Deploying AMT for Scale Versus Scope: A Contingency Approach

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Flexibility and efficiency are twin capabilities of advanced manufacturing technologies (AMT). Much research has focused on AMT's role in bolstering manufacturing flexibility. Meanwhile, AMT's potential for efficiency is often disregarded, even proscribed by researchers, because that dampens the effect on flexibility. Yet, research shows that practitioners frequently implement AMT to pursue efficiency over flexibility. This problem has not been addressed in the literature. We approach this problem by viewing AMT through a strategic lens and examining AMT at the deployment level. Firms with different strategic goals must deploy AMT differently due to flexibility and efficiency often being opposite ends of a tradeoff. We identify two modes of deployment – AMT_{Scale} versus AMT_{Scope} – with characteristically different features, which explains AMT's ability to support opposed strategies. Our unique conceptualization puts into proper perspective the mixed empirical results reported in the literature. Drawing on the contingency theory, we find that firms deploying AMT_{Scope} (to support a 'differentiation' strategy) derive flexibility, while firms deploying AMTScale (to support a 'cost-leadership' strategy) sacrifice flexibility.

Keywords: advanced manufacturing technology, manufacturing strategy, manufacturing flexibility, contingency theory, PLS

INTRODUCTION

The global hyper-competition environment has presaged an unprecedented era of innovation in manufacturing technologies. Smart production systems – the backbone of Industry 4.0 and Industry 5.0 – marry information and communication technologies with various underlying advanced manufacturing technologies (AMT) (Szalavetz, 2019; Bravi & Murmura, 2021). These technologies have continued to evolve since AMT was coined in the 1970s (Farooq, et al., 2017; Khanchanapong, et al., 2014).

Many of these technologies have been widely considered synonymous with manufacturing flexibility, so much so that often even the raison d'être for AMT installation was to "allow for a much greater flexibility in manufacturing" (Adler, 1988, p.34; see also Schmenner & Tatikonda, 2005). Pointing to the tradeoffs between flexibility and low cost, researchers have gone so far as to caution that AMT "should not be used by companies competing mainly based on cost" (Karuppan & Ganster, 2004, p.537). Rejecting this cautionary advice, managers often deploy these technologies within their processes with the "primary, realized manufacturing objective" of high-volume, low-cost production (Khanchanapong, et al., 2014, p.192). Thus, we find a glaring mismatch between the conceptual understanding advanced by scholars and the practical preferences of managers, thus leaving the area open for further inquiry.

As a sizeable investment, it is necessary to address the question: What are the ramifications of deploying AMT to attain flexibility versus low-cost? The push for smart production systems exacerbates the urgency of this question, as firms are finding out that "there is no choice between whether to invest in technology or not" (da Costa & de Lima, 2009, p.75). The rest of the paper is organized as follows. Section 2 provides a literature review that highlights the conflicting and inconclusive empirical research. Section 3 develops our research model and hypotheses. Section 4 describes our research methodology. Section 5 presents an exploratory empirical examination of our model using survey data. Section 6 discusses the theoretical contributions and managerial implications of our findings, followed by directions for future research.

LITERATURE REVIEW

AMT refers to an evolving collection of manufacturing technologies that includes "a variety of both hard and soft technologies developed to improve manufacturing capabilities" (Chung & Swink, 2009, p.533; also see Farooq, et al., 2017). At its core, this umbrella encompasses product design, process, logistics/planning, and information exchange technologies (Kotha & Swamidass, 2000). These technologies form the building blocks of smart production systems, now increasingly subsumed under the Industry 4.0 and 5.0 umbrellas (Szalavetz, 2019).

Many of these technologies have flexibility built into their very architecture. For example, computer numerically controlled machines (CNC) support a wide product range by reducing setup times through special holding devices, automatic loading devices, and so on (Koc & Bozdag, 2007). Likewise, computer-aided design/engineering/manufacturing (CAD/CAE/CAM) links product design to manufacturing, allowing easy design modifications and expanding product range. Many technologies incorporate modular platforms, which enable easy installation of varied combinations as well as easy "assembl[y] and disassembl[y] during the operation stage to obtain different configurations for satisfying different manufacturing requirements" (Gadalla & Xue, 2017, p.1440). Thus, it is easy to appreciate why researchers have argued that AMT and "computer-based controls have improved machine and process flexibility" (Schmenner & Tatikonda, 2005, p.1184).

Despite robust conceptual arguments, however, empirical studies have offered only "mixed conclusions concerning the relationship between advanced manufacturing technologies and manufacturing flexibilities" (Narasimhan, et al., 2004, p.93). While some have found positive relationships (e.g., Khanchanapong, et al., 2014; Lei, et al., 1996; Mishra, et al., 2018; Zhang, et al., 2003), others have reported that "machine flexibility undermines rather than fosters … [manufacturing] flexibility" (Karuppan & Ganster, 2004, p.539; also see Bicheno & Holweg, 2009; Nicholas, 2011; Prester, et al., 2018). Our literature search identified three major shortcomings that have contributed to the confusion surrounding the AMT-flexibility relationship.

The Impact of AMT-Deployment

A major source of conflicting results could be emerging from the ambidextrous nature of AMT, which allows them to be deployed to support markedly different operations capabilities, namely flexibility or cost (Narasimhan, et al., 2004). Thus, studies that ignore the motivating purpose behind AMT deployment are likely to be confounded. AMT's numerous mix-and-match modules, together with need-based activation, can provide economies of scope (Gadalla & Xue, 2017), while rapid capacity expansion through modular platforms (Deif & ElMaraghy, 2017) can enable economies of scale with large volume production at higher efficiency, tighter tolerances, better quality, and higher yield rates. Both flexibility and scalability are prized as valuable characteristics of the manufacturing system under Industry 4.0. This ambidexterity is not limited to selecting suitable AMT elements or modules. Rather, even very similar-looking AMT portfolios can yield different outcomes depending on each firm's "different structural and infrastructural choices" (Chung & Swink, 2009, p.541). Conversely, a particular "capability can be related to more than one AMT" (da Costa & de Lima, 2009, p.91), so different firms can choose "to achieve the same operational objectives by having different portfolios of AMTs" (Cheng, et al., 2018, p.244). Thus, many AMT elements can be ambidextrous ex-ante, but they get locked into a particular orientation depending on the host of accompanying structural and operational decisions; that is, the die is finally cast at the deployment stage.

