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Integrated Product Design and Development:
Lessons Learned from Lean Manufacturing Practices

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Abstract

This article aims to establish potential relationship between lean manufacturing (LM) practices and integrated product design and development (IPDD). Comparisons of several critical factors show high degree of resemblances between the two methods. Several hypotheses regarding the relationships between factors for the two methods were developed and tested. Survey data strongly supports the hypotheses regarding similarities between the LM and IPDD methods. Statistical results also indicate compared with conventional companies, by utilizing IPDD, lean manufacturing organizations are able to design and develop products with better quality, less development time, higher frequency, and lower development and manufacturing costs.

Keywords: Integrated, Product, Design, Development, Lean, Manufacturing.

1. Introduction

In a global market, innovation and speedy new product development is crucial for companies to gain competitive advantage. Creating new product ideas that are consistent with organizational strategy and moving these ideas through the stages of design, development, and introduction quickly has been the hallmark of successful world class organizations (Jacobs and Chase, 2017; Ferioli et al. 2010; Roulet et al. 2010). Introducing new products to the market early has several strategic and operational advantages. It often means premium prices, building name recognition, controlling a large market share, and enjoying the bottom line profits. Better competitive position in the market makes it also difficult for competition to enter the market (Cooper and Kleinschmidt, 1994; Lofstrand, 2010; Kristav, 2016; Wen et.al.; 2020).

Despite its well-known strategic role, for large number of manufacturing organizations innovation, design, and successful management of product design and development (PDD)has often been a major challenge. Long development time, prohibitive development and manufacturing costs, and questionable quality have been the common result for many of these organizations. The primary factor contributing to such

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unsuccessful result is perhaps the use conventional method of PDD by these organizations (Blackburn, 1991; Morgan and Liker, 2006). However, recent manufacturing literature clearly shows through their lean manufacturing practices, world class organizations such as Toyota have dominated competition not only in the area of manufacturing but also in the area of innovation, design, development, and quick commercialization of new technologies ((Marisa et al. 2008; Heinzen and Hoflinger 2017; Ulrich and Eppinger, 2004; Michael, 2008; Unger and Eppinger 2009). Instead of traditional sequential approach to PDD, successful world class organizations employed integrated product design and development. The focus of this article is to understand such contrast between the two type of organizations. The question of interest in this article is: Are there relationship between success in LM practices and success in IPDD?

2. Literature Review

Lean manufacturing has been a great force in the world of manufacturing since early 1990's. Some of the main benefits of a LM such as lower inventory, quicker delivery, and lower cost have been well documented (Cook and Rogowski, 1996; Hobbs, 1994; Payne, 1993; Temponi and Pandya, 1995; Deshpande and Golhar, 1995; Billesbach, 1991; Handfield, 1993; Lawrence and Hottenstein, 1995; Golhar, Stamm, and Smith, 1990; Moras and Dieck, 1992). In the simplest form, LM requires maximizing value added production activities by removing unnecessary wastes. Identification and elimination of waste and respectful treatment of employee are the two fundamental principles of a LM system (Hobbs, 1994; Payne, 1993; Womack and Jones, 2003). Elimination of waste is achieved by adopting practices such as continuous quality improvement, setup time reduction, utilizing flexible resources, group technology layout, and pull production system (Gargeya, and Thompson, 1994; Sohal, Ramsay, and Samson, 1993). Respectful treatment of people often means employee empowerment; it includes elements such as team work, fair compensation, employee training and new positive attitude toward suppliers (Sohal, Ramsay, and Samson, 1993; Weeth et.al. (2020).Unfortunately, since its beginning in early 1990's, often a narrow view of LM has been accepted and utilized by western manufacturers. Application of LM to reduce inventory and increase deliveries is only a small fraction of the full potential benefits of a LM system (Blackburn, 1991; Goffin et.al., 2019; Kristav, 2016). To take advantage of the full benefits of LM, one needs to have a much broader view of LM principles (Blackburn, 1991). Looking at LM as a process of eliminating waste and respectful treatment of employee, its principles can be applied to other areas including service areas such as healthcare, education, government, and PDD (Womack and Jones (2003). Application of lean principles to PDD has great opportunity to shorten product development time, improve design quality, and reduce product development and manufacturing costs (Anand and Kodali, 2008). The company that originated famous LM system known as Toyota Production System (TPS) also developed Toyota Product Development System (TPDS). TPDS employs LM principles and tools such as value stream mapping, Kanban, 5S system, and continuous improvement to eliminate waste from product development activities and bring quality products to market faster than their leading competition (Morgan and Liker, 2006; Ward, 2007). The focus of this article is on special case of TPDS called integrated product design and development (IPDD).With regard to the question stated earlier, the objective of the article is to answer the following questions:

1. Are there relationships between LM and IPDD practices?
2. Are there differences between PDD performances for LM companies using IPDD and conventional companies?

