technovation

Technovation 24 (2004) 573–583

www.elsevier.com/locate/technovation

Constructing a virtuous cycle of manufacturing agility: concurrent roles of modularity in improving agility and reducing lead time

Chihiro Watanabe*, Bernadetta Kwintiana Ane

Tokyo Institute of Technology, Department of Industrial Engineering and Management 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan

Abstract

The implementation of modularity coupled with the application of platform strategy enables vertical product line extension to satisfy dynamic fast-changing customer preferences. Modularity plays crucial roles in strengthening positive correlations between a platform of products and models, and/or its derivative models. Simultaneously, modularity increased manufacturing agility. This paper focuses on the automotive industry with the objective of investigating the concurrent roles of modularity in improving the agility of manufacturing and reducing manufacturing lead time. Our findings provide supportive demonstrations to the research hypotheses. First, in investigating the effect of modularity towards agility, we find that by playing with various possibilities for combining modules, it is possible to assemble a single flexible production line: (i) a single model in several variants, as long as production is organized in such a way as to ensure the co-ordination of the variety, (ii) several models, whereas each of which is a variation of a single platform, and (iii) customized models, simply by rearranging the different variations of the modules. Second, with respect to these findings, there is evidence that an increase in manufacturing agility reduces manufacturing lead time, which has become a significant factor in corporate competency. Modularity as a source of comprehensive innovation kickstarts the learning process that enables auto manufacturers to explore new methods of designing and manufacturing automotive products.

Keywords: Modularity; Product platform; Manufacturing agility; Manufacturing lead time

1. Introduction

Nowadays the implication of the dramatic advancement of information technology (IT) in the global marketplace is featured by fast-changing customer preferences and the increasing rate of product obsolescence. These circumstances have consequently urged manufacturing companies to offer a wider variety of products and to manage product life cycle, in order to keep steady growth (Goldman and Preiss, 1991; Nicholas, 1998). Henceforth, manufacturing companies have to increase ability to rapidly react to evolution through more frequent product replacements and the broadening of product range to penetrate different market niches in order to lead to an agile environment.

Recently, the increasing complexity of products and the greater demand for product integrity requires development and mobilization of new technologies as a set of competencies. Conventional management of product variety is based on a fundamental strategy for sharing platforms as well as mechanical and other components. In this regard, the application of modularity enables manufacturing companies to explore new methods of designing and manufacturing products, which leads to shifting from an integral and closed architecture to a modular and open architecture.

To date, the concept of modularity is still in a fluid and transitional stage. This paper attempts to provide a practical identification on the effect of modularity on machine flexibility and mix flexibility, the specific nature of flexibility on the shop-floor, as *catalysts* in the construction of a virtuous cycle of manufacturing agility.

Reviewing the literature, Anderson (1997) defined modules as building blocks, which enable manufacturing companies to customize a product by assembling various combinations of modules. *Modularity* is necessary for constructing a robust product platform (Meyer et al., 1997) and it enables manufacturing companies to offer original versions, which were in fact derivatives of their basic models.

* Corresponding author. Tel.: +81-3-5734-2248; fax: +81-3-5734-2252.

E-mail addresses: chihiro@me.titech.ac.jp (C. Watanabe); kwintian@me.titech.ac.jp (B.K. Ane).

0166-4972/$ - see front matter © 2002 Elsevier Ltd. All rights reserved.
doi:10.1016/S0166-4972(02)00118-9

Focusing on the automotive product, the application of modularity is to create flexibility in platform architecture, whereas a product can be well designed around versatile modules, common parts, common fixturing geometries, and standardized interfaces. Belis-Bergouignan and Lung (1999) defined a *platform* as a specific wheelbase: the distance between front and rear axles. This definition refers to upstream variability that represents the potential for combinatorial variety through component sharing. Meanwhile, a *model* represents a particular technical product, which has been given its own name that reflects the positioning strategy of the company in the marketplace. Then, the definition of *variant* can be distinguished into two different natures: a variant with a different type of body (sedan/saloon, coupe, and station wagon) and/or number of doors (for the same type of body), and a variant with different engines for different cylinder size. In this context, modularity provides auto manufacturers with *upgrade-ability* to extend product life cycle for a *quasistandard* product if only particular modules need to be changed, then, quickly integrate the extended product in an agile manufacturing environment.

Referring to the Center for Automation and Intelligent Systems Research (1996), agile manufacturing is defined as the ability to accomplish rapid changeover between manufacturing of different assemblies. Changeover, or setup time, represents the ability to move from the assembly of one product to the assembly of another product with a minimum of change in tooling and software. Rapid changeover has a profound effect on the manufacturing system performance since it increases flexibility, reduces work-in-process inventory, and enables production of small lot sizes (Greenwood, 1988).

Probing previous literature, Goranson (1992) found overlaps in the dimensions of agility as well as lack of a universal metric. There is no measure that identifies certain parameters or indicators of the agility. Coping with this challenge, Goldman et al. (1995) presented a comprehensive questionnaire as a guideline for monitoring various factors of agility. Then, Tsourveloudis et al. (2000) introduced an adaptive knowledge-based methodology in *fuzzy IF–THEN rules*. This metric provides decision-makers with an opportunity to examine and to compare different manufacturing systems at different agility levels. To date, inconsistent behavior of some parameters in the measurement of agility still remains. This problem emerges from the lack of one-to-one correspondence between agility factors and physical characteristics of the production system.

Meantime, the concept of manufacturing flexibility is conventionally associated with uncertainty in all levels of a firm's operation, such as variation in the demand and product characteristics or unanticipated interruptions of the production process because of machine failures, and economically external changes (Barad and Sipper, 1988; Brill and Mandelbaum, 1989; Tsourveloudis and Phillis, 1998). Olhager (1993) noted that a general relationship between profitability and manufacturing flexibility could not be developed, due to the vague character of the latter. In order to solve this problem, Browne et al. (1984) and Sethi and Sethi (1990) analyzed flexibility by defining it into 10 distinct types.