Against this backdrop, the contingency theory provides a very useful lens for studying the AMT-flexibility relationship (Cheng, et al., 2018; Prester, et al., 2018). Different firms are likely to deploy AMT differently depending on whether they pursue Porter's (1980) differentiation versus cost-leadership strategies (Kotha & Swamidass, 2000). Conceptually, firms following such vastly "different market strategies" (Chung & Swink, 2009, p.541) can be expected to seek quite varied levels of flexibility; therefore, they will deploy their AMT accordingly. As a result, we see a need to introduce an intermediary construct in the AMT-flexibility relationship, namely AMT-deployment.

Using an Input-Based Approach to Measure AMT

Another drawback is that researchers have frequently conceptualized AMT "in terms of a list of individual technologies" (Cheng, et al., 2018, p.244), or discrete choices that a firm can either adopt or not (Mathiesen, 2012). Such an input-based approach "can be problematic" (Cheng, et al., 2018, p.244) since AMTs "are usually elements of broader manufacturing and business systems with different characteristics … [which] can be modified in numerous ways to match the peculiar needs of the specific organization" (Matthiesen, 2012, p.5). Thus, we concur with other researchers that the literature has not matured to the point where it can clarify "to what extent the input variables chosen are relevant and sufficient to explain different performance levels" (Matthiesen, 2012, p.4; see also Bennett, 2014; Farooq, et al., 2017).

As the contingent resource-based view of the firm (RBV) informs us, firms derive competitive advantage not just by acquiring resources but by strategically assimilating them into their business processes (Costa, et al., 2012; Jacobides, et al., 2012). Even more significant than the specific AMT elements, it is "the issues regarding the management process, from the planning to installation/implementation" that will determine the outcomes (da Costa & de Lima, 2009, p.75; see also Farooq, et al., 2017; Mishra, et al., 2018). Thus, an important weakness of the input-based approach is a lack of consideration of the whole host of "different structural and infrastructural choices" (Chung & Swink, 2009, p.541), including differences such as shopfloor practices, setup practices, changeover frequency, production run length, scheduling and inventory policies, training practices, engineering staffing levels, and so on. These very choices allow different firms to pursue similar ends even by adopting dissimilar AMT elements or dissimilar ends while adopting similar AMT elements. Thus, it can be misleading to associate specific AMT elements with scope versus scale.

Exciters Becoming Satisfiers in Technology Growth Cycle

Another confusion arises with rapid innovations in manufacturing technologies. As AMT features that were yesterday's exciters/delighters become today's satisfiers embedded into the basic machine architecture, firms are compelled to adopt technologies more advanced than their needs (da Costa & de Lima, 2009). Therefore, it is not uncommon for firms to possess features they don't care to deploy. Thus, even if two firms possess similar AMT elements, different strategic objectives will motivate differences in deployment, which can confound the AMT-flexibility relationship using an input-based approach. Given the limitations of survey-based research, not only is it impractical to evaluate every possible combination of technologies installed, but even more impossible to capture every nuance of deployment. Moreover, few firms will feel comfortable divulging detailed information on their technology, some of which may be proprietary, making an input-based examination of AMT somewhat unreliable.

To conclude our literature review, the current research regarding the AMT-flexibility relationship is still inconclusive. In particular, inadequate attention has been paid to the strategic context that motivated AMT deployment. When different firms deploy AMT to pursue vastly differing strategic objectives, the ensuing levels of flexibility are bound to be different. Moreover, when different firms can pursue similar (dissimilar) strategic objectives using dissimilar (similar) AMT portfolios, the particular combination of AMT elements adopted is unlikely to fully explain the level of flexibility attained. Thus, there is a great need to examine how flexibility is impacted by the deployment of AMT in the pursuit of scope versus scale, including the totality of infrastructural and operational decisions.

MODEL DEVELOPMENT

The AMT universe is complex, with endless mix-and-match combinations of AMT elements, modules, operationalization, managerial practices, etc. Therefore, instead of taking the existing approach of viewing AMT from the input side, we approach it in terms of its deployment. Invoking the rational choice theory (Becker, 1976), we can infer that decision makers will make rational choices consistent with their strategic focus, driving the totality of infrastructural and operational decisions, including what AMT elements to adopt and how to operationalize them. We refer to this totality of decisions as "AMT deployment". Our research model examines how such differences in AMT deployment impact the level of manufacturing flexibility attained. To help the reader better visualize our conceptualization of AMT deployment and how it may be exhibited at the shopfloor level, we present some observations from our field visits to ten plants in the printed circuit board (PCB) industry, with the caveat that these should not be viewed as grounded or case study research.

Shopfloor View of AMT Deployment

The PCB industry presented an excellent venue to observe AMT deployment at the shopfloor level since it is common to find deployment instances in pursuit of both cost-leadership and differentiation. The typical customers of PCB firms are original equipment manufacturers (OEMs). We noticed one set of PCB firms catering to OEMs that faced rapid new product development and frequent product changes, and whose end products featured ever-increasing functionality and miniaturization, for example, cell phones, laptops, and tablets. The complexity of PCBs required left no recourse but to employ AMT. The demand cycle was often very short. The OEM placed an order of 5 to 50 prototype PCBs to be delivered rapidly. Next came a quick turnaround pilot order of 100 to 1000 PCBs. These PCBs were rapidly incorporated into OEM products and test marketed, which often brought design modifications. The final OEM product launch then translated into larger PCB orders, but the proprietary nature of PCB designs precluded inventory. The managers opined that their profitability depended on the ability to produce a wide range of complex PCBs with high functionality and miniaturization, so they equipped themselves with AMT that could produce multi-layered PCBs with minutely small holes and lines. To switch products quickly, these firms also installed substitutable AMT modules. They employed more design engineers who interacted frequently with the OEM's engineers, such as performing design-for-manufacturing (DFM) checks and recommending design changes, especially in complex designs. The firms adopted several lean management practices and pursued process improvements such as setup reduction, throughput reduction, reduced material handling time, and so on. Finally, the firms valued employee skills and experience and provided extensive training. As we can see from the above description, this group of firms had adopted AMT along with a host of structural and operational decisions, all harmonized in pursuit of scope. We characterized such deployment as $\text{AMT}_{\text{Scope}}$.