The remainder of the article is organized in the following manner: First, an overview of the differences between conventional sequential method and IPDD method is presented. Second, the article compares and analyzes similarities between LM and IPDD for a number of critical factors followed by a set of hypotheses on similarities between the factors. Third, the article tests PDD performances for conventional sequential method and IPDD method. Research methodology, results, and conclusion are the final sections of the article.

3. Conventional vs. Integrated Methods of Product Design and Development

PDD process is a sequence of inter-connected activities in which information regarding customer needs is translated into final product design. In a conventional method, also known as sequential or “over-the-wall” approach, the PDD process typically involves phases such as idea generation and validation, preliminary design, final design and prototyping, and pilot production and ramp-up (Wheelwright and Clark, 1992; Russell, and Taylor, 1998).

Traditionally, this design process is managed sequentially by personnel from various functions of the organization. A major drawback of this approach to NPD is that the output from one design stage is passed to the next stage with little or no communication. Lack of communication and feedback among sequential stage causes the process to require too many design changes which causes the process to require longer development time which indeed causes the process to be too slow, too costly, and often of poor quality. The two elements of long delay and design changes during the delay creates a never-ending cycle where time delay causes design change and to accommodate design change it needs more time. The final result is that the designs are often rejected because the design is either outdated due to long development time or it is infeasible in term of manufacturing capability (DeWall and Knott, 2019; Ulrich and Eppinger, 2000).

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Unlike traditional “over-the-wall” approach to PDD where functional units work sequentially and downstream functions are not involved until late in the process, IPDD requires early involvement of cross functional teams. It requires that designers, manufacturers, marketers, suppliers, and customers work jointly to design product and manufacturing process in parallel. The design team must truly understand the concept of simultaneous engineering in which activities of product and process design are performed in parallel and in a coordinated manner The objective is to integrate product design and process planning into a common activity (Albers and Braun, 2011; Liang, 2009; Anderson, 2008; Donnellon, 1993; Millson, Ranj, and Wilemon, 1992; Shunk, 1992).

Application of IPDD under various manufacturing environments in order to shorten development time, improve quality, reduce risks, and reduce development cost is reported by these researchers (Anderson, 2008; Skalak, 2002; Kowang and Rasli, 2011; Lofstrand, 2010;Yamamoto and Abu Qudeiri, 2010; Moges, 2009). Due to early cross-functional communication, IPDD approach enables an organization to be more innovative in terms of improving design quality, shortening development time, reducing design risks, and reducing development and manufacturing costs (Lynch et.al, 2016; Blackburn, 1991; Ulrich, and Eppinger, 2000; Johansson and Safsten, 2015; Arora and Mital, 2012; Katzy et.al, 2012; Zirger and Hartley, 1996).

4. Comparison of Lean Manufacturing and IPDD Factors

For the past two decades, there has been an extensive volume of research in the area of LM. As a result, there is a set of generally accepted guidelines that organizations can follow to achieve manufacturing success. However, there has been limited research on the application of LM principles to PDD and there is no comparable set of guidelines for successful management of product development process.

Recently, a number of world class product development companies have attempted to apply the principles of lean manufacturing to PDD activities. A number research on the application of lean principles to PDD process has shown that achieving certain manufacturing process improvement such as reducing variation, reducing rework and yield loss, solving process bottlenecks, and managing capacity, can significantly reduce PDD times. Similarities between LM and IPDD for a number of critical factors are shown in Table 1, (Blackburn, 1991; Spencer and Guide, 1995).