Borrowing the taxonomy of Sethi and Sethi, *machine flexibility* is regarded as the ease of making changes among various operations required to produce a set of products. Traditionally, it was measured by the number of different operations that a machine performs, and the time needed to switch from one operation to another (Buzacott, 1982; Falkner, 1986). Contrary to this traditional measurement, *mix flexibility* is defined as the number and variety of products that can be produced without incurring high transition penalties or large changes in performance outcomes (Pelaez-Ibarrondo and Ruiz-Mercader, 2001).

This paper attempts to investigate the effect of modularity towards the agility of manufacturing. Conceptually, embodiment of modularity in product architecture induces an increasing value of manufacturing agility through altering the degree of machine flexibility and mix flexibility, which in turn leads to shorter manufacturing lead time. These cause and effect relationships represent concurrent roles of modularity in constructing a virtuous cycle of manufacturing agility, which prompts us to mention the following two hypothetical views:

(i) Implementation of modularity in product architecture results in the increasing of manufacturing agility, and
(ii) Higher value of manufacturing agility leads to shorter manufacturing lead time.

In order to demonstrate the first hypothesis, we develop value of manufacturing agility which is governed by machine flexibility and mix flexibility, composed of mean completion time and total amount of products a machine is capable of fabricating in a scheduled time, as intermediary variables. We presume that an optimum level of manufacturing agility exists between its lower and upper-boundaries. For the second hypothesis, we apply the model of Viswanadham et al. (1992), which employs the variables: setup time, processing time, time to move a workpiece from one operation to the next operation, inspection time, and waiting time in the queue in front of a machine. In our research, measurement is conducted under a framework of flow-type of mass production, mass customization, and job shop for customized models.

Section 2 explains the analytical framework that involves our research methodology and data construction, Section 3 clarifies the research findings, Section 4 describes the analysis, and Section 5 briefly summarizes new findings and implications.

2. Analytical framework

An empirical analysis was conducted focusing on a passenger car chassis. Using the Toyota Eco Cars: *Prius*, *Estima*, and *Crown*, we design a research methodology that encompasses the stages of hypothetical system development, model development, a simulation scenario and data construction.

2.1. The hypothetical system

The Toyota Eco Cars are hybrid vehicles, which are assumed to be designed from the same platform using the Toyota Hybrid System (THS) technology. Toyota Motor Corporation (2002) is to develop the original THS technology for *Prius* as a combination of the high expansion-ratio Atkinson cycle engine and an electric motor, which is powered by a sealed nickel–metal hydride (Ni-MH) battery. This ultimate eco fuel doubles the fuel economy and decreases the CO_2 emissions of a gasoline engine by half, while enabling CO, HC, and NO_x emissions to be reduced below those of the Euro4 and California SULEV engine. In addition, according to *Estima*, this model is manufactured using the Toyota Hybrid System-CVT (THS-C), which features a gasoline engine, a front–rear electric motor, an Ni-MH battery, and CVT for front-wheel power of larger cars and minivans. Then, *Crown* is designed to use the "mild hybrid" (THS-M) technology, a simpler and less expensive alternative to fully fledged THS, which is assembled as a combination of a gasoline engine, a motor/generator, and 12–36 V batteries to create an economical system.

We develop a hypothetical U-shaped single production line of hybrid vehicle chassis. The production line, a system of linked cells that are completely automated by virtue of robots and computer control, is aimed to achieve high-variety output at low cost (Gerwin, 1982; Zelenovic, 1982). This system is promoted as an agile manufacturing system, which is designed referring to real modules of Toyota Eco Cars, as illustrated in Fig. 1. Manufacturing and assembling of each chassis is realized using different processes. Table 1 describes the processes needed to manufacture each respective type of chassis.

Fig. 2 illustrates the structure of workstations and alternative manufacturing and assembling processes.

2.2. The Model

Aiming at demonstrating the foregoing hypotheses, we introduce the following logarithm model of manufacturing agility A_M (Watanabe and Ane, 2002), which represents the interaction between machine flexibility (MF_j) and mix flexibility (XF_j) of the system:

$$A_M = \ln a + \sum_{i=1}^{m}\sum_{j=1}^{n}(\alpha \ln MF_j + \beta \ln XF_j) \tag{1}$$
$$i \neq j$$
$$i = 1,2,\ldots,m; j = 1,2,\ldots,n$$

Based on the model of Tsourveloudis (1998), machine flexibility can be enumerated using this following equation:

$$MF_j = W_s \frac{\min_k[s_k]}{s_j} + W_v \frac{v_j}{\max_k[v_k]} + W_r \frac{r_j}{\max_k[r_k]} \tag{2}$$
$$j,k \in M$$
$$M = \{1,2,\ldots,p\}$$

Mix flexibility is derived as a product of mean completion time, C_j, based on Continuous Time Markov Chain models (Viswanadham et al., 1992) and total amount of products a machine is capable of fabricating in a scheduled time, Q_j, (Pelaez-Ibarrondo and Ruiz-Mercader, 2001) as follows:

$$XF_j = \sum_{j=1}^{n}(C_j \times Q_j) \tag{3}$$

$$C_j = \left(1 + \frac{f_j}{r_j}\right)\frac{1}{p_j} \tag{4}$$

$$Q_j = \frac{At_j - \sum_{i=1}^{n} Ts_{ij}}{\sum_{i=1}^{n}(w_i T_{ij})} \tag{5}$$

where a is constant; α is elasticity of machine flexibility; β is elasticity of mix flexibility; M is a set of competing machines; s_j is the setup time of machine j; v_j is the

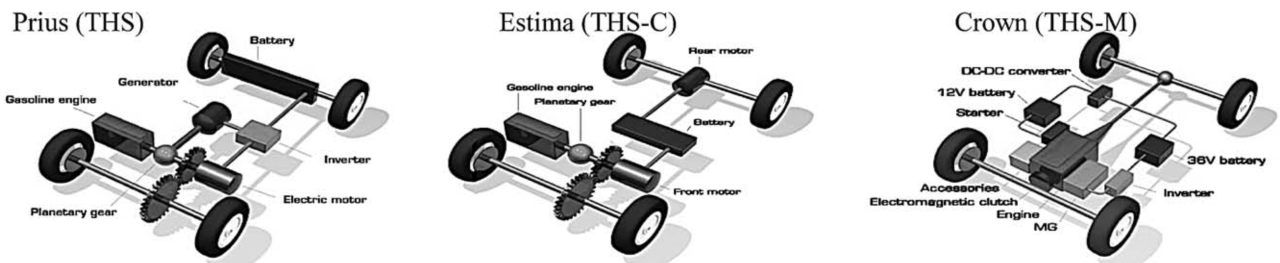

Fig. 1. Chassis modules and its interfaces (source: Toyota Motor Corporation, 2002).