We also observed another set of PCB firms catering to OEMs in mature markets with infrequent design changes (e.g., toys, LED-lights, timing-circuits, etc.) who demanded extremely high volumes and low cost. These simple PCBs could often be produced using simple equipment, therefore not requiring AMT. Yet, the firms acquired AMT to improve their performance by cutting down processing time, providing tighter tolerances, and improving yield rates. Managers commented that high capital intensity due to AMT hindered their ability to economically handle small volume orders, so they catered to exceptionally large orders, often repeating orders from a relatively limited number of customers. Simpler PCB designs and infrequent design changes allowed these firms to reduce costs by employing fewer design engineers. Thus, we see that this group of firms had adopted AMT along with a set of structural and operational decisions harmonized in pursuit of scale. We characterized such deployment as $\text{AMT}_{\text{Scale}}$.

Model

To develop our model, we conceptualized AMT deployment along a continuum anchored at scale-oriented ($\text{AMT}_{\text{Scale}}$) on one end and scope-oriented ($\text{AMT}_{\text{Scope}}$) on the other. Intuitively, we may expect that the more exclusively a firm focuses on one or the other orientation, the greater its ability to harmonize the countless decisions associated with its AMT deployment will be. Thus, firms with a clear focus on scale would fall at the lower end of the continuum, firms with a clear focus on scope would fall at the upper end, and firms with mixed priorities would fall in the middle.

Drawing on the contingency theory, Kotha & Swamidass (2000) introduced the notion of strategy-AMT fit. Extending that notion to our model, we may expect firms pursuing differentiation strategy to emphasize $\text{AMT}_{\text{Scope}}$. These firms would adopt appropriate AMT elements and operationalize them suitably to seek high flexibility. Thus, the greater a firm's scope orientation, the markedly higher levels of flexibility we may expect to see. Alternatively, firms pursuing a cost-leadership strategy would emphasize $\text{AMT}_{\text{Scale}}$. These firms would seek greater scale-orientation that would lead to markedly lower flexibility. Meanwhile, firms with mixed priorities would achieve moderate flexibility.

As the above discussion illustrates, conceptualizing AMT deployment along a continuum allows us to cut through the complexity of the AMT universe by focusing on the salient commonalities that endure across vastly different AMT installations without getting confounded by the potentially endless dissimilarities.

Hypotheses

Our research model specifically focuses on the AMT deployment-flexibility relationship, so manufacturing flexibility is our dependent variable of interest. While researchers have introduced many dimensions of flexibility, most agree that the core dimensions include (1) mix flexibility (ability to offer a wide product range), (2) delivery flexibility (ability to shorten delivery time to expedite customer requests), and (3) volume flexibility (ability to offer a wide range of order sizes) (e.g., Gerwin, 1987; Sawhney, 2006; Slack, 1983). Accordingly, we focus on these three flexibility dimensions.

Mix Flexibility

Several researchers have reported evidence that AMT adoption will positively impact flexibility (e.g., Khanchanapong, et al., 2014; Lei, et al., 1996; Meredith, 1988; Mishra, et al., 2018; Mohamad, et al., 2001; Zhang, et al., 2003). These studies did not make a distinction between differentiation versus cost-leadership strategies. However, the contingency theory informs us that firms pursuing differentiation will seek greater scope. The deployment of $\text{AMT}_{\text{Scope}}$ aligns well with meeting varied customer demand, in other words, mix flexibility. Several studies have pointed out that computer-based controls, faster setups, automated tool changing, and so on allow rapid product changeover (Koc & Bozdag, 2007). Deploying $\text{AMT}_{\text{Scope}}$ to emphasize such features can improve mix flexibility.

Meanwhile, researchers have repeatedly cautioned that deploying AMT for high-volume production of few parts will dampen flexibility (e.g., Gerwin, 1987; Jaikumar, 1986; Karuppan & Ganster, 2004; Schonberger & Brown, 2017). These warnings provide strong rationale that firms deploying $\text{AMT}_{\text{Scale}}$ will experience lower flexibility. Scale implies long production runs with infrequent product changeovers, precluding a wider range of customer orders. Accordingly, we hypothesize that:

H-1: *Deployment of AMT for scope (scale) over scale (scope) will have a positive (negative) effect on mix flexibility.*

Delivery Flexibility

As noted above, AMT features that enable rapid changeover will allow the firm to pivot quickly, which can shorten the response time. Thus, $\text{AMT}_{\text{Scope}}$ can facilitate shrinking of the delivery timeframe to expedite customer requests, improving delivery flexibility. On the other hand, high-volume production will not allow rapid pivoting from one customer order to the next, thus hampering the ability to expedite customer requests. Although requests may be accommodated via make-to-stock (MTS) inventory, the manufacturing process itself would not boast delivery flexibility. Accordingly, we hypothesize that:

H-2: *Deployment of AMT for scope (scale) over scale (scope) will have a positive (negative) effect on delivery flexibility*.

Volume Flexibility

As a firm deploys $\text{AMT}_{\text{Scope}}$ to pursue differentiation, its chances of encountering a wide range of orders with varying volumes will be greater. Often, "practices supporting mix flexibility … support volume flexibility too" (Salvador, et al., 2007, p.1187), for example, setup reduction can improve both flexibilities (Hallgren & Olhager, 2009). On the other hand, there is also evidence that "multiple trade-offs do exist" (Salvador, et al., 2007, p.1187). Thus, the effect of $\text{AMT}_{\text{Scope}}$ on volume flexibility is not entirely clearcut.

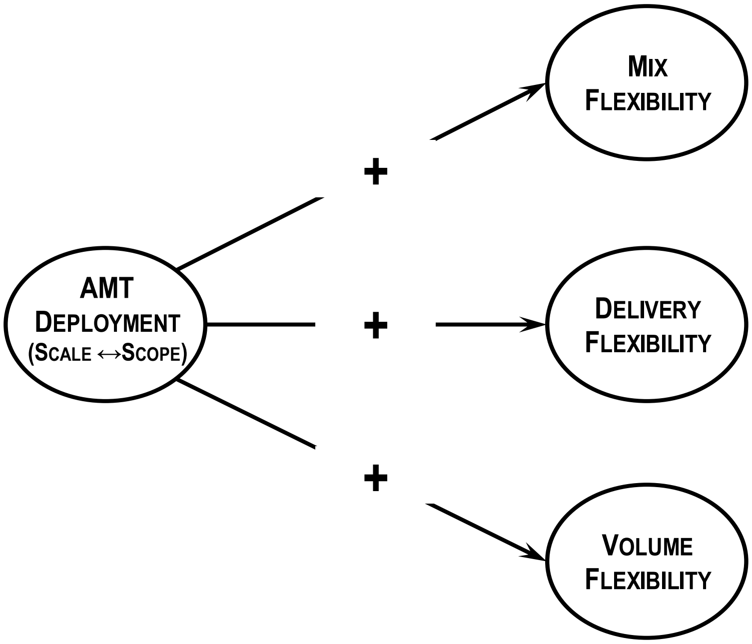
Looking at scalability, a firm deploying $\text{AMT}_{\text{Scale}}$ can quickly ramp production volume up or down, which can potentially enhance volume flexibility. However, high-volume production often becomes mandatory in a highly competitive market with standard products "to help offset high costs of equipping with such machines" (Schonberger & Brown, 2017, p.84). As such, the inability to undertake small jobs becomes verily the opposite of volume flexibility. Thus, the effect of $\text{AMT}_{\text{Scale}}$ on volume flexibility is also not clearcut.

