.2 Process modularity. PRM refers to the practice of standardizing manufacturing process modules so that the components can be easily re-sequenced or new components can be added in response to changing product requirements. Feizinger and Lee (1997) suggest that PRM is based on three basic principles:

(1) *Process standardization*. Breaking down the process into "standard sub-processes" that produce standard base units and "customization sub-processes" that further customize the base units.

(2) *Process re-sequencing*. Re-sequencing the sub-processes so that standard sub-processes occur first while customization sub-processes occur last.

(3) *Process postponement*. Postponing the customization sub-processes until a customer order is received or put them into distribution centers to achieve maximum flexibility.

Pine (1993) also suggests that traditional tightly coupled processes should be broken apart and modularized, so that at its ideal, any process can link to any other process, creating the unique end-to-end value chain that will best satisfy each individual customer.

2.4.3 Dynamic teaming. DT applies modularity principles to team-building processes and involves re-organizing production teams and linking them to the resources necessary to respond to product/process changes. Although many firms have experimented with production teams, not all results have been positive (Adler and Cole, 1993). One reason behind the mixed results is that changing a manufacturing environment requires a more dynamic team structure which differs from the traditional cross-functional teams (Henke *et al.*, 1993).

Pine (1993) argue that cross-functional teams are usually tightly integrated to improve efficiency but lack flexibility. To achieve DT, companies must break apart tightly coupled teams and form loosely coupled networks of modular, flexible working units, so that these units of people, processes, and technology can be easily reconfigured to meet changing customer needs. These loosely coupled systems are better at error diagnostics, and thus promote learning (Levinthal and March, 1993); however, the information linkages supporting the continuous learning capability of these reconfigurable working units become crucial.

2.5 Manufacturing performance

Although the concept of MP has been widely used and discussed, researchers have often designed different measures of individual aspects of MP as needed by the research projects. It is a comprehensive measure of all major dimensions of MP.

3. Hypothesis development

To illustrate and test the relationships between absorptive capacity and a firm's aptitude for implementing innovative management practices in a turbulent environment, MSI and MBMP are used. The proposed model in Figure 1 suggests that absorptive capacity affects a firm's ability to integrate its manufacturing systems and affects its adoption of MBMP. These practices, in turn, may impact the firm's MP.

3.1 Research hypothesis 1

Absorptive capacity represents some important ideas in organizational design, specifically with regard to learning mechanisms and communications infrastructure. The relationship between organizational/cultural factors and AMT usage has been a major topic area in manufacturing management literature. Zammuto and O'Connor (1992) proposed that firms with an organic structure and an open CC are more likely to gain AMT's productivity and flexibility benefits. They also emphasized the importance of employee knowledge and skills because of the complex nature of AMTs. Duimering *et al.* (1993) also argued that organizations must be redesigned to ensure effective cross-functional communication before implementing AMTs. Lei *et al.* (1996) further illustrated the positive effects of appropriate organizational learning mechanism on AMT success. Given AMT complexity and importance, we suggest that the expertise found in an absorptive capacity skill set will positively relate to its manufacturing integration. In other words, we propose that:

H1. There is an overall positive relationship between a firm's absorptive capacity and its level of MSI.

3.2 Research hypothesis 2

As noted previously, modularity is a very effective strategy for organizing complex products and processes. However, not all products and processes can be modularized. Baldwin and Clark (1997) suggest that modular systems are more difficult to design than comparable interconnected systems, resulting in greater implementation complexity and/or even avoidance of the option. A successful modular design requires in-depth knowledge of the inner workings of the overall product and extensive use of cross-functional communication. Baldwin and Clark (1997) also suggest that, to take full advantage of modularity, firms need knowledgeable leaders, highly skilled workers, and effective communications mechanisms. Given that these firm needs are all key components of a firm's absorptive capacity, the second hypothesis is proposed:

H2. There is an overall positive relationship between a firm's absorptive capacity and its level of MBMP.