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Table 1. Comparison of Lean Manufacturing (LM) and Integrated Product Design and Development (IPDD) Factors

Factor	**LM**	**IPDD**
Layout	GT/Cellular manufacturing	Project/Design teams
Process and information flow	Two way flow: material downward, information backward	Parallel activities: Two way flow of information among team members
Set-up/Transition time	Short	Short
Lot size	Small	Small (batches of information)
Quality	Quality at the source, continuous quality improvement, low rework activities	Early detection of design quality problems, continuous design improvement, low redesign activities
Inventory	Low	Low
Manufact./Develop. Cost	Reduced	Reduced
Lead time	Fast delivery	Short development time
Customer focus	Customer satisfaction is the focus	Uses voice of the customers & QFD to design for customers
Market responsiveness	More responsive to changes in customer demand	More responsive to product design changes
Workforce empowerment teamwork	High	High
Workforce flexibility	High	High
Scheduling	Localized team control, team responsibility	Localized team control, team responsibility
Decision making	Manufacturing team	Design team
Supplier involvement	High level of sharing information, quality partners	High level of involvement in product development
Technology	Integrated systems, new technology after process simplification	Integrated CAD, CAE, CAM
Workplace organization	Utilizes 5S practices to organize, clean, and sustain the workplaces	Utilizes 5S practices to organize design team and data for easy access to information to conduct NPD activities
Standardization	Standardization of parts and components is a critical component of LM	Creates a standard method of doing activities (i.e. data collection, flow charting, blue prints, etc.)
Waste	Elimination of waste is the focus	Elimination of waste during the design is the focus

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5. Factor Hypotheses

Comparison of factors in Table 1 shows a high degree of similarities between LM and IPDD. To study further, a set of twenty hypotheses (H1-H20) that statistically test similarities between LM and IPDD will be presented. The hypotheses are shown in Table 2. Each hypothesis in Table 2 consists of two parts a and b. In part a, the test is conducted for LM factors and the corresponding test for IPDD factors is conducted in part b. The last hypothesis examines the overall impact of LM principles on IPDD.

Hypotheses (H1-H20):

There is a high degree of similarities between LM and IPDD factors.

5. Product Design and Development Performances

The following dimensions of quality, time, competency, development cost, and manufacturing cost are used to measure the performance of NPD (Ulrich and Eppinger, 2000; Wheelwright and Clark, 1992; McKay et.al. 2011):

- **Quality**: Quality is ultimately reflected in the price customers are willing to pay, the market share, and the bottom line profit. In NPD, quality problems are often the results of incomplete information and miscommunication among various functions. Quality often means a minimal number of redesign or rework. In this article, number of design changes during the development process and early manufacturing phase is used as a measure of design quality.
- **Development time**: Development time is the length of time between initial idea generation until new product is ready for introduction to the market. Shorter development time raises the competitive value of new product in terms of premium price, larger market share, and higher profit margin.
- **Development competency**: Development competency is the ability of the organization to develop future products better, faster, and cheaper. Competent workforce and effective use of technologies are important elements of organizational NPD competency. Frequency of new product introduction to the market is used as a measure of development competency.
- **Development cost**: This is the total cost from the early idea generation until the product is ready for manufacturing. For most organizations, development cost is usually a significant portion of the budget and must be considered in light of budget realities and the timing of budget allocations.
- **Manufacturing cost**: Manufacturing cost includes initial investment on equipments and tools as well as the incremental cost of manufacturing the product. There is a close relationship between manufacturing cost and the type of decisions made during the early design stage. Although early design decisions determine about 70 percent of future manufacturing cost, organizations often spend far too little time and resources

during this stage (Huthwaite, B. 1991). To save future manufacturing cost, it is prudent for the companies to spend more time and resources during the early design phases of NPD process where critical design decisions are made.

Performance Hypotheses

In the second set of hypotheses (H21-H25), the differences between PDD performances for lean manufacturing and conventional companies are tested.

Hypotheses (H21-H25):

H21: By utilizing IPDD approach, LM companies are able to design new products with fewer design changes than conventional companies (better quality).

H22: By utilizing IPDD approach, LM companies are able to design new products faster than conventional companies.

H23: By utilizing IPDD approach, LM companies are able to design new products more often than conventional companies.

H24: By utilizing IPDD approach, LM companies are able to design new products with less development cost than conventional companies.

H25: By utilizing IPDD approach, LM companies are able to design new products with less manufacturing cost than conventional companies.