In view of the conflicting effects noted above, we adopt a conservative viewpoint to hypothesize that:

H-3: *Deployment of AMT for scope (scale) over scale (scope) will have a small positive (negative) effect on volume flexibility*.

The above hypotheses are captured in the research model shown in Figure 1.

FIGURE 1
RESEARCH MODEL



RESEARCH METHODOLOGY

PCB Industry

As we described earlier, the printed circuit board (PCB) industry provided an ideal venue to study dissimilar patterns of AMT deployment. In addition, the level of equipment sophistication in this industry is such that every plant will surely have deployed some form of AMT. Finally, this industry operates with minimal inventories. Inventory is well-recognized as a variable that can confound the AMT-flexibility relationship since "buffer stocks can increase … volume, mix, or delivery responsiveness" (Reichhart & Holweg, 2007, p.20). Eliminating this confound provides a cleaner examination of true flexibility, with no inventory to fall back upon. As expected, the firms pursuing differentiation operated on a make-to-order (MTO) basis. Interestingly, even the firms pursuing cost leadership were precluded from holding inventory due to the proprietary nature of PCB designs, resulting in a quasi-MTO environment.

Survey Approach

The respondent in each PCB plant was the senior manager responsible for operations. A stratified sample of 180 plants included an equal number of plants from each of the three plant-size strata. Thirteen plants were outside the sample frame. 74 usable responses from the reduced sample of 167 firms resulted in a 45% response rate. This high response rate across all plant-size strata indicates that the responses are well representative of the population (see Table 1). Moreover, the responding firms accounted for nearly 70% of total industry sales, indicating that the sample size was ample relative to the industry.

TABLE 1
SAMPLE STRATIFICATION AND RESPONSE RATE

PLANT SIZE (EMPLOYEES)	< 50	51-100	> 100	Total
RESPONSE	21/54 (39%)	26/56 (46%)	27/57 (47%)	74/167 (45%)

Measuring the Variables

Our conceptualization of AMT deployment as a continuum from $\text{AMT}_{\text{Scale}}$ to $\text{AMT}_{\text{Scope}}$ is simple in concept. It yet seeks to holistically capture: (1) the strategic intent behind the deployment, (2) the numerous mix-and-match combinations of AMT elements, as well as (3) the variations in activation at the day-to-day operational level. Recognizing the difficulty of such measurement, we limited our study to a single industry (PCB) to avoid the confounds of dealing with vastly different AMTs. Focusing on a single industry also anchors the comparability of individual responses and supports localized theory building (Stevenson & Spring, 2007). These inherent advantages outweighed the disadvantages, such as limiting our sample size or potentially restricting generalizability.

As we noted earlier, looking simply at a tally of the installed AMT elements "can be problematic" (Cheng et al., 2018, p.244) since firms can deploy the same AMT elements to achieve different ends. Moreover, the measures commonly found in the literature do not capture the variable that is of interest in this study, namely the strategic deployment of AMT as $\text{AMT}_{\text{Scale}}$ versus $\text{AMT}_{\text{Scope}}$. For example, measurement items used by previous researchers, such as "CAM technology practice is applied" (Nair & Swink, 2007, p.747) or "this machine can use many different tools" (Karuppan & Ganster, 2004, p.544) fail to consider the strategic context, nuances of deployment, or even the interplay among the technologies (Cheng, et al., 2018).

Leaning on our field observations, we noticed that the firms we characterized as deploying $\text{AMT}_{\text{Scale}}$ were more heavily geared for high-volume production. Accordingly, we measured three items to capture the deployment of $\text{AMT}_{\text{Scale}}$ in the PCB industry, each focusing on volume from a different angle: (1) the typical order size produced, (2) the maximum number of panels produced per shift, and (3) the maximum number of panels produced in any one month within the last two years. Within the context of this industry, these items readily captured what the firm was geared to accomplish, minimizing any halo effect inherent in managers' perceptions (Boyer & Lewis, 2002).

Conversely, the plants we characterized as deploying AMT_{Scope} were more heavily geared for producing a greater complexity and range of PCBs, such as boards with multiple layers, smaller drilled holes, and thin lines. Accordingly, we measured three items to capture the deployment of AMT_{Scope} in the PCB industry: (1) the largest number of layers, (2) the smallest micro-vias, and (3) the thinnest traces (linewidth) that the plant was capable of producing.

To form the AMT deployment continuum, we reverse-coded the three AMT_{Scale} items, then standardized and averaged all six AMT_{Scale} and AMT_{Scope} items. This procedure allowed us to create an index with the following characteristics. (1) Firms with a clear strategic scope orientation would obtain high scores on the AMT_{Scope} items *and* low scores on the AMT_{Scale} items, thereby scoring high on the index. (2) Firms with a clear strategic scale orientation would obtain high scores on the AMT_{Scale} items *and* low scores on the AMT_{Scope} items, thereby scoring low on the index. (3) Firms without a clear strategic focus on either scope or scale would obtain mediocre scores on the AMT_{Scale} and AMT_{Scope} items, thereby scoring moderately on the index.

Mix flexibility is defined as the ability of the system to produce a particular mix of products within the minimum planning period (Gerwin, 1993; Slack, 1983). Specifically in the context of strategy-AMT fit, Kotha & Swamidass' (2000, p.261) description of the differentiation strategy led us to view mix flexibility in terms of: "wide range of products", "frequent new product development and high product variety", "more complex product lines and several discontinuities in the process side". In the PCB product lifecycle, most design changes occur at the prototype stage. Therefore, we measured mix flexibility using four items: (1) the extent to which each order is different from others in terms of process complexity; (2) the extent to which prototype orders are encouraged; (3) the extent to which rush orders are encouraged; and (4) how this plant compares with competitors on the range of PCBs. The fourth item was included based on Hallgren and Olhager (2009), who asked plant managers to compare against their competition.