3.3 Research hypothesis 3

Doll and Vonderembse (1991) pointed out that while technology is a driving factor in the relatively stable industrial stage, technology becomes only an enabling factor as the market environment becomes more turbulent in the post-industrial stage. To successfully cope with high market uncertainty, manufacturers must first achieve a high level of system integration before implementing new technology (Duimering *et al.*, 1993). To achieve systems integration, many firms now advocate "open automation", a standard-based system in which components can easily integrate and share data with other systems (Kinsella, 1998).

Parthasarthy and Yin (1996) empirically verified that organization-wide integration significantly moderates CIM's impact on competitive performance, while Rondeau *et al.* (2000) confirmed that higher integration leads to higher competitive capabilities. In addition, Droge *et al.* (2004) concluded that integration has direct effects on time-based performance, market share performance, and financial performance, and Swink and Nair (2007) further confirmed that strategic integration leads to cost efficiency and new product development flexibility capabilities that contribute to market-based performance. Based on this previous research, MSI would be indicated as a valuable method to respond to increased turbulence in a business environment and maintain or even improve MP. Thus, we propose our third hypothesis:

H3. MSI has a positive impact on MP.

3.4 Research hypothesis 4

As noted previously, Baldwin and Clark (1997) suggest that MBMP permit firms to successfully cope with turbulent manufacturing environments. Lau Antonio *et al.* (2007) also indicate that modularity positively influences the capabilities of delivery, flexibility, and customer service. Warren *et al.* (2002) suggest that a positive relationship exists between modular product architectures and performance by enabling a firm to achieve modularity in product design, production process design, and organizational design. Indeed, MBMP works to facilitate manufacturing flexibility and time-based results. Developing the ability to produce a diverse variety of goods through the assembly of standardized modules, manufacturers can expect to reduce uncertainty and complexity, shorten product development time, and lower overall costs (Sanchez, 2000). Building on the above associations, the fourth hypothesis is proposed:

H4. MBMP have a positive impact on MP.

4. Research methodology

In this section, instrument development and survey administration research methods are described. The measurements of absorptive capacity are adopted from a previous study by Tu *et al.* (2006); MBMP from Tu *et al.* (2004); and MP from Liao and Tu (2008). The measurement items for MSI were developed for this study and are validated below.

4.1 Item generation and pilot study

A comprehensive literature review was completed to identify the content domain and generate initial construct items and definitions for manufacturing systems integration. The items for MSI were developed mainly from the AMT usage literature (Cooper and Zmud, 1990; Vonderembse *et al.*, 1997).

The pre-pilot study involved structured interviews with four manufacturing managers in the midwest region of the USA and six faculty members to further refine the definitions and contents of measurement items of each construct. Q-Sort methodology (Nahm *et al.*, 2002) was applied to the interviews. The results of the Q-Sort process show the content validity of each construct.

To further refine the instruments, a pilot study was targeted at senior manufacturing managers of medium- to large-sized domestic US companies. A total of 40 usable responses were received. Cronbach's alpha (Cronbach, 1951) was computed to evaluate the scale reliability. Alpha value over 0.7 was considered acceptable (Nunnally, 1978). Corrected item-total correlation (CITC) was used to purify the scales (Kerlinger, 1978). An item was eliminated if its correlation with the corrected item total was below 0.50. A slightly lower CITC was deemed acceptable if that item was considered to be important to the construct. Based on the pilot study results, the questionnaire was further revised and prepared for the large-scale data collection phase.

4.2 Large-scale data collection

For this study, respondents were expected to have detailed knowledge of more than one functional area, plus an in-depth understanding of manufacturing. Respondents were expected to represent different geographic areas, industries, and firm sizes, so that results could be generalized. To achieve these goals and to obtain an acceptable response rate, the survey sample was obtained from the Society of Manufacturing Engineers (SME), a well-known organization of manufacturing managers and engineers with 65,000 active members from across the world and across almost every industry.

The research questionnaire was administered through a large-scale mailing to 2,831 manufacturing managers, randomly selected from SME's US membership database. Questions used a five-point Likert scale, ranging from $1 =$ "strongly disagree" to $5 =$ "strongly agree". Of the total 320 responses received, 303 were complete and usable. The response rate was 10.7 percent. Demographic results show that all major types and sizes of manufacturing industries were well represented in the study. Early respondents and late respondents were compared on the basis of firm size, industry type, and sales volume to assess response/non-response bias. No statistically significant differences were detected between early respondents and late respondents using a χ^2-test at $p < 0.05$ level.