Table 1
Manufacturing and assembling process

Process order	Chassis modules and parts		
	Prius	Estima	Crown
1	Planetary gear, and sun gear	Planetary gear, and sun gear	THS-M engine
2	High Exp.-ratio Atkinson cycle	THS-C engine	Electromagnetic clutch
3	Electric motor	Front motor	Drive shaft
4	Drive shaft	Drive shaft	Accessories
5	Generator	Ni-MH battery	Motor-generator
6	THS inverter	Rear motor	THS-M inverter
7	Ni-MH battery	Front–rear axles, and sun gear	Starter
8	Front-rear axles, and sun gear	–	12 V battery
9	–	–	DC–DC converter
10	–	–	36 V battery
11	–	–	Front–rear axles

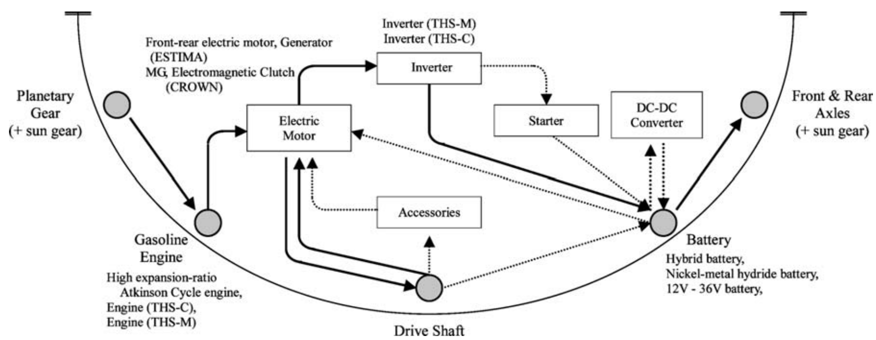

Fig. 2. Hypothetical agile manufacturing system.

number of operations machine j can perform; r_j is the range of adjustment of machine j; f_j is the failure rate; r_j is the repair rate; p_j is the processing rate; At_j is the available time of machine j; Ts_{ij} is the setup time of machine j to process product i, according to a predetermined sequence; w_i is the percentage of product i to be fabricated according to the chosen combination, divided by 100; and T_{ij} is the processing time of machine j for product i. Noteworthy, in Eq. (2), notations W_s, W_v, W_r represent weights of importance for s_j, v_j, and r_i,, respectively, while the sum of the values of $W_s + W_v + W_r = 1$.

Regarding the manufacturing lead time (MLT), here measurement is conducted with different production types. In this research, we employ the models of Viswanadham et al., which enable measurement of MLT for flow-type mass production as follows:

$$\mathrm{MLT} = n(m + \max_{1 \le i \le n} t_i) \tag{6}$$

This model is reliable for application subject to the following assumptions: production line is set up in advance, inspection is done as a part of machine operation, waiting time is determined by the machine with the longest processing time, and moving time is the same for all parts, which is denoted by m. Measurement of mass customization is carried out by implementing production smoothing for effective utilization of the mixed-model line as follows:

$$\mathrm{MLT} = \sum_{i=1}^{n} s_i + Q(t_i + a_i) + m_i + q_i \tag{7}$$

Then, for the job shop, $Q_j = 1$, which produced a customized model and the workpiece goes through the manufacturing cycle as many times as the number of machine operation as follows:

$$\mathrm{MLT} = \sum_{i=1}^{n} (s_i + t_i + a_i + m_i + q_i) \tag{8}$$

where s_i is the set-up time; Q is the number of the workpiece; t_i is the processing time; a_i is the inspection times for the ith operation; m_i is the moving time to move a workpiece from the ith to the $(i+1)$th operation; and q_i is the waiting time in the queue in front of the machine for the ith operation.

2.3. Simulation scenario and data construction

Based on the hypothetical system and the model of manufacturing agility, we developed a simulation scen-

Table 2
Manufacturing and assembling process data

Workstation (W_x)		Prius			Estima			Crown		
		(s_P)	(t_P)	(m_P)	(s_E)	(t_E)	(m_E)	(s_C)	(t_C)	(m_C)
W_1	Planetary (+ sun gear)	1	0.1		1	0.1	–	–	–	–
W_2	Gasoline engine	14	1.0	0.2	14	1.0	0.2	14	1.0	-
W_3	Electric motor	2	0.4	0.5	2	0.2	0.6	2	0.5	0.5
W_4	Drive shaft	22	0.5	0.2	23	0.5	0.2	20	0.5	0.2
W_5	Accessories	–	–	–	–	–	–	1	0.1	0.1
W_6	Inverter	1	0.2	0.2	–	–	–	1	0.2	0.1
W_7	Starter	–	–	–	–	–	–	1	0.3	0.1
W_8	Battery	1	0.2	0.2	1	0.2	0.2	2	0.4	0.4
W_9	DC–DC converter	–	–	–	–	–	–	1	0.2	0.2
W_{10}	Front–rear axles (+ sun gear)	19	0.8	0.2	19	0.8	0.4	18	0.8	0.2
Total (in min)		60	3.2	1.5	60	2.8	1.6	60	4	1.8

ario, which is designed subject to the following constraints[1]:

(a) 16 h normal production hours per day,
(b) 8 h overtime per day, and
(c) maximum capacity 450 units of mixed-model per day.

Manufacturing and assembling of each chassis uses different processes through 10 workstations (W_x) according to the model, and/or variants, which should be manufactured. Table 2 tabulates raw data on the manufacturing and assembling process of each model. In this regard, we assume inspection time $a_i = 1.1$ min, and waiting time, $q_i = 0$, for each model and/or of its variants. Table 3 summarizes probability of variables, each of which governs the value of the mean completion time.

The simulation scenario is subject to the following parameters: demand, chassis models (and/or variants), production cycle, production flow-type, and leveling. Avoiding any misconception, here the term of the production cycle (k) refers to a set time that is needed to fabricate the same number of product(s) in different combinations of product type without significantly changing the manufacturing and assembling process (Monden, 1998). In order to enable the immediate manufacturing capacity and facilities adjustment because of economically external changes, parameters of demand are determined by demand per day (d). These scenarios are designed to be well fitted to circumstances under the flow-type of mass production, mass customization, and job shop for the customized model. Table 4 describes the simulation scenarios in detail.

In scenario 1, manufacturing and assembling is aimed at fabricating the chassis for Prius (P) and its variant, Prius Deluxe (P_D), under the flow-type of mass production. Manufacturing is enabled within 9.6 min production cycle for 2 units of chassis with the possibility of the following combinations: (P, P), (P_D, P_D), (P, P_D), or (P_D, P). Scenario 2 and scenario 3 are aimed at fabricating chassis for Prius (P), Estima (E), and Crown (C), which also enables manufacture of a variant of Prius

Table 3
Mean completion time data

Variables	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}
Failure rate (f_j), per 8 h	0.02∗	0.05∗	0.05∗	0.05∗	0.01∗	0.01∗	0.01∗	0.01∗, C=0.02	0.01∗	0.02∗
Repair rate (r_j), per 8 h	1∗	1∗	1∗	1∗	1∗	1∗	1∗	1∗	1∗	1∗
Processing rate (p_j)	0.1∗	1∗	P=0.2 E=0.1 C=0.2 C= 0.3	0.5∗	C=0.1	P=0.2 C=0.2	C=0.3	0.2∗	C=0.2	0.8∗

Note: ∗holds in general, P: Prius, E: Estima, C: Crown.

[1] These constraints are limitation on production hours and number of models.

Table 4
Simulation scenario

Parameters	Scenario 1	Scenario 2	Scenario 3
Demand per day (d)	200–300 units	200–300 units	200 units
Model (and/or variants)	2 var. of Prius	1 var. of Prius, Estima, Crown	2 var. of Prius, Estima, Crown
Production cycle (k)	9.6 min/2 units	16 min/5 units	16 min/1–5 units
Production flow-type	Mass production	Mass customization	Job shop, customized model
Leveling	4 combinations	32 combinations	128 combinations

suitable for the manufacturing combination. Manufacturing is conducted within 16 min production cycle for 5 units of chassis, which should encompass two units of P, 2 units of E, and 1 unit of C within 32 possible manufacturing combinations in scenario 2, and 128 combinations in scenario 3. The simulation is conducted under the assumptions:

$$a \approx 0 \tag{9}$$

$$W_s = 0.2,\ W_v = 0.5, \text{ and } W_r = 0.3 \tag{10}$$

under several constraints, subject to:

$$\alpha = \frac{\partial \ln A_{\mathrm{M}}}{\partial\left\{\ln W_s + \ln\left(\frac{\min_k[s_k]}{s_j}\right)\right\}} = \frac{\partial \ln A_{\mathrm{M}}}{\partial\left\{\ln W_v + \ln\left(\frac{v_j}{\max_k[v_k]}\right)\right\}} = \frac{\partial \ln A_{\mathrm{M}}}{\partial\left\{\ln W_r + \ln\left(\frac{r_j}{\max_k[r_k]}\right)\right\}} \tag{11}$$

$$\beta = \frac{\partial \ln A_{\mathrm{M}}}{\partial \ln XF_j} \tag{12}$$

$$\frac{\partial T_{ij}}{\partial Ts_{ij}} > 2.5 \tag{13}$$

where $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$; and MF_j on processing time of product i under circumstances ($\min\,[s_k]/s_j$) and ($r_j\,/\max\,[r_k]$) are constant, should satisfy this following relation:

$$\mathrm{MF}_{T_{ij}} = w_i \sum_{j=1}^{n} 0.5 \frac{v_j}{\max_k[v_k]} \tag{14}$$

Simulating the model subject to these constraints, we obtain 1807 random sample data. The following sections describe the simulation findings and statistical evaluation of the outcomes.

3. Research findings

Here we describe research findings in line with the simulation stages, which encompass findings upon machine-mix flexibility trade-off, manufacturing agility, optimal trajectory of manufacturing agility, and manufacturing lead time. In addition, in order to assure the validity and reliability of the findings, we provide a statistical test of normality and of autocorrelation at the end of this section.

3.1. Machine-mix flexibility trade-off

Analyzing the behavior of flexibility, we find facts that machine flexibility and mix flexibility create trade-offs during the observation period. There are two correlations that can be identified as sources of the machine-mix flexibility trade-off:

(i) Trade-off between setup time and processing time. Shifting of setup time (s_j, Ts_{ij}) and of processing time (t_i, $T_{ij,}$), requires decreasing Ts_{ij} by 0.01 which should be followed by a decrease in the value of T_{ij} greater than 0.025, in the multiplication of changing in T_{ij}.
(ii) Trade-off between elasticity and weights of importance of machine flexibility. Relationship amongst weights of importance (W_s, W_v, and W_r) and elasticity (α) of machine flexibility requires increasing α by 1.0, which should be followed by a decrease in value,

$$\alpha = 0.625 \frac{\partial \ln A_{\mathrm{M}}}{\partial \ln\left(\frac{\min_k[s_k]}{s_j}\right)} = 0.693 \frac{\partial \ln A_{\mathrm{M}}}{\partial \ln\left(\frac{v_j}{\max_k[v_k]}\right)} = 1.204 \frac{\partial \ln A_{\mathrm{M}}}{\partial \ln\left(\frac{r_j}{\max_k[r_k]}\right)} \tag{15}$$

Based on these correlations, in the simulation we find an optimal value of machine flexibility, $\mathrm{MF}_O = 7.8592$.

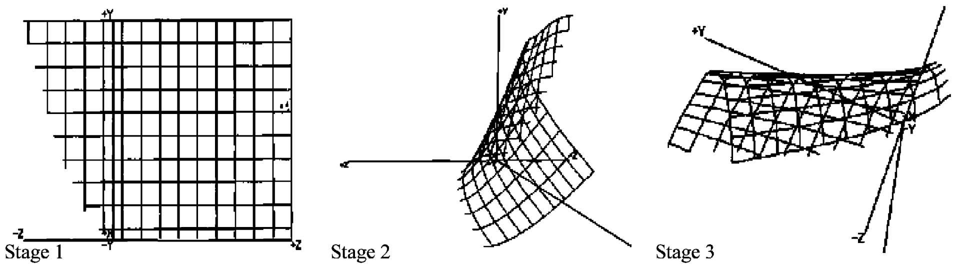

Fig. 3. Optimal value of machine flexibility.

Table 5
Value of manufacturing agility

Scenario	MF_j	C_j	Q_j	XF_j	A_M
Scenario 1	7.8592	0.1353	282	38	5.69
Scenario 2	7.8592	0.4157	280	116.48	6.82
Scenario 3	7.8592	0.5543	282	155.95	7.11

Fig. 3 visualizes the result as a three-dimensional graph, where the x-axis represents the range of adjustment of machine j (r_j), the y-axis represents the setup time of machine j (s_j), and the z-axis represents the number of operations machine j can perform (v_j).

3.2. Manufacturing agility

Applying the optimal value of machine flexibility, in the second stage the result demonstrates scenario 3, that is the run under a flow-type of job shop for a customized model has the highest degree of manufacturing agility, $A_M = 7.11$. The complete results are summarized in Table 5 and Fig. 4. Here we find the value of manufacturing agility increases in line with increases in effective utilization of modules in the product and manufacturing process. This finding supports the hypothesis that the implementation of modularity in product architecture results in an increase in manufacturing agility.

3.3. Optimal trajectory

Furthermore, with regard to manufacturing agility, in the third stage our findings provide evidence towards the presumption that between lower and upper boundaries of manufacturing agility, an optimum level of manufacturing agility (A_{MO}) exists. Figs. 5 and 6 support this result. In the simulation we find the optimum level, $A_{MO} = 8.5373$, is achieved when $\mathrm{MF}_j = 4.0992\text{–}4.1492$ and $\mathrm{XF}_j = 1229.48\text{–}1244.48$. On the basis of these findings, the following postulates are obtained:

(i) The value of A_{M} is dominantly governed by MF.
(ii) When MF_j has achieved its lower boundaries, $L_{\mathrm{L_{MF}}}$, simultaneously A_{M} will achieve its lower boundaries ($L_{\mathrm{L_{AM}}}$). In the case of XF_j, even though XF_j has achieved its lower boundaries, $L_{\mathrm{L_{XF}}}$, on the other hand increasing the value of MF_j will leverage the value of A_{M}.
(iii) When A_{M} has achieved its optimum level, for the following terms increasing the value of MF_j not coupled with increasing the value of XF_j leads to a decreasing value of A_{M}, and vice versa.

3.4. Manufacturing lead time

Finally, in the fourth stage, according to manufacturing lead time (MLT), measurement under flow-type mass

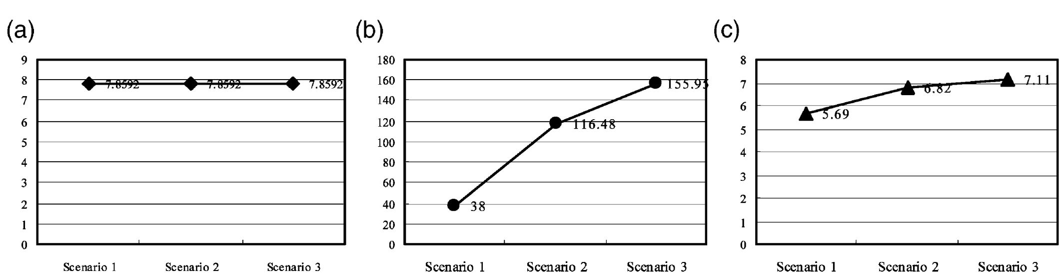

Fig. 4. Value of machine flexibility (a), mix flexibility (b), and manufacturing agility (c).

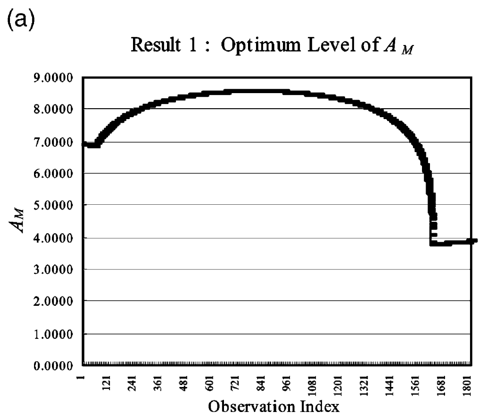

Fig. 5. Optimum level of manufacturing agility, two dimensions.

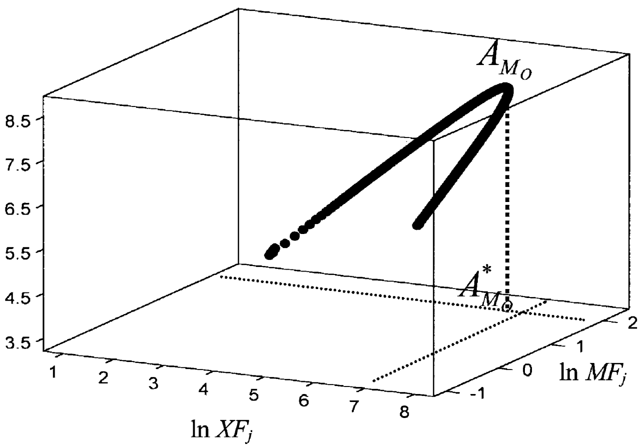

Fig. 6. Optimum level of manufacturing agility, three dimensions.

production and mass customization (scenarios 1 and 2) results in decreasing MLT, with $\Delta MLT_1 = 26$ min ($d = 200$ units) and $\Delta MLT_2 = 32$ min ($d = 300$ units). Meanwhile, measurement on flow-type mass customization and job shop (scenarios 2 and 3) results in $\Delta MLT_3 = 1$ h 51 min due to the characteristic of the production flow that enables the manufacturing of a customized model in small batches, as described in Table 6 and Fig. 7. These findings, even though they do not provide solid evidence, do suggest that a higher degree of manufacturing agility leads to a shorter manufacturing lead time.

3.5. Statistical test

Referring to the normality assumption (Gujarati, 1995), theoretically classical normal linear regression (CNLR) assumes that each u_i is distributed normally as

$$u_i \approx N(0,\sigma^2) \tag{16}$$

where u_i represents the disturbance term of sample group i, and N stands for normal distribution with parameters

$$\text{Mean: } E(u_i) = 0 \tag{17}$$

$$\text{Variance: } E(u_i^2) = \sigma^2 \tag{18}$$

$$\text{Cov}(u_i,u_j)\text{:}E(u_i,u_j) = 0, i \neq j \tag{19}$$

In this regard, for two normally distributed variables, zero covariance or correlation means independence of the two variables. Therefore, under the normality assumption, Eq. (19) means that u_i and u_j are uncorrelated and independently distributed. Then, Eq. (16) can be written as

$$u_i \approx \text{NID}(0,\sigma^2) \tag{20}$$

where NID stands for normally and independently distributed. In the simulation, we presume variables MF_j and XF_j are derived from a population that is normally distributed. Thereby, the hypotheses on the normality can be defined as follows: H_0: data follows a normal distribution; H_1: data follows a specific distribution, except a normal distribution.

Table 6
Manufacturing lead time

Scenario	Manufacturing lead time (MLT)			
	d=200 units		d=300 units	
1. Mass production	16 h 7 mins	ΔMLT_1= 26 min	23 h 30 min	ΔMLT_2=32 min
2. Mass customization	15 h 41 min		22 h 58 min	
3. Job shop	21 h 7 min		–	ΔMLT_3=1 h 51 min

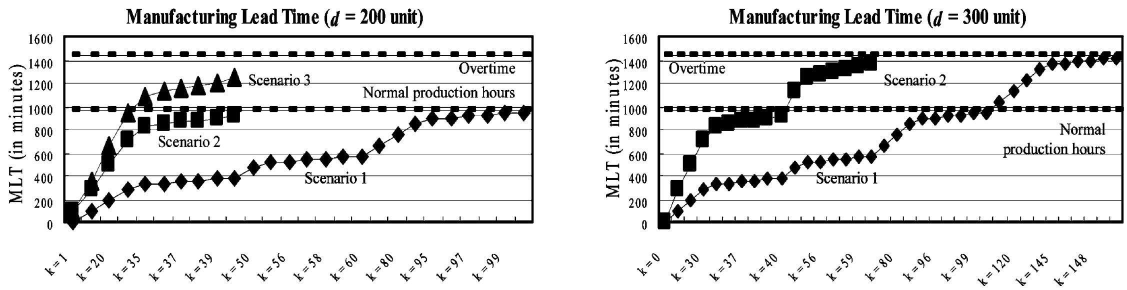

Fig. 7. Manufacturing lead time.

Table 7
Normality test statistic

Variable	Test statistic	Critical value		Mean	Standard deviation	p value	Sample
	D	$D-$	$D+$	μ	σ		N
MF_j	0.058	0.058	0.059	4.63715	2.61069	<0.01	1807
XF_j	0.070	0.059	0.070	1098.38	763.171	<0.01	1807

Here test of normality is done using the Kolmogorov–Smirnov Goodness-of-Fit test, which is based on the empirical distribution function (ECDF). Statistically, the Kolmogorov–Smirnov test is defined as

$$D = \max_{1 \le i \le N} \left| F(Y_i) - \frac{i}{N} \right| \tag{21}$$

where F is the theoretical cumulative distribution of the distribution being tested, which must be a continuous distribution. Table 7 summarizes the normality test statistics and Fig. 8 illustrates the normal probability.

Analyzing the result, it is demonstrated that test statistic, D, of MF_j ($D_{MF_j} = 0.058$) coincides with the critical value, $D- = 0.058$. Meanwhile, the test statistic of XF_j ($D_{XF_j} = 0.070$) coincides with the critical value, $D+ = 0.070$. Therefore, based on this result the null hypothesis (H_0) is accepted. Then, it can be pointed out that MF_j and XF_j are normally and independently distributed.

Afterwards, with respect to the result of the normality test, we examine the autocorrelation between the disturbance terms of A_M. Consistently holding CNLR, the classical model assumes that the disturbance term relating to any observation is not influenced by the disturbance term relating to any other observation. Here test of autocorrelation is done using the Durbin–Watson d test (Gujarati, 1995), which is defined as follows:

$$d = \frac{\sum_{t=2}^{t=N} (\hat{u}_t - \hat{u}_{t-1})^2}{\sum_{t=2}^{t=N} \hat{u}_t^2} \tag{22}$$

which is simply the ratio of the sum of squared differ-

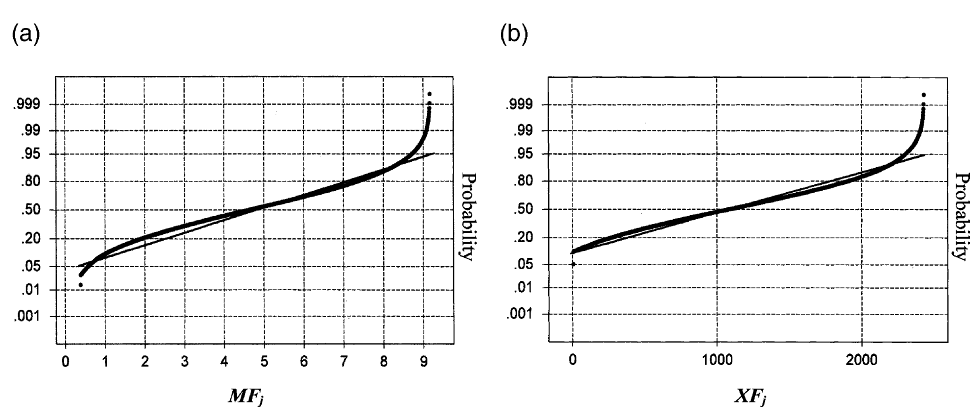

Fig. 8. Normal probability plot.

ences in successive residuals to the residual sum of squares (RSS). Applying equation (3.5.7) (Gujarati, 1995), we find autocorrelation test statistics of A_M, $d = 1.92$. Fig. 9 shows a scatter plot for the disturbance term. Therefore, as a rule of thumb, because d is found closer to 2 in the application, then, it can be pointed out that there is no first-order autocorrelation, either positive or negative. These statistical tests validate the reliability of the research findings.

4. Interpretation

Investigating thoroughly optimal trajectory of manufacturing agility, we recognize the dynamic interaction of machine flexibility (MF_j) and mix flexibility (XF_j) in determining the optimal trajectory. In this regard, the embodiment of modularity in product architecture stimulates the creation of a job family in manufacturing and assembly processes, whereas in the following phases this leads to changing the number of operations a machine can perform (v_j), the processing time (t_i, T_{ij}), the setup time (s_i, S_j, Ts_{ij}), and the range of adjustment (r_j). Pragmatically, the interaction between setup time and range of adjustment determines the value of MF_j. In the meantime, interaction between setup time and processing time has an implication towards the value of XF_j, through changing the value of the mean completion time (C_j) and the number of products a machine is capable of fabricating in a scheduled time (Q_j). Then, the dynamic interaction between these two natures of flexibility leads to an optimal trajectory of manufacturing agility. Fig. 10 illustrates the dynamic interaction and optimal trajectory. With respect to this finding, we state that changing the value of MF_j and/or XF_j leads to a new trajectory of manufacturing agility, whereas, in turn, performing in a shorter MLT. These cause and effect relationships represent the concurrent roles of modularity in constructing a virtuous cycle of manufacturing agility, as illustrated in Fig. 11.

Finally, with respect to findings on MF_j, XF_j, and A_M, here we point out that machine flexibility is a *catalyst* in the construction of a virtuous cycle of manufacturing

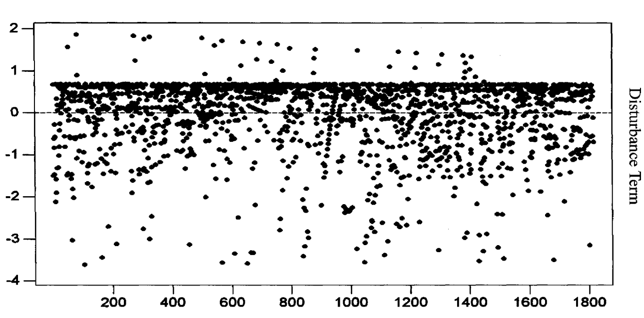

Fig. 9. Scatter plot of disturbance term.

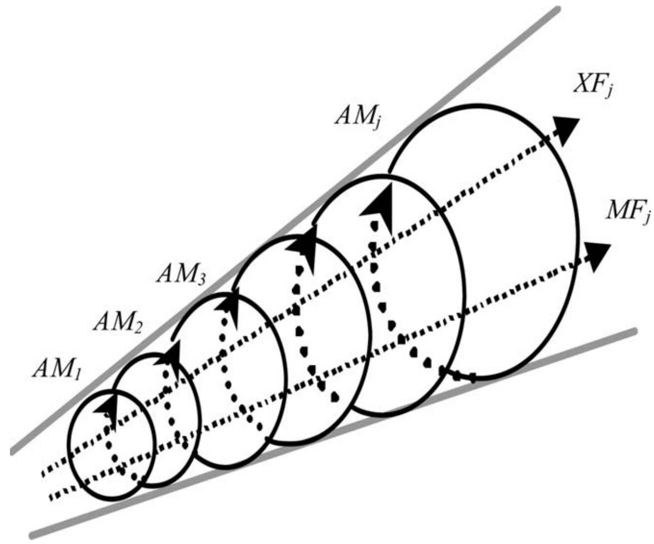

Fig. 10. Optimal trajectory.

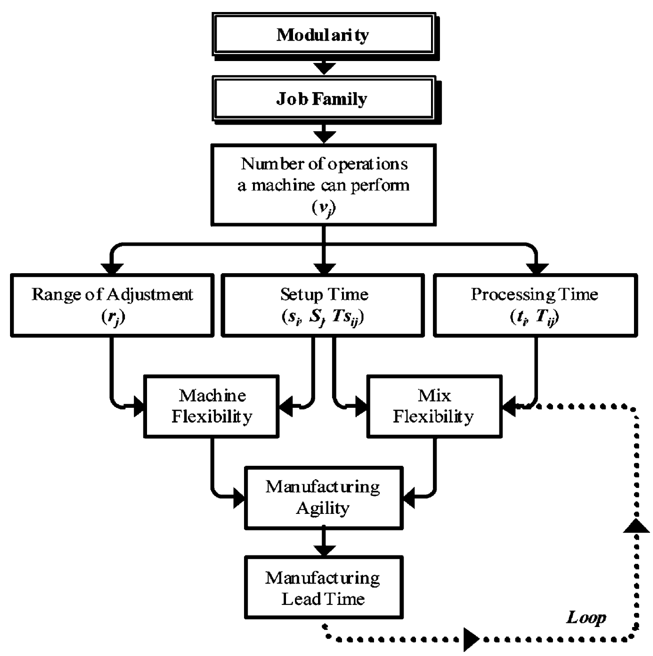

Fig. 11. Virtuous cycle of manufacturing agility.

agility. Analogous to a chemical reaction, machine flexibility is a catalyst for influencing the increasing value of manufacturing agility by reducing the activation effort, while leaving the process unchanged. Meanwhile, mix flexibility changes proportionally in line with the changing value of variables, which influence the intermediary variables C_j, Q_j, and MF_j.

5. Conclusions

On the basis of an empirical analysis focusing on the concurrent roles of modularity in constructing a virtuous cycle of manufacturing agility, the following noteworthy findings are obtained:

(i) The embodiment of modularity in product architecture enables firms to assemble individual modules into a product on a single production line for manufacturing of: (a) a single model in several variants, which refers to operational flexibility, (b) several models, each of which is a variation of a single platform, refers to strategic flexibility, and (c) customized models, which refers to structural flexibility. This manufacturing capability leads to increasing manufacturing agility.
(ii) The increasing capability of a manufacturing system to assemble a product based on modular architecture on a single flexible production line in small batches results in a higher degree of manufacturing agility, which leads to a shorter manufacturing lead time.

Implementing this concept at the shop-floor, one should realize that an optimum level of manufacturing agility exists between its lower and upper boundaries, whereas its achievement is governed by the degree of machine flexibility and mix flexibility. In addition, the optimum level of manufacturing agility can be maintained through setting-up the machine-mix flexibility trade-off in balance.

References

Anderson, M., 1997. Agile product development for mass customization: just-in-time, build-to-order, and agile manufacturing. Management Consultant Lafayette.
Barad, M., Sipper, D., 1988. Flexibility in manufacturing systems: definitions and petri net modeling. International Journal of Production Research 26 (2), 237–248.
Belis-Bergouignan, M.-C., Lung, Y., 1999. Coping with Variety: Flexible Productive Systems for Product Variety in the Auto Industry. Ashgate Publishing Ltd.
Brill, P.H., Mandelbaum, M., 1989. On measures of flexibility in manufacturing systems. International Journal of Production Research 27 (5), 747–756.
Browne, J., Dubois, D., Rathmill, K., Sethi, S.P., Stecke, K.E., 1984. Classification of flexible manufacturing systems. The FMS Magazine 2 (2), 114–117.
Buzacott, J.A., 1982. The fundamental principles of flexibility in manufacturing system. In: Proceedings 1st International Conference on Flexible Manufacturing System., pp. 23–30.
Center for Automation and Intelligent Systems Research, 1996. What is agile manufacturing? Case Western Reserve University. Available from: http://dora.eeap.cwru.edu/agile/home.html.
Falkner, H., 1986. Flexibility in manufacturing plants. In: Stecke, K.E., Suri, R. (Eds.), Proceedings of 2nd ORSA/TIMS Conference on Flexible Manufacturing Systems. Elsevier, Ann Arbor, MI, pp. 95–106.
Gerwin, 1982. Do's and don't's of computerized manufacturing. Harvard Business Review 60 (2), 107–116.
Goldman, S.L., Preiss, K., 1991. 21st Century manufacturing enterprise strategy: an industry-led view. Iaccoca Institute at Lehigh University, Bethlehem, PA.
Goldman, S.L., Nage, R.N., Preiss, K., 1995. Agile Competitors and Virtual Organizations: Strategies for Enriching the Customer. Van Nostrand Reinhold Company, New York.
Goranson, H.T., 1992. Metrics and models. In: Petrie, C.J. Jr (Ed.), Enterprise Integration Modeling. MIT Press, Cambridge, MA.
Greenwood, N.R., 1988. Implementing Flexible Manufacturing Systems. Macmillan.
Gujarati, D.N., 1995. Basic econometrics. McGraw-Hill International, Singapore.
Meyer, March, H., Lehnerd, Alvin, P., 1997. The power of product platforms: building value and cost leadership. Free Press, New York.
Monden, Y., 1998. Toyota Production System: An Integrated Approach to Just-In-Time, 3rd ed. Engineering and Management Press, Georgia.
Nicholas, J.M., 1998. Competitive Manufacturing Management. McGraw-Hill, Irwin.
Olhager, J., 1993. Manufacturing flexibility and profitability. International Journal of Production Economics 30-31, 67–78.
Pelaez-Ibarrondo, J.J., Ruiz-Mercader, J., 2001. Measuring operational flexibility. In: Proceedings of the 4th SMESME International Conference, Aalborg University, Denmark
Sethi, Sethi, S., 1990. Flexibility in manufacturing: a survey. International Journal of Flexible Manufacturing Systems 2, 289–328.
Tsourveloudis, N.C., 1998. Fuzzy assessment of machine flexibility. IEEE Transactions on Engineering Management 45 (1), 78–87.
Tsourveloudis, N.C., Phillis, Y.A., 1998. Fuzzy measurement of manufacturing flexibility. Dissertation, University of Greece.
Tsourveloudis, N.C., Valavanis, K., Gracanin D., Matijasevic, M., 2000. On the Measurement of Agility in Manufacturing Systems, Research Publication. Technical University of Crete, Department of Production Engineering and Management.
Viswanadham, N., Narahari, Y., 1992. Performance modeling of automated manufacturing systems. Prentice-Hall Inc., New Jersey.
Watanabe, Ane, B.K., 2002. Modularity as a source of comprehensive innovation: its concurrent roles in improving agility and reducing lead time. In: Proceedings of the 5th World Automation Congress. Albuquerque: TSI Press.
Zelenovic, D.M., 1982. Flexibility: a condition for effective production systems. International Journal of Production Research 20 (3), 319–337.

Chihiro Watanabe is currently a Professor at the Department of Industrial Engineering and Management, Tokyo Institute of Technology, Japan. He is also Senior Advisor to the Director of Technology at the International Institute for Applied Systems Analysis (IIASA), Austria and Adjunct Professor of the United Nations University/Institute of Advanced Studies, Japan. Previously he was the former Deputy Director-General of Technology Development at Japan's Ministry of International Trade and Industry (MITI). He began his affiliation with MITI in 1968 and worked mainly in the fields of industrial policy, industrial technology policy, and energy and environmental policies. Professor Watanabe graduated from Tokyo University with a Bachelor's degree in Engineering (Urban Planning) in 1968 and received his PhD (Arts and Science) in 1992 also from Tokyo University.

Bernadetta Kwintiana Ane is a PhD candidate at the Department of Industrial Engineering and Management, Tokyo Institute of Technology, Japan. Currently she is also a research fellow at the Production Resources, Logistics, and Telematics Division, University of Bremen and Bremen Institute of Industrial Technology and Applied Work Science, Germany. Ms Ane graduated from Diponegoro University, Semarang, Indonesia, majoring in Economics (Production Management) in 1994 and received a Master's degree from Bandung Institute of Technology majoring in Industrial Engineering and Management (Product Planning and Design) in 1996.