Delivery flexibility is frequently defined in terms of time and speed. It is viewed as the ability (i) to offer quick delivery (Ketokivi, 2006; Sawhney, 2006), and (ii) to change planned delivery dates (e.g., Gosling et al., 2010), such as by shrinking the lead time at short notice. Therefore, we measured delivery flexibility using four items (reverse coded): (1) the time promised for regular orders; (2) the time promised for rush orders; (3) the time taken to finish regular orders once released to the shopfloor; and (4) the time taken to finish rush orders.

Volume flexibility is defined as the ability to increase or decrease volume within the short term while remaining profitable (Gerwin, 1993; Slack, 1983). It is also viewed as the "ability to rapidly adjust capacity" (Vickery, et al., 1999, p.19; see also Narasimhan, et al., 2004), typically "within a small range at least in the short-term" (Rogers, et al., 2011, p.3777). Hallgren & Olhager (2009) asked plant managers to compare it to their competition. Therefore, we measured volume flexibility using four items: (1) how the plant compares with its competitors on the speed of ramping production volumes up and down; (2) customer need of a large range of volumes; (3) the extent to which each order is different from others in terms of quantity requested; and (4) how much the plant capacity can be increased within two weeks.

Our final measurement scales are shown in Table 2.

Model Testing

The model was estimated using partial least squares structural equation modelling (PLS-SEM) with SmartPLS software (version 4.0.8.4; Ringle, et al., 2022). Given the previously uncharted territory we sought to explore in our research model, we considered an exploratory approach the most appropriate. The PLS-SEM methodology fits well with this exploratory approach as it imposes fewer constraints regarding prior theory (Chin, 1998); it can handle relatively small sample sizes such as with our single-industry sample; it does not impose requirements of multivariate normal data distributions; and the measurement properties of constructs are less restrictive (Hair, et al., 2019). The results of the analysis are shown in Figure 1. We first proceed to validate the constructs before examining the model relationships.

Construct Validation

We undertook several steps to ensure the validity of the measurement instruments. The survey instrument was developed after interviews at different organizational levels, factory visits, and analysis of company documents, followed by pilot tests at two sites. After review by both industry experts and colleagues, a revised questionnaire was pre-tested with three managers to ensure content validity. A 45% response rate on the survey also indicated the strong support received from the PCB industry.

To check for non-response bias, we compared the profiles of responding and non-responding plants to identify any systematic differences that might explain the non-responses. Further, the last one-fourth of the surveys received were not statistically different from the first one-fourth. We made random telephone calls to cross-validate the data. We also compared the survey responses against the respondents' web sites and other public information and made calls to verify seemingly questionable responses and complete missing responses.

TABLE 2
MEASUREMENT SCALES

AMT DEPLOYMENT (SCALE↔SCOPE)	
AMT_{Scale}	
AMT_{Scale}-1 *	What is the maximum square meters of panels that can be processed per shift?
AMT_{Scale}-2 *	What was the plant's highest panel production in any one month?
AMT_{Scale}-3 *	What is the quantity for a typical order that is most representative of this plant?
AMT_{Scope}	
AMT_{Scope}-1	What is the largest number of layers the plant can produce (@ 95% yield rate)?
AMT_{Scope}-2 *	What is the smallest hole size the plant can produce (@ 95% yield rate)?
AMT_{Scope}-3 *	What is the smallest line size the plant can produce (@ 95% yield rate)?
MIX FLEXIBILITY	**COMPOSITE RELIABILITY = 0.809; AVE = 0.586**
MF1	Each order is different from others in terms of process complexity (Agree/Disagree)
MF2	Prototype orders are encouraged (Agree/Disagree)
MF3	Rush orders are encouraged (Agree/Disagree)
MF4 †	How does this plant compare with your competitors on product range?
DELIVERY FLEXIBILITY	**COMPOSITE RELIABILITY = 0.909; AVE = 0.716**
DF1 *	Time (days) promised for regular order delivery
DF2 *	Time (days) promised for rush order delivery
DF3 *	Time (days) taken to finish regular orders once released to the shopfloor
DF4 *	Time (days) taken to finish rush orders once released to the shopfloor
VOLUME FLEXIBILITY	**COMPOSITE RELIABILITY = 0.811; AVE = 0.683**
VF1	How does this plant compare with your competitors on speed of ramping production volumes up and down?
VF2	What is your assessment of customer need of PCBs in large range of volumes?
VF3 †	Each order is different from others in terms of quantity requested (Agree/Disagree)
VF4 †	How much can the plant capacity be increased within two weeks?

* Reverse coded; † Dropped from model (poor loading)

We examined the indicator loadings to ensure construct reliability and employed bootstrapping (n = 5,000) to test their significance. As shown in Figure 2, we had to drop one item for mix flexibility and two items for volume flexibility. The remaining loadings are ≥ 0.7 and significant at $p \leq 0.01$. The descriptive statistics for these items are given in the Appendix. We also examined the internal consistency of the model constructs using Composite Reliability (Werts, et al., 1974) which, being "computed within the context of a research model, … better reflects the fact that theory and measurement are necessarily intertwined"

(Sumukadas & Sawhney, 2004, p.1020). Moreover, unlike Cronbach's alpha, Composite Reliability is more general and is not adversely influenced by a smaller number of scale items, average item inter-correlation, and dimensionality. As shown in Table 2, all the values are adequate and ≥ 0.7. In addition, the average variance extracted (AVE) values are ≥ 0.5, which assesses the variance that each construct shares with its indicators (Table 2). To assess discriminant validity, we employed the Fornell-Larcker criterion (Fornell & Larcker, 1981) to ascertain that the square roots of AVE were considerably higher than the inter-construct correlations, which demonstrates that each construct shares more variance with its own indicators than with other constructs (Table 3). Further, we examined the indicator cross-loadings to ascertain that each construct's indicators did not load highly on the remaining constructs (Table 4).

TABLE 3
DISCRIMINANT VALIDITY – FORNELL-LARCKER CRITERION

LATENT VARIABLE	AMT	MF	DF	VF
AMT	1.000 [*]			
MF	0.414	0.765		
DF	0.362	0.302	0.846	
VF	-0.105	-0.043	-0.107	0.826

[*] Values on the diagonal are square roots of the AVE

TABLE 4
DISCRIMINANT VALIDITY – CROSS LOADINGS

ITEMS	LATENT VARIABLES			
	AMT	MF	DF	VF
AMT	1.000	0.414	0.362	-0.105
MF1	0.385	0.765	0.162	-0.050
MF2	0.307	0.818	0.300	-0.009
MF3	0.219	0.709	0.263	-0.037
DF1	0.313	0.260	0.877	-0.166
DF2	0.333	0.383	0.829	-0.135
DF3	0.222	0.113	0.749	-0.030
DF4	0.336	0.227	0.919	-0.018
VF1	-0.093	-0.051	-0.110	0.856
VF2	-0.079	-0.018	-0.063	0.796

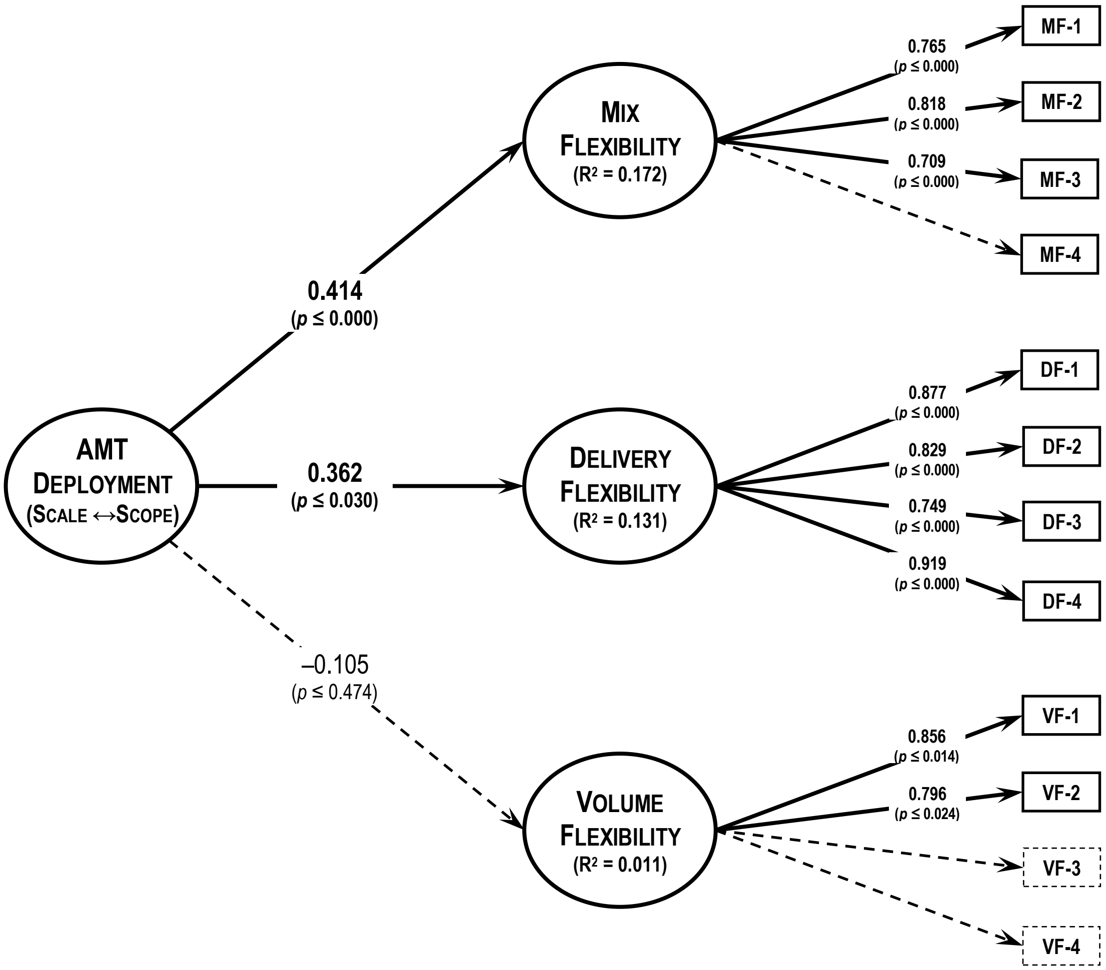
Since some variables in our model employ perceptual measures, common method variance (CMV) can present a potential threat. As recommended by Podsakoff et al. (2003, pp.887), we emphasized "procedural remedies … [to] eliminate or minimize [CMV] through the design of the study". Our study employed a relatively lengthy survey instrument with the questions spread out across the survey, thus "separat[ing] the measures of the predictor and criterion variables" (Podsakoff et al., 2003, p.897). We also followed "good measurement practice … e.g., eliminat[ing] item ambiguity, demand characteristics, social desirability" (Podsakoff et al., 2003, p.897). The variables in our model are "more concrete and less ambiguous", which also reduces the threat of CMV (Malhotra et al., 2006, p.1866). Finally, we conducted Harman's single-factor test, "arguably the most widely known approach" (Malhotra et al., 2006, p.1867), which did not indicate a single-factor structure. Accordingly, we can conclude that CMV does not present a major threat to our findings.

RESULTS

Next, we examined the structural model, that is, the relationships among the model constructs. R^2 is considered the primary indicator of model fit in PLS-SEM given its prediction orientation (Hair, et al., 2011). Our results indicate that the model explains 17.2% of the variance in Mix Flexibility ($R^2 = 0.172$) and 13.1% in Delivery Flexibility ($R^2 = 0.131$), which can be considered adequate given the exploratory context of this research. Meanwhile, the model explains only 1.1% of the variance in Volume Flexibility ($R^2 = 0.011$), suggesting that some explanatory factors for this flexibility dimension lie outside the model.

The path coefficients are shown in Figure 2 along with significance levels established through bootstrapping (*n* = 5,000). AMT deployment has a significant positive effect on mix flexibility (0.414, $p \leq 0.000$), which supports Hypothesis 1. Likewise, AMT deployment has a significant positive effect on delivery flexibility (0.362, $p \leq 0.030$), which supports Hypothesis 2. However, AMT deployment does not significantly impact volume flexibility (–0.105, $p \leq 0.474$).

FIGURE 2
RESULTS



The significant effect across two of the three flexibility dimensions dovetails directly into the widely held view that AMT supports flexibility, yet it clarifies that only AMT_{Scope} supports flexibility. This result also bolsters the criticisms researchers have repeatedly leveled that deploying AMT_{Scale} for high-volume production of fewer product lines will dampen flexibility. Indeed, Schonberger & Brown (2017) had coined the term *monument machines* in that very context, cautioning that “localized efficiency” could result in “the neglect of responsiveness in fulfilling customer needs” (p.84). As such, understanding the context and nature of AMT deployment can help us better explain the mixed results reported in the literature. It is important to note that our results do not simply reinforce the prevailing view that AMT should be deployed only for flexibility but not for cost. Rather, the results clarify that AMT deployed as $\text{AMT}_{\text{Scope}}$ is suitable for pursuing flexibility, but AMT deployed as $\text{AMT}_{\text{Scale}}$ will not support flexibility and will instead support cost efficiency.

AMT deployment’s nonsignificant effect on volume flexibility confirms the conflicting effects we expected based on the literature. Yet, this result is puzzling in some respects since we might expect that deploying $\text{AMT}_{\text{Scope}}$ would allow PCB firms to cater to the entire PCB lifecycle – from prototype to full production runs – which implies a wide range of production volumes. On the other hand, the “multiple trade-offs” between mix and volume flexibility (Salvador, et al., 2007, p.1187) appear to have dampened $\text{AMT}_{\text{Scope}}$’s support of volume flexibility.

CONCLUSION

Theoretical Contributions

Our study set out to unravel the confusion surrounding the AMT-flexibility relationship and examine how AMT deployment causes some firms to experience positive flexibility outcomes with their AMT while others experience negative outcomes. To grapple with the conflicting empirical evidence, we have reevaluated the prevailing paradigm to identify and eliminate confounding effects.

Researchers have stressed the “need to identify contingencies that may govern the AMT-performance relationships” (Prester, et al., 2018, p.763), many of which lie in the domain of “implementation” and “management processes” (da Costa & de Lima, 2009, p.75; also Farooq, et al., 2017). Our findings reveal that the deployment of AMT as $\text{AMT}_{\text{Scale}}$ versus $\text{AMT}_{\text{Scope}}$ is an important contingency that helps reconcile the inconsistent prior findings. Given the salience of this contingency, as is evident from our results, we suspect that the prior findings are likely to be confounded because those studies have not factored in this contingency. Firms pursuing differentiation versus cost-leadership strategies are known to make different infrastructural and operational choices, which will naturally lead to different flexibility outcomes despite apparently similar AMT. Our findings indicate that, driven by their strategic needs, firms deploying $\text{AMT}_{\text{Scope}}$ derive flexibility, specifically mix and delivery flexibility. Meanwhile, those deploying $\text{AMT}_{\text{Scale}}$ sacrifice multiple dimensions of flexibility in favor of cost-efficiency. In that regard, our results support the contingency theory view that “strategy-AMT fit leads to superior firm performance” (Kotha & Swamidass, 2000, p.258; also Congden, 2005).

Our model also eliminates another confound that researchers have commonly encountered in measuring AMT adoption. As noted earlier, AMTs are not discrete units but can be modified endlessly, so different firms may achieve similar strategic objectives by deploying different portfolios (Cheng, et al., 2018; da Costa & de Lima, 2009). Our conceptualization of AMT deployment along a continuum from $\text{AMT}_{\text{Scale}}$ to $\text{AMT}_{\text{Scope}}$ greatly simplifies the classification of AMT based on salient similarities. This classification not only dovetails nicely with two common operations strategies – differentiation and cost-leadership – but also allows us to bring both the scalability and flexibility features of AMT into the realm of strategic considerations. In contrast, measuring the numerous possible mix-and-match combinations of AMT features is not only a complex exercise, but the literature reveals that it has also not clarified the AMT-flexibility relationship (Matthiesen, 2012).

Another interesting result is AMT deployment’s non-significant effect on volume flexibility. Speculation has sometimes been expressed that because AMT can provide scalability, it will naturally result in greater volume flexibility by enabling rapid transitioning between low- and high-volume production (Schmenner & Tatikonda, 2005). However, as suggested by our results the efficiency focus of $\text{AMT}_{\text{Scale}}$ stresses high-volume production to the exclusion of low-volume, which detracts from volume flexibility.

Our results show that AMT can have a different impact on delivery, mix, and volume flexibility. Thus, our findings highlight the need for future studies to re-conceptualize the link between *machine flexibility* and each dimension of *manufacturing flexibility*. It is an oversimplification to assume that machine flexibility will produce all-round enhancements across different dimensions of manufacturing flexibility.

Studies have often overlooked the impact of inventory on flexibility, whereas it must be treated as a non-trivial factor. Focusing on the PCB industry with its predominantly MTO environment, our study has provided some level of natural control for this factor. Thus, our study has brought this additional level of clarity, which we enjoin other researchers studying manufacturing flexibility to incorporate in their studies.

Managerial Implications

Instead of viewing AMT as a bundle of diverse technologies, our findings reveal that a focus on AMT deployment better captures the principle of "strategy-AMT fit" (Kotha & Swamidass, 2000; Prester, et al., 2018). Our results confirm what many researchers have feared – that deploying AMT for cost-leadership will dampen flexibility. The literature has frequently viewed this result to imply that deployment of AMT for cost-leadership is tantamount to mismanagement. However, our study suggests a different conclusion – that $\text{AMT}_{\text{Scale}}$ can be an intentional, strategic deployment decision related to the firm's scalability needs. This latter implication is more congruent with managerial practice, even as it upends the prevailing view that AMT "should not be used by companies competing mainly on the basis of cost" (Karuppan & Ganster, 2004, p.537).

There is often a presumption in the literature that firms always have a choice to acquire simple versus sophisticated machines according to their exact needs. This notion is not completely accurate. Over time, the optional, "order winning" features from previous vintages get absorbed into the base architecture of future models, so newer equipment tends to be more heavily automated and feature rich (e.g., Schmenner & Tatikonda, 2005). Thus, firms often have little choice between investing in AMT versus non-AMT (da Costa & de Lima, 2009), so the option to use "simple, inexpensive, focused equipment" (Schonberger & Brown, 2017, p.84) for high-volume production may be infeasible. In such circumstances, the managerial question becomes not about whether to adopt AMT, but rather about how best to deploy AMT to support the strategic goals. As we noticed in the PCB industry, while firms that pursue differentiation must necessarily adopt AMT for producing complex products, firms that pursue cost-leadership also choose to adopt AMT to improve efficiency, quality, and yield rates. These latter firms must deploy $\text{AMT}_{\text{Scale}}$, which will naturally compromise flexibility. Yet, they must take this step knowingly and make suitable adjustments such as by pursuing high efficiency, running large volume orders, and so on.

The conflicting results to date in the literature have caused much uncertainty for managers wanting to invest in AMT. Our results clarify that AMT can serve either the flexibility or the efficiency requirements of the firm, provided it is matched by appropriate deployment and reinforced with suitable business processes and managerial practices. Thus, our conceptualization brings the *implementation* of technology into the forefront rather than the discrete technologies themselves. Managers need to be clear upfront about their strategic objectives and must consciously deploy AMT to derive either flexibility or efficiency. AMT being a sizable investment, it can be a very expensive mistake to simply assume that it will enhance flexibility without considering its strategic deployment. Paying attention to strategy-AMT fit will force managers to recognize the numerous accompanying changes that need to be made to ensure that investments in AMT do not end up as expensive white elephants.

It is worth highlighting that this strategic decision has implications beyond just manufacturing; this information needs to also be shared with the marketing and human resources (HR) managers so that appropriate adjustments are also made to the marketing and HR strategies. While $\text{AMT}_{\text{Scope}}$ requires marketing to attract differentiated orders at premium price (such as PCB orders that go through the entire cycle of prototype, pilot and regular orders), $\text{AMT}_{\text{Scale}}$ requires marketing to attract orders of large volumes (such as contract manufacturing). Similarly, $\text{AMT}_{\text{Scope}}$ requires HR to train employees in quick product changeovers and hire a larger number of design engineers. As well, when deploying $\text{AMT}_{\text{Scope}}$ managers must ensure that performance criteria do not incentivize high equipment utilization, which would push "localized efficiency to the neglect of responsiveness in fulfilling customer needs" (Schonberger & Brown, 2017, p.84), thereby essentially negating the very purpose of $\text{AMT}_{\text{Scope}}$. As such this paper highlights the need for the operations, marketing, and HR managers to work together to make the deployment of $\text{AMT}_{\text{Scale}}$ or $\text{AMT}_{\text{Scope}}$ a financially viable decision.

Directions for Future Research

The development of a strong theoretical foundation for deploying AMT as either $\text{AMT}_{\text{Scale}}$ or $\text{AMT}_{\text{Scope}}$ is yet in its infancy. Therefore, additional theoretical and empirical research is needed regarding the relationships examined in this paper. Given the paucity of prior empirical work regarding the AMT deployment-flexibility relationship in general, and especially the newness of our conceptual framework examining deployment patterns in terms of $\text{AMT}_{\text{Scale}}$ and $\text{AMT}_{\text{Scope}}$, the construct development and measurement aspects of our study should be further refined. Our study has explored these relationships using measurement items that are somewhat specific to the PCB industry context. A natural order of progression would involve repeating this study with larger samples of firms in other industry settings; it will also allow researchers to tease out the impact of AMT deployment on volume flexibility, which was non-significant in our study. Our study has been limited to a single industry (PCB), which by design has afforded us greater clarity by excluding potential extraneous factors, but also limited our sample size and the generalizability of our findings in some respects. In addition to examining the model in other industries, more research is also needed on the strategic motivators of investments in AMT, as well as the link between AMT deployment and other flexibility dimensions.

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APPENDIX: DESCRIPTIVE STATISTICS AND ITEM CORRELATIONS

	ITEM	MEAN	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	AMT$_{\text{Scale}}$-1	-312.873	701.234	1.000																	
2	AMT$_{\text{Scale}}$-2	-9278.141	17981.677	0.781	1.000																
3	AMT$_{\text{Scale}}$-3	-29.774	60.764	0.176	0.354	1.000															
4	AMT$_{\text{Scope}}$-1	3.812	1.828	0.023	0.039	-0.059	1.000														
5	AMT$_{\text{Scope}}$-2	-2.056	0.815	-0.031	-0.144	-0.057	0.534	1.000													
6	AMT$_{\text{Scope}}$-3	-3.208	0.815	-0.116	-0.182	-0.263	0.475	0.568	1.000												
7	MF1	4.338	1.353	0.005	0.195	0.124	0.376	0.270	0.227	1.000											
8	MF2	5.833	1.546	0.176	0.338	0.033	0.197	0.148	0.094	0.335	1.000										
9	MF3	5.817	1.316	0.050	0.203	0.080	0.223	0.136	0.003	0.222	0.627	1.000									
10	MF4	4.886	1.220	-0.234	-0.259	-0.259	0.306	0.327	0.310	0.116	0.051	0.092	1.000								
11	DF1	-17.957	8.23	0.307	0.489	0.657	-0.053	-0.172	-0.158	0.120	0.303	0.197	-0.389	1.000							
12	DF2	-5.714	2.666	0.233	0.344	0.294	0.115	-0.011	0.114	0.226	0.348	0.340	-0.214	0.587	1.000						
13	DF3	-12.485	5.282	0.172	0.262	0.314	-0.012	-0.023	0.025	-0.046	0.195	0.169	-0.073	0.693	0.371	1.000					
14	DF4	-4.067	2.137	0.376	0.471	0.454	0.012	-0.106	-0.071	0.190	0.159	0.170	-0.182	0.707	0.750	0.613	1.000				
15	VF1	4.859	1.17	-0.194	-0.319	-0.080	-0.068	0.094	0.231	-0.126	0.041	0.002	0.376	-0.142	-0.174	0.079	-0.082	1.000			
16	VF2	4.347	1.643	-0.084	-0.153	0.009	0.065	-0.121	0.023	0.058	-0.065	-0.068	0.125	-0.131	-0.038	-0.146	0.064	0.368	1.000		
17	VF3	5.38	1.388	0.130	0.153	0.208	0.082	-0.006	-0.151	0.317	0.116	0.098	0.094	0.060	0.093	-0.126	0.202	0.006	0.263	1.000	
18	VF4	26.875	15.533	0.022	0.106	0.181	0.063	-0.226	-0.161	0.060	0.184	0.051	-0.044	0.385	0.406	0.189	0.426	-0.098	0.018	0.233	1.000