4.3 Measurement instrument validation

The instrument validation processes for the construct of MSI, included the following two steps:

(1) item purification through dimension-level reliability analysis, which checks the CITC scores and Cronbach's alpha, to ensure unidimensionality and convergent validity of the instrument dimensions; and
(2) construct-level second-order confirmatory factor analysis to ensure the discriminant validity of the measurement instrument using AMOS (Byrne, 2001).

The MSI instrument asks respondents to rate the level of each AMT with other components of the manufacturing systems listed. The construct was initially represented by two dimensions and ten items in the large-scale survey, including manufacturing equipment and process technology usage (MEPB) (five items), and manufacturing planning and control technology usage (MPCB) (five items). Examination of CITC scores (higher than 0.5) along with checking the contents and importance of each item in each dimension resulted in the elimination of one item for each dimension. The reliability scores (α) after the purification were 0.73 for the MEPB dimension (four items) and 0.78 for the MPCB dimension (four items), all above the minimum recommended value of 0.70. All eight items were then submitted to second-order confirmatory factor analysis (Tables II and III). Each factor loading of the item to the dimension is close to or above 0.60. The loading of each dimension to the construct is higher than 0.80; this indicates a good discriminant validity of MSI.

The average value of all items in a dimension was used for hypothesis testing. Overall, the final measurement instruments for the MSI construct were found to be valid and reliable. Measurement item details are found in the Appendix.

5. Structural equation modeling and hypotheses testing

The correlations between each pair of measurements are listed in Table IV.

Latent variable	Item	Unstandardized factor loading	Standardized factor loading	SE	*t*-value
$\xi 1$	MEP1B	1	0.638	–[a]	–[a]
	MEP2B	1.060	0.669	0.122	8.696
	MEP1B	0.922	0.668	0.106	8.691
	MEP2B	0.918	0.583	0.116	7.910
$\xi 2$	MPC1B	1.177	0.736	0.120	9.791
	MPC2B	0.906	0.635	0.102	8.852
	MPC1B	1.015	0.696	0.107	9.458
	MPC2B	1	0.651	–[a]	–[a]

Notes: [a]Indicate a parameter fixed at 1.0 in the original solution; fit indices: $\chi^2 = 59.09$, df = 19, $\chi^2/\text{df} = 3.11$, NNFI = 0.92, and CFI = 0.94

Table II. Second-order CFA of MSI – convergent validity and item reliability

Variables	1	2	Factor loading
1 Manufacturing equipment and process	0.73[a]		0.89
2 Manufacturing planning and control	0.74[b,*], 48.4[c]	0.78[a]	0.83

Notes: *Significant at: 0.01; [a]reliability on the diagonal; [b]correlation; [c]χ^2 difference between the fixed and free solution

Table III. Second-order CFA of MSI – discriminant validity and construct reliability

Path analysis within the AMOS-structured equation-modeling framework was used to test the hypotheses of the current study. Because each construct in the model is measured by multiple sub-dimensions and each contains multiple items, composite scores were computed for each construct and then input to the AMOS structural equation modeling process.

The AMOS algorithm provides several goodness-of-fit statistics to evaluate the hypothesized model and also suggests ways in which the model might be modified given sufficient theoretical justification.

The overall fit measure of chi-square statistic (χ^2) is the most commonly used index for model assessment. The current study uses the proportion of variance goodness-of-fit index (GFI) provided by AMOS. A GFI value of > 0.90 is considered acceptable (Segars and Grover, 1993). Root Mean Square Residual (RMSR) is a residual-based measure of overall fit. A smaller value of RMSR represents a better model fit. The recommended maximum value of RMSR is 0.1 or 0.05 (Joreskog and Sorbom, 1984).

Comparative fit measures compare the proposed model to a baseline model (null model) – some realistic model that all other models should be expected to exceed. Comparative fit indices include normed fit index (NFI) and root mean square error of approximation (RMSEA). One of the most popular measures of this kind is the NFI. A commonly recommended value is 0.90 or greater (Hair *et al.*, 1992). Another comparative fit measure is the RMSEA. Acceptable RMSEA values are 0.06 or less, with values greater than 0.10 indicating poor fit (Tabachnick and Fidel, 2007).

Parsimonious fit measures relate the goodness-of-fit of the model to the number of estimated coefficients required to achieve this level of fit. The most widely used measure of parsimonious fit is adjusted GFI (AGFI) provided by AMOS. A recommended acceptance value of AGFI is 0.80 or greater (Segars and Grover, 1993).

As shown in Figure 2 and Table V, the structural model fit was very good with all indices meeting the recommended criteria: GFI = 0.961, RMSR = 0.022, NFI = 0.944,

Table IV.
Correlation between each pair of measurements

	1	2	3	4
1. Absorptive capacity	1			
2. Manufacturing integration	0.421	1		
3. Manufacturing modularity	0.547	0.362	1	
4. Manufacturing performance	0.575	0.470	0.421	1

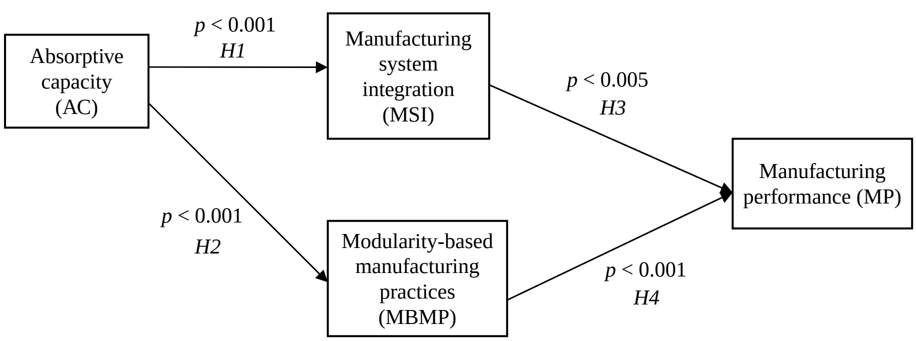

Figure 2.
AMOS path analysis model

AGFI = 0.935, and RMSEA = 0.030. The AMOS path coefficients resemble those derived through multiple regressions. The path coefficients for *H1*, *H2*, and *H4* are significant at the 0.001 level. The path coefficient for *H3* is significant at the 0.005 level.

6. Discussion of analytical results

The analytical results presented above comprehensively suggest that absorptive capacity, MSI and MBMP do have a distinctive impact on MP. These results may prove useful to managers in understanding and dealing with performance problems in manufacturing firms.

The statistically significant absorptive capacity antecedent to MSI (*H1*) and MBMP (*H2*) indicates a strong and direct positive relationship from absorptive capacity to both successful systems integration and the implementation of modularity practices. Of the two relationships, absorptive capacity has a stronger relationship with MBMP than with MSI.

In combination, the components of absorptive capacity (existing knowledge base, KS, communication network, and CC) appear to have a significant influence on the level of systems integration at a manufacturing firm. This finding is consistent with the basic requirements for integration efforts, specifically with regard to the development and sharing of novel information needed to ensure the high level of expertise desired to successfully optimize the use of AMTs. But, as was indicated previously, the mere acquisition of AMTs is not sufficient to produce success. Possession and absorptive capacity would appear to be necessary complements to success.

The components of absorptive capacity would also appear to have a significant influence on the MBMP, including PM, PRM, and DT. This finding is consistent with the premise that successful modular designs entail a high level of in-depth and shared knowledge, requiring the basic components of a firm's absorptive capacity (knowledgeable leaders, highly skilled workers, and effective communication mechanisms). Indeed, "the ability of a firm to recognize the value of new, external information (and) assimilate it . . . " would be a necessary part of teaming efforts, as well as transitions to modularity in product and/or process (Cohen and Levinthal, 1990).

The strong relationship found between MBMP and MP likely reflects the needs of today's firms to adapt to and survive in the turbulent external climate in which they exist. The development of modular practices brings with it the inherent benefits of quick changeovers and flexibility in manufacturing. Although both constructs contribute to a firm's MP, perhaps the ability to quickly adapt to change is considered as a more valuable contributor than that of the integrated AMTs present in a firm's

Table V. AMOS structural modeling and hypotheses testing results

Hypotheses	Relationship	AMOS coefficient	*t*-value	*p*-value	Significant?
H1	AC → MSI	0.478	5.64	< 0.001	Yes
H2	AC → MBMP	0.672	6.09	< 0.001	Yes
H3	MSI → MP	0.265	3.18	< 0.005	Yes
H4	MBMP → MP	0.479	4.91	< 0.001	Yes

Notes: GFI = 0.961; RMSR = 0.022; NFI = 0.944; AGFI = 0.935; RMSEA = 0.030

manufacturing systems. Thus, the ability to quickly adapt and evolve to changes in conditions may be more essential to manufacturing success.

7. Implications and future research directions

Driven by continuously increasing competitive pressure due to environmental uncertainty in the post-industrial era, firms must find the right approach to improve MP. The current study includes several important academic and practical contributions regarding how firms should react when facing environmental turbulence.

Modularity has been viewed as a very effective way to achieve higher performance. Our results show that MBMP provide the advantages of flexibility, low cost, high quality, innovation, and fast delivery. Modularity can be applied not only to product design, but also to production and teaming, and recently, has also been used to manage suppliers and other aspects of manufacturing firms.

The study has theoretically defined MSI, and developed and empirically validated a measurement instrument for this construct. Researchers may now use these definitions and measurement items to further evaluate potential MSI relationships with other factors in different research scenarios and models to further extend our understanding to the post-industrial manufacturing system. Practitioners can also benefit from using the instrument to measure their system integration and automation performance to benchmark with competitors for implementation purposes.

This research has also suggested a direction for firms to improve their MP. Several studies have demonstrated that system automation using AMT can significantly increase productivity, product quality, and speed to market. This study implies that firms that have implemented AMT but are experiencing lower than promised performance should think about a combination strategy of MSI and organizational modularity practices. Company-wide functional integration and DT could help unleash AMT's full potential.

These results align with the findings of several case studies on AMT implementation. After observing three European companies that had recently adopted AMT, Sun and Gertsen (1995) found that organizational change was a critical factor for the achievement of expected AMT benefits. Sohal's (1996) case study on seven Australian firms also indicated similar results: after advocating inter-functional holistic approach in planning, acquiring, implantation, and exploitation, firms saw significant performance improvements such as inventory cost savings, increased customer satisfaction, higher delivery reliability, rapid and more accurate production planning, etc. Thus, firms running AMT should continuously update their organizational practices to encourage flexible, inter-functional communication, and coordination.

In studying system integration and modularity practices, the current study focuses on functional collaboration within an organization. Future studies could expand the collaborative and modular perspective to the supply chain level, as well as investigate other potential contributing constructs to these relationships. Inter-firm integration and supply chain modularity allow manufacturing managers access to a greater volume of information and more comprehensive levels of expertise. Utilizing these, managers can then achieve a better understanding of the firm's operating environment and act more quickly when addressing emerging market challenges and uncertainties. A re-examination of how supply chain integration and modularity would affect supply chain-wide system performance would also prove interesting.

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Appendix. Construct measurement items

Table AI. Manufacturing system integration

Code names	Questionnaire items
MSI: manufacturing equipment and process technologies integration (MEPB) ($\alpha = 0.73$)[a]	
MEP1B	Automatic numerically controlled machines
MEP2B	Automated inspection and testing equipment
MEP3B	Automated flexible manufacturing systems
MEP4B	Automated rapid prototyping in product design process
MEP5B[b]	Automated storing and retrieving systems
MSI: manufacturing planning and control technologies integration (MPCB) ($\alpha = 0.78$)[a]	
MPC1B	Computer-aided technology that determines routings between machines
MPC2B	Computer-aided technology that facilitates production by classifying parts into families according to similarities
MPC3B	Computer-aided technology that plans machining operations
MPC4B	Computer-aided technology that plans and controls shop floor material requirements
MPC5B[b]	Computer-aided technology that monitors the production process and provides feedback

Notes: [a]For MSI, the respondents were asked to rate the level of connection of each of the AMT with other components of the manufacturing system; [b]item was deleted in the purification process

Table AII.
Absorptive capacity

Code names	Measurement items
Communications climate (CC)	
CC1	Our employees tend to trust each other
CC2	Our employees are supportive of each other
CC3	Our employees have strong feelings of belonging to our organization
CC4	Our employees share ideas freely with each other
CC5	Our employees have no difficulty accepting new ideas
CC6	Our employees are willing to accept changes
Knowledge scanning (KS)	
KS1	We seek to learn from tracking new market trends in our industry
KS2	We seek to learn from routine search of useful information
KS3	We seek to learn from benchmarking best practices in our industry
KS4	We seek to learn from trying out new technologies
KS5	We seek to learn from our customers and suppliers
KS6	We seek to learn from taking new business opportunities
KS7	We seek to learn from conducting R&D activities
Communications network (CN)	
CN1	The communications between supervisors and their subordinates are extensive
CN2	The communications among functional areas are extensive
CN3	The communications among functional areas are frequent
CN4	The communications between supervisors and their subordinates are frequent
CN5	The communication of new ideas from one department to another is extensive
Worker knowledge (WK)	
WK1	The general knowledge level of our first-line workers is high
WK2	The overall technical knowledge of our first-line workers is high
WK3	The general educational level of our first-line workers is high
WK4	The overall job competence of our first-line workers is high
Management knowledge (MK)	
MK1	The knowledge of our managers is adequate when making business decisions
MK2	The knowledge of our managers is adequate when dealing with new technologies
MK3	The knowledge of our managers is adequate when managing daily operations
MK4	The knowledge of our managers is adequate when solving technical problems

Source: Tu *et al.* (2006)

Table AIII.
Modularity-based manufacturing practices

Code names	Measurement items
Product modularity (PM)	
PM1	Our products use modularized design
PM2	Our products share common modules
PM3	Our product features are designed around a standard base unit
PM4	Product modules can be reassembled into different forms
PM5	Product feature modules can be added to a standard base unit
Process modularity (PRM)	
PRM1	Our production process is designed as adjustable modules
PRM2	Our production process can be adjusted by adding new process modules
PRM3	Production process modules can be adjusted for changing production needs
PRM4	Our production process can be broken down into *standard sub-processes* that produce standard base units and *customization sub-processes* that further customize the base units
PRM5	Production process modules can be re-arranged so that *customization sub-processes* occur last
Dynamic teaming (DT)	
DT1	Production teams that can be re-organized are used in our plant
DT2	Production teams can be re-organized in response to product/process changes
DT3	Production teams can be re-assigned to different production tasks
DT4	Production team members can be re-assigned to different teams
DT5	Production team members are capable of working on different teams

Source: Tu *et al.* (2004)

Code names	Measurement items
Cost (CO)	
CO1	Reduce material costs
CO2	Increase capacity utilization
CO3	Reduce production cost
CO4	Better price competitiveness
CO5	Reduce inventory cost
CO6	Increase labor productivity
CO7	Reduce unit cost
Quality (QL)	
QL1	Better product performance
QL2	Improved product durability
QL3	Better product reputation
QL4	Better product conformance to specifications
QL5	Improved product reliability
QL6	Reduce defective rate
Innovation (IN)	
IN1	Develop new ways of customer service
IN2	Develop new forms of shop floor management
IN3	Develop new ways of supply chain management
IN4	Develop new products and features
IN5	Develop new process technologies
Flexibility (FL)	
FL1	Make rapid design changes
FL2	Make rapid production volume changes
FL3	Make rapid changeover between product lines
FL4	Process both large and small orders
FL5	Produce a variety of different products
Delivery (DL)	
DL1	Meet delivery promises
DL2	Decrease manufacturing lead time
DL3	Provide faster delivery
DL4	Provide on-time delivery
DL5	Provide reliable delivery

Table AIV. Manufacturing performance

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