6. Research Methodology

The target population for this study consisted of manufacturing firms in the states of Illinois, Indiana, Ohio, Michigan, and Wisconsin. A sample of 500 manufacturing firms with more than 50 employees was chosen from manufacturers' directories of those states. The sample covers organizations in variety of industries ranging from fabricated metal, communication, electronics, automotive, toots, chemicals, rubber, and paper products. A comprehensive survey instrument based on examination of the literature and critical factors listed in Table I was developed. A panel of practitioners and researchers with experience in LM and NPD was used to validate the survey. In addition to general organization and managerial profile items, the survey contained 40items (20 paired) regarding similarities between LM and IPDD factors. The twenty paired questionnaire items are shown in Table 2.

Also, the survey instrument contained a number of questionnaire items on PDD performances for LM companies using IPDD and conventional companies. Out of 91 completed surveys received, 84 surveys were usable resulting in a response rate of 17%. Based on a number of questionnaire items on the principles of LM practices, 33 organizations were grouped as LM companies and 51 organizations were categorized as conventional companies.

The survey data indicates that majority of respondents had various high level managerial positions from organization with less than 500 employees. Presidents and vice presidents accounted for 29% and plant managers accounted for 30% of the sample. About 35% of the sample had other managerial positions such as operations/production managers, quality managers, and the remaining 6% were production line supervisors. In terms of manufacturing and PDD experience, about 28% of the respondents had between 10 to 20 years and 60% had more than 20 years of manufacturing experience. About 72% of the sample had more than 10 years of LM experience and close to 65% of the sample had more than 10 years of PDD experience.

7. Research Results

As stated earlier, in the first set of hypotheses the objective was to examine similarities between LM and IPDD for a set of paired factors shown in Table 2. For each item, the null hypothesis was that the mean response for LM is equal to the mean response for IPDD. The differences between the mean responses for LM and IPDD were compared using the statistical t-test. The respondents were asked to rate each element of Table II based on the degree of their agreement (1=strongly disagree, 5=strongly agree) to the question. Table 3 shows the result of similarities between LM and IPDD.

Table 2. Survey Items for Comparison of LM and IPDD Factors
(1=strongly disagree, 5=strongly agree)

1a. In LM, layout is often in form of group technology (GT) or cellular manufacturing (CM).	1b. In IPDD, the layout emphasizes is on cross-functional integration and formation of project or design team.
2a. In LM, GT or cellular manufacturing layout allows smooth flow of materials downward and information flow backward.	2b. In IPDD, project layout formed by the design team allows frequent and two way flow of information among team members.
3a. LM system requires short set-up time.	3b. IPDD requires fast transition (i.e. short set-up time) from one part of the design to another.
4a. LM system requires production of small lot-sizes.	4b. In IPDD, continuous and two-way flow of information among team members is equivalent to releasing small batches of information.
5a. In LM, due to production of small lot-size, quality at the source and continuous quality improvement are essential to the success of the system.	5b. In IPDD, due to simultaneous development of product and process, early detection of design quality problems and continuous improvement of the design are essential to the success of NPD process.
6a. In LM, production of small lot-size is associated with improving quality.	6b. In IPDD, continuous and two-way communication among team members encourages early detection of the design problems, which is associated with improving

	design quality.
7a. In LM, production of small lot-size is associated with reducing inventory.	7b. In IPDD, continuous and two-way communication among team members associated with reducing unnecessary amount of information among team members.
8a. In LM, production of small lot-size is associated with reducing manufacturing cost.	8b. In IPDD, continuous and two-way communication among team members encourages early detection of the design problems, avoids costly design changes, which is associated with reducing development cost.
9a. In LM, production of small lot-size and smooth flow of materials downward and information flow backward is associated with reducing delivery time.	9b. In IPDD, continuous and two-way communication among team members encourages early detection of the design problems, avoids time consuming design changes, which is associated with reducing NPD time.
10a. In LM, organizations are more responsive to the changes in customer demand.	10b. In IPDD, the design teams are more responsive to the changes in product design.
11a. In LM, management encourages workforce empowerment and teamwork.	11b. In IPDD, management encourages employee empowerment and teamwork.
12a. LM requires high level of workforce flexibility.	12b. IPDD requires high level of design team flexibility.
13a. In LM, detailed shop floor responsibilities such as job and employee scheduling are passed to the local teams.	13b. In IPDD, detailed design responsibilities such as development activities and employee scheduling are passed to the design teams.
14a. In LM, suppