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Abstract: Under a uncertain environment (i.e., growing global competition, changing customer demand, shorter product life cycles, and increasing market diversity), two manufacturing strategies often emerge: manufacturing technology automation and manufacturing system integration. Existing case studies indicate that firms should adapt manufacturing integration first and then automate the manufacturing system to improve manufacturing performance. Using 288 responses from manufacturing managers, the findings of this study empirically supports this proposition. Analytical results also show that the combination strategies of manufacturing system integration followed by manufacturing technology automation have more than twice the effect on manufacturing performance than using manufacturing automation strategy alone.

Keywords: environmental uncertainty; EU; manufacturing performance; MP; integration; automation; manufacturing technology.

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1 Introduction

The global business environment is experiencing drastic changes characterised by growing global competition, changing customer demands, shorter product life cycles, increased market diversity, and advances in manufacturing and information technology (Doll and Vonderembse, 1991; Koufteros et al., 2002). Champlin and Olson (1994) summarised three revolutionary change forces in the post-industrial manufacturing era, including global competition, technology advancement, and new managerial practices. In order to meet the competitive challenges resulted from these fundamental change forces, manufacturers have adopted two major manufacturing strategies: automation and integration. Implementations of manufacturing automation are mainly through the effective use of advanced manufacturing technologies (AMT), including CAD/CAM, FMS, and CIMS. AMT are flexible manufacturing systems (FMS) which have capabilities of increasing economies of scope for manufacturing companies. However, evidences show that many US firms are not realising the full benefits offered by these new technologies or even forced to withdraw them from use (Chen and Small, 1994; Small, 2007). A study by Mansfield (1993) on 175 Japanese, Western Europe, and the US firms indicated that US firms have been relatively slower in assimilating FMS technologies than elsewhere due to a lower return rate. To address this issue, several studies proposed manufacturing system integration (MSI) as a solution to effectively manage AMT (Duimering et al., 1993). A case study by Burcher et al. (1999) further confirmed the importance of integration for a company to implement AMT.

System integration is a valuable way to respond to increasing turbulence of business environment. MSI includes production engineering integration and production process integration (Cagliano and Spina, 2000). Nahm et al. (2003) found that a high level of horizontal integration in a firm leads to better communication. Droge et al. (2004) utilised a sample of 57 first-tier US automotive suppliers to empirically support their conclusion that integration has direct effects on time-based performance, market share performance, and financial performance. Swink and Nair (2007), using empirical data collected from US manufacturing firms, further confirmed that strategic integration leads to cost efficiency and new product development flexibility capabilities that contribute to market-based performance.

Recently, the issue of manufacturing technology automation (MTA) vs. system integration has attracted greater attention due to the increasing level of (environmental uncertainty) EU. A case study by Vonderembse et al. (1997) provided some initial empirical evidence on the role of automation vs. integration under a highly uncertain environment. The study suggests that manufacturing systems must be redesigned in the post-industrial era by focusing first on integration and then automation. Jonsson (2000) studied 324 manufacturing companies in Sweden and divided those companies into three groups (i.e., traditionalists, hard integrators, and high investors) according to the degree of automation and integration (defined as data and information transactions both within the manufacturing function and between the manufacturing function and other functions). He viewed AMT as both automation and information integration and concluded that companies with heavy AMT investments perform better than those without. However, he indicated that "the analyses conducted were mostly descriptive in nature, and did not look for cause-and-effect relationship between underlying variables and high performance." Empirical evidences of whether manufacturing automation and integration really make a difference in terms of manufacturing performance (MP) under EU are almost non-existent. This paper attempts to address the gap of lacking empirical studies in this important research area.

The authors are very interested in two research questions:

1 What are the implications of EU on manufacturing automation and integration?

2 What are the impacts of automation and integration on MP? The current study is the first large-scale survey research to address the above research questions. The next section will present the theoretical model and development of hypotheses. Research methodology is then presented along with analytical results from path analysis using structural equation modelling, followed by discussions of implications and conclusion.

2 Theoretic framework and hypothesis development

The theoretical framework under investigation in the current study can be depicted as follows (Figure 1).

Figure 1 Theoretical framework

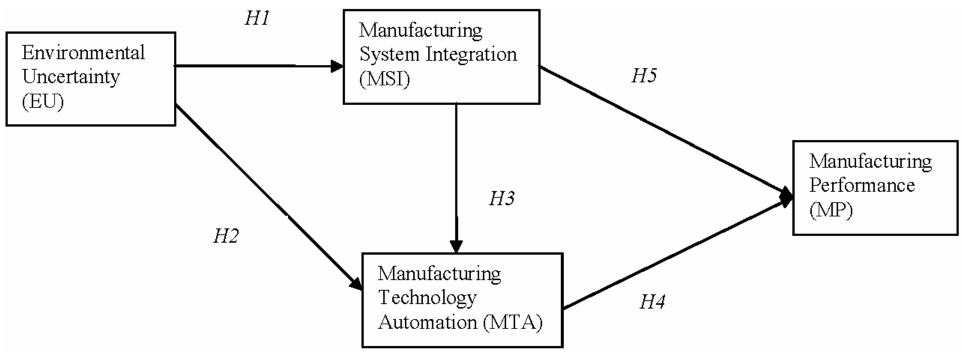

Table 1 Construct definitions and literature

Construct	*Definition*	*Literature*
Environmental uncertainty	The degree of turbulence of post-industrial environment resulted from the increasing competition, changing customer demand, shorter product life cycle, and rapidly advancing technology innovation.	Doll and Vonderembse (1991), Champlin and Olson (1994) and Koufteros et al. (2002)
Manufacturing technology automation	Substituting labour with automatic facilities and equipment so that the system can operate with fewer labour hours per unit produced	Cooper and Zmud (1990), Dean et al. (1992), Lowe (1995), and Vonderembse et al. (1997)
Manufacturing system integration	Physical connections and information flows among the manufacturing system components	Vonderembse et al. (1997), Lapalus et al. (1995), Frohlich and Westbrook (2001), Bhatt (2000), Dan et al. (2005), Deng et al. (2002), Gao et al. (2002), Zhang et al. (2003), Cho et al. (2002), Chikan (2001), and Gimenez and Ventura (2005)
Manufacturing performance	The level of attainment of various manufacturing objectives, which are commonly considered to include cost, quality, delivery, flexibility, and innovation	Swamidass and Newell (1987), Boyer and Lewis (2002), Rosenzweig et al. (2003), Swink and Nair (2007), and Liao and Tu (2008)

There are three basic arguments in this model:

1. the EU drives the needs of MTA and MSI
2. MSI has a positive impact on MTA
3. both MSI and MTA have positive impacts on MP.

There are also four constructs in the above model, as specified in Table 1. The highly turbulent environment (i.e., EU) is largely resulted from the increasing competition, changing customer demand, shorter product life cycle, and rapidly advancing technology innovation (Koufteros et al., 2002). These factors will definitely affect manufacturing practices and performance.

MTA can be defined as substituting labour with automatic facilities and equipment so that the system can operate with fewer labour hours per unit produced (Vonderembse et al., 1997). This usually involves the adoption and implementation of various AMTs, such as robotics, CNC machines, computer-aided design/manufacturing (CAD/CAM), and FMS. Thus, in manufacturing management literature, the level of automation is often represented by the level of AMT usage.

MSI refers to both the physical connections and information flows among the manufacturing system components (Frohlich and Westbrook, 2001). It may include cooperation of application systems, consistency of the information model and continuity of communication through all management and control levels (Lapalus et al., 1995). Information integration can improve business process and plays a critical role in a firm (Bhatt, 2000). In the manufacturing function, information integration is implemented through utilising network and other information technologies (Dan et al., 2005) to share product and process data (Deng et al., 2002; Gao et al., 2002) and coordinate process planning and scheduling (Zhang et al., 2006). Process integration mainly includes integration of design, manufacturing and inspection systems (Cho et al., 2002), and integration of production and logistics functions (Chikan, 2001; Gimenez and Ventura, 2005).

In the current study, MP is defined as the level of attainment of various manufacturing objectives, which are commonly considered to include cost, quality, delivery, flexibility, and innovation (Swamidass and Newell, 1987). These five dimensions are grounded in seminal manufacturing research works (Hayes et al., 1988) and well recognised by prior researchers. The actual measurement items we employed are adapted from the scales validated in other MP studies (Boyer and Lewis, 2002; Swink and Nair, 2007; Liao and Tu, 2008).

2.1 The impact of EU on MSI

MTA did offer some localised benefits in terms of quality, cost, and productivity (Monge et al., 2006). However, as the competitive environment gets much more turbulent, a highly integrated yet flexible system is required to respond to unexpected changes in order to get global optimisation of the whole system. Newman et al. (1993) developed an equilibrium model to show that internal and external uncertainties of manufacturing calls for better MSI. Vonderembse et al. (1997) concluded in their case studies that integration across the value chain is the first step to respond to the EU. Paulraj and Chen (2007) studied the impact of EU from the resource dependence perspective and found that when facing uncertainty, firms were more likely to seek integration with trading partners and form a strategic supply chain. Thus, we have the following hypotheses:

Hypothesis 1 EU leads to higher levels of MSI.

2.2 The impact of EU on MTA

AMT (e.g., CAD/CAM, FMS, and CIMS) have the characteristics of using software or computer programs to control machines. This type of manufacturing systems has advantages in increasing market responsiveness while maintaining low costs (Doll and

Vonderembse, 1987). The economy of scope provided by AMT gives firms much higher level of strategic flexibility to deal with increasing environmental turbulence (Hayes and Pisano, 1994). Zhang et al. (2006) empirically confirmed that in order to respond to increasing EU, manufacturers can utilise AMT to enhance flexible manufacturing capability as a source of competitive advantage. Therefore, we have the following hypotheses:

Hypothesis 2 EU leads to higher levels of MTA.

2.3 The impact of MSI on MTA

Duimering et al. (1993) proposed that the key to effective management of flexible automation is to improve MSI before implementation. Vonderembse et al. (1997) conducted some in-depth case studies concerning the issue of automation versus integration. They found that under the industrial paradigm of thinking firms tend to automate specific tasks to solve local problems, which often results in 'islands of automation' that are not capable of responding quickly to rapidly changing customer needs. Thus, firms operating in the post-industrial environment should focus first on integration across the value chain and then automate the activities that add value to customers. A case study by Burcher et al. (1999) also confirmed the importance of integration in AMT implementation. Swink and Nair (2007) found similar results in their empirical study of 224 manufacturing plants which used manufacturing integration to enhance AMT usage and system automation. Therefore, we have the following hypotheses:

Hypothesis 3 MSI has a positive impact on MTA.

2.4 The impact of MTA on MP

The increasing use of advanced automation technologies in the US manufacturing firms started in the early 1980s. Since then, there have been many cases reporting improved quality and productivity as a result of manufacturing systems automation (Swamidass and Kotha, 1998). Routine tasks can be embedded into automated hardware and software, thus, reducing costs including direct labour costs, rework costs, and work-in-progress inventories (Zummato and O'Connor, 1992). AMT utilisation can improve product design and process design, thus, substantially cutting down product changeover time and process variability and thereby improving manufacturing productivity and product quality (Swink and Nair, 2007). Therefore, we have the following hypothesis:

Hypothesis 4 MTA has a positive impact on MP.

2.5 The impact of MSI on MP

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 when market environment gets more turbulent in the post-industrial stage. To successfully cope with the high uncertainty, manufacturers must first achieve a high level of system integration before implementing new technology (Duimering et al., 1993). Many firms now advocate the concepts of 'open automation', a standard-based system in which components can be easily integrated and share data with other systems (Kinsella, 1998). Several studies have addressed the importance of manufacturing infrastructure element integration on the benefits attained from use of flexible manufacturing technology (Lei et al., 1996). Parthasarthy and Yin (1996) empirically verified that organisation-wide integration significantly moderates CIMs impact on competitive performance. Rondeau et al. (2000) also empirically confirmed that high integration leads to high competitive capabilities. Therefore, we have the following hypotheses:

Hypothesis 5 MSI has a positive impact on MP.

3 Research methodology

In this section, research methods are described for the instrument development and survey administration. The measurement items for EU and MPare adopted directly from a previous study by Liao and Tu (2008) and listed in the Appendix. The measurement items for MTA and MSI are developed and validated below. The instrument development process can be roughly divided into four phases:

1 item generation
2 pre-pilot study
3 pilot study
4 large-scale data analysis and instrument validation.

3.1 Item generation and pilot study

A comprehensive literature review was done to identify the content domain of major constructs in the current research framework. Initial items and the definitions of each construct were generated from the literature review. The items for MTA were developed mainly from advanced manufacturing technology (AMT) usage literature (Dean et al., 1992; Lowe, 1995; Vonderembse et al., 1997). The items for MSI were generated based on the AMT integration literature, especially works by Cooper and Zmud (1990) and Vonderembse et al. (1997).

The pre-pilot study involves 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. The 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.

The third phase is a pilot study targeted at senior manufacturing managers of medium to large size companies nationwide to further refine the instruments. Forty usable responses were received. Cronbach's alpha 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 acceptable if that item was considered to be important to the construct. Based on the pilot study results, the questionnaire was further revised and made ready for the large-scale data collecting phase. All items were measured on five point Likert scale: from 1 – strongly disagree to 5 – strongly agree.

3.2 Large-scale data collection

For this study, the respondents should have detailed collective knowledge in more than one functional areas plus in-depth understanding of manufacturing. Respondents should also represent different geographical areas, industries, and firm sizes, so that the results can be generalised. 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 organisation of manufacturing managers and engineers with 65,000 active members all over the world and in almost every industry.

The research questionnaire was administered through large-scale mailing to over 2,800 manufacturing managers, randomly selected from SMEs US membership database. Out of the total of 295 responses received, 288 were complete and usable. The response rate is 10.3%. The 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 chi-square test at $p < .05$ level.

3.3 Measurement instrument validation

The instrument validation processes for the two new constructs, MTA and MSI, include 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. Unidimensionality ensures that all items measure the same underlying theoretical construct. It is a necessary condition for scale reliability and validity (Segars, 1997).
2. Construct-level exploratory factor analysis to ensure the discriminant validity of the measurement instrument.

The MTA instrument asks respondents to rate the extent of usage of each AMT listed. Examination of CITC scores (should be higher than 0.5) along with checking for the contents and importance of each item resulted in the elimination of one items. The reliability scores (α) after the purification is 0.72, above the minimum recommended value of 0.70. Composite reliability is another measure of reliability for the construct. The estimate of composite reliability is 0.80 for MTA. It exceeds the criterion value of 0.70 (Nunnally and Bernstein, 1994). The MSI instrument asks the respondents to rate the level of connection of each subsystem with other subsystems of the manufacturing system. One item is deleted because the CITC scores are lower than 0.50. The final reliability scores (α) is 0.78 for MSI. The estimate of composite reliability is 0.84 for MSI. Therefore, MTA and MSI have acceptable reliability.

All nine items for MTA and MSI were then submitted to construct-level exploratory factor analysis. Two clear factors emerged with all factor loadings close to or above 0.60 and no cross-loadings were observed, indicating good discriminant validity.

Overall, the final measurement instruments for the MTA and MSI constructs in the current study were found to be valid and reliable. Details of the measurement items are listed in the Appendix.

3.4 Construct-level correlation analysis

To check for the preliminary statistical validity of the five hypotheses presented earlier, we calculated the Pearson correlation coefficients of the five hypothesised relationships, using a composite score for each construct. The composite score was computed by taking the average score of all items in a specific construct. All correlations are significant at the 0.01 level. Thus, all hypothesised relationships of interest are statistically supported by the Pearson correlation. Further hypotheses testing using AMOS structural equation modelling will be discussed next.

4 Structural equation modelling and hypotheses testing

Path analysis within the AMOS structured equation modelling (SEM) 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 modelling process (Li et al., 1993; Prajogo, 2005).

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

Overall fit measures of Chi-square statistic ($\chi 2$) is the most often used index for model assessment. The current study uses the goodness-of-fit index (GFI) provided by AMOS. A GFI value of greater than 0.90 is considered acceptable (Segars and Grover, 1993). Root mean square residual (RMSR) is another 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 some baseline model (null model) – some realistic model that all other models should be expected to exceed. One of the most popular measures of this kind is the normed fit index (NFI). A commonly recommended value is 0.90 or greater (Hair et al., 1992).

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 goodness-of-fit index (AGFI) provided by AMOS. A recommended acceptance value of AGFI is 0.80 or greater (Segars and Grover, 1993).

As illustrated in Figure 2 and Table 2, the structural model fit was very good with all indices meeting the recommended criteria: GFI = 0.949, RMSR = 0.051, NFI=0.908, and AGFI = 0.927. The path coefficients for H1, H2, H3, and H4 are significant at or above the 0.05 level. The path coefficient for H5 is not significant. Therefore, hypotheses H1, H2, H3, and H4 are supported by the AMOS path analysis results, while H5 is not supported.

Figure 2 AMOS path analysis results

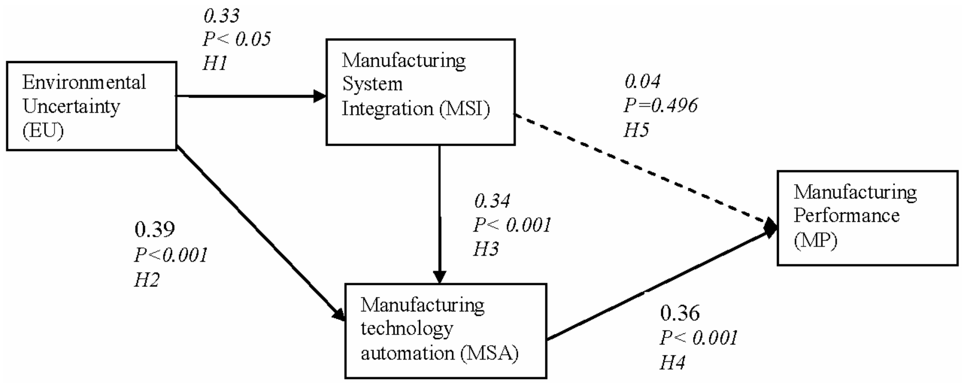

Table 2 AMOS structural modelling results

Hypotheses	*Relationship*	*AMOS coefficients*	*t-value*	*p-value*	*Significant?*
H1	EU → MSI	.33	2.42	<0.05	Yes
H2	EU → MTA	.39	3.84	<0.001	Yes
H3	MSI → MTA	.34	5.34	<0.001	Yes
H4	MTA → MP	.36	3.40	<0.001	Yes
H5	*MSI → MP*	*.04*	*0.68*	*0.496*	*No*

Notes: GFI = 0.949; RMSR = 0.051; NFI = 0.908; AGFI = 0.927.

5 Discussion of analytical results

Statistical significance and model fit are not the ultimate objectives of academic research. They are just the means to achieve our end, which is better understanding of the subject under investigation and discovery of new relationships. The results from the research will be of great value to practitioners in terms of assisting their business decision-making processes and to researchers in terms of providing some new instruments for further academic exploration.

Overall, four out of five of the hypothesised relationships (Hypotheses 1, 2, 3, and 4) were significant at or above the 0.05 level, and the final AMOS structural model displayed very good fit to the data. For the non-significant direct relationship between MSI and MP (Hypotheses 5), an indirect path was identified, which is the effect of integration on performance through automation.

Hypotheses 1 and 2 indicate that EU calls for the needs of MSI as well as automation. The effect of EU on MSI is 0.33 (H1), which is similar to the effect of EU on automation (i.e., 0.39 in H2). In the evolution process of manufacturing systems, adopting manufacturing automation is typically the first reaction of firms to cope with EU, but it does not mean manufacturing automation is the way to go (Vonderembse et al., 1997). This study shows that firms are focusing on better integration among different components of the manufacturing system in response to increasing EU.

In manufacturing strategy literature (e.g., Swamidass and Newell, 1987; Pagell and Krause, 1999), EU has long been identified as one of the major factors for consideration in manufacturing system design. Some researchers (e.g., Williamson, 1983) tried to use transaction cost theory to explain that limited and sometimes false information from turbulent environment tends to drive companies towards a vertically integrated organisational structure. The findings from our study support such theoretical proposition with strong empirical evidence. It demonstrates that when organisations are operating in an environment with complex technology and unpredictable and unreliable customers/suppliers, they have no choice but to streamline their manufacturing processes and establish standard institutional norms for system integration.

Although Hypothesis 5 (i.e., the positive impact of MSI on MP) is supported by the Pearson correlation, it is not supported in AMOS structural equation modelling. This implies that manufacturing integration doesn't have direct effect on MP. However, MSI does have an indirect effect on MP through MTA.

The linkage between MSI and MP is another basic research question of this study. Most of the literature (e.g., Wong and Boon-itt, 2008; Pagell and Krause, 1999) merely argue that in an uncertain environment, companies with higher level of functional integration has better performance such as quality, dependability and cost. However, the research community has not fully examined how exactly system integration enhances performance. The analysis from the current study identified MTA as a mediating variable. Our findings indicate that simply having an integrated system alone will not boost firm performance. An institutional norm promoting system integration will strengthen the manufacturer's ability to adopt AMT. The higher level of automation then improves MP. This finding should provide guiding pathway to organisations that are interested in performance improvement when facing uncertain environment.

Hypothesis 3 that MSI has positive effect on manufacturing automation and Hypothesis 4 that MTA has positive impact on MP is statistically supported in this study. These results do indicate that MTA is a valid strategy for improving MP. In order to identify a better strategy to increase MP under EU, the aggregated effects of two routes starting at EU are calculated: The effect from EU on MP through MSI and manufacturing automation is 0.18, 1.29 times of the effect from EU on performance through MTA only (0.14).

Therefore, firms should focus on MSI first and then use manufacturing automation to maximise their performance (i.e., cost, quality, delivery, innovation, and flexibility). This empirically confirmed the Vonderembse et al. (1997)'s proposition that "firms operating in the post-industrial environment should focus first on integration and innovation across the value chain. Once this redesign has occurred, firms should automate those activities which add value to customers."

6 Managerial implications and future research directions

Driven by continuously increasing competitive pressure due to environment uncertainty in the post-industrial era, firms have to find the right approaches to improve their MP. The current study has several important contributions to academia and practitioners regarding how firms should react when facing environmental turbulence.

The study has theoretically defined MSI and MTA, developed and empirically validated measurement instruments for these two constructs. Researchers can use the definitions and measurement items to evaluate the relationships of these two constructs with other factors in different research scenarios and models to further extend our understanding of the post-industrial manufacturing environment. Practitioners can also benefit from using the instruments in measuring their system integration and automation performance and benchmarking with competitors for implementation purposes. Firms implement manufacturing automation should include not only manufacturing automation but also manufacturing planning and control technology. MTA includes the automatic equipments from parts and tools design, to manufacturing, and to inspection and testing. Manufacturing planning and control technology includes computer-aided technologies for routing, classification, machining operations planning, and shop floor material requirements. Manufacturing integration focus on how to connect or link the above technologies and planning effectively to improve efficiency of manufacturing and operations. Firms should take care of every subprocess mentioned above for manufacturing automation and integration.

This research has also pointed out a direction for firms to improve their MP. Numerous studies have demonstrated that system automation using AMT can significantly increase productivity, product quality, and speed to market. This study implies that those firms that have implemented AMT but are experiencing lower than promised performance should think about reengineering their manufacturing systems. Company-wide system integration would help unleash AMTs full potential. This result aligns with the findings of a number of case studies on AMT implementation. After observing three European companies that had adopted AMT, Sun and Gertsen (1995) found organisational change 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 an integrated holistic approach in planning, acquiring, implantation, and exploitation, firms saw significant performance improvements such as inventory cost saving, increased customer satisfaction, higher delivery reliability, rapid and more accurate production planning, etc. Thus, firms running AMT should continuously update their system structure that encourages inter-system communication and coordination.

For those organisations that are about to introduce AMT to their systems, this study can help the planning of appropriate AMT implementation roadmaps. It empirically proves that system integration leads to higher usage levels of automation. Sohal (2000) observed smoother AMT implementation attempts when comparing the adopting processes of six Australian firms. It was found that with regular project meetings promoting communication and continuous flow of information, firms were faster to fully implement new CAD and CAE systems and encountered fewer problems and lower resistance from employees.

This study also indicates that in the uncertain post-industrial environment, implementing system integration alone was not expected to achieve MP improvements (as indicated by H5). Firms should always be aware of the availability of new technologies and be willing to invest in adopting new technologies to improve system efficiency and to reduce operating costs. Functional departments must work closely with each other in the system for integrated efforts in adopting and implementing those new automation technologies. Then firms can maintain their sustainable competitive advantages.

This study has following limitations. First, since there are only about 300 responses, the measurements in this study are developed through exploratory analysis. The confirmatory analysis for the measurements is left for future study. Second, measures of MP are subjective and thus, contain self-reporting biases.

In studying system integration, the current study focuses on connection between an organisation's manufacturing subsystems. Future studies can expand the perspective to the supply chain level. Inter-firm integration allows manufacturing managers to have access to a greater volume and more comprehensive level of information and expertise. They can achieve better understanding to the firm's operating environment and act quicker to emerging market challenges and uncertainties. It would be interesting to re-examine how supply chain integration would affect supply-chain-wide system automation. Confirmatory study based on new data set will also be useful to further validate the measurement instrument and our theoretical framework. With more and more adoption of modularity in operations and supply chain research, the relationship among automation, integration, and modularity is another future research.

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Appendix

Manufacturing technology automation (MTA), manufacturing system integration (MSI), environmental uncertainty (EU), and manufacturing performance (MP) construct measurement items

Manufacturing technology automation (MTA) items

For MTA, the respondents were asked to rate the extent of usage of each of the AMT component.

Code names	*Questionnaire items*
MEP1	Automatic numerically controlled machines
MEP2	Automated inspection and testing equipment
MEP3	Automated flexible manufacturing systems
*MEP4	Automatic storing and retrieving systems
MEP5	Automated parts and tools design process technology
MEP6	Automated rapid prototyping in product design process

Note: *Items dropped after purification.

Manufacturing system integration (MSI) items

For MSI, the respondents were asked to rate the level of connection of each subsystem with other subsystems of the manufacturing system.

Code names	*Questionnaire items*
*MPC1	Production process monitoring system
MPC2	Routings planning system
MPC3	Product group planning system
MPC4	Machining operations system
MPC5	Shop floor material planning system

Note: *Items dropped after purification.

Environmental uncertainty (EU) items and unidimensional factor loadings

Item	*Description*	*Factor loading*
1	The tastes and preferences of our customers change quickly	0.70
2	The rate of product innovation in our industry is high	0.86
3	The rate at which products are getting obsolete in our industry is high	0.72
4	The rate of process technology innovation in our industry is high	0.77

Manufacturing performance (MP) measurement items

Code names	*Questionnaire items*
Cost performance	
CO1	Reduce material costs
CO2	Increase capacity utilisation
CO3	Reduce production cost
CO4	Better price competitiveness
CO5	Reduce inventory cost
CO6	Increase labour productivity
CO7	Reduce unit cost
Quality performance	
QL1	Better product performance
QL2	Improved product durability
QL3	Better product reputation
QL4	Better product conformance to specifications
QL5	Improved product reliability
Delivery performance	
DL1	Meet delivery promises
DL2	Decrease manufacturing lead time
DL3	Provide faster delivery
DL4	Provide on-time delivery
DL5	Provide reliable delivery
Innovation performance	
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 performance	
FL1	Make rapid production volume changes
FL2	Make rapid changeover between product lines
FL3	Process both large and small orders

Reliability and unidimensionality assessments of MP variable

Item	*Description*	*Factor loading*	*Reliability (α)*	*Average variance extracted*	*Composite reliability*
1	Cost performance	0.72	0.77	0.46	0.85
2	Quality performance	0.77	0.84	0.58	0.87
3	Delivery performance	0.77	0.90	0.62	0.89
4	Flexibility performance	0.74	0.77	0.38	0.64
5	Innovation performance	0.81	0.74	0.40	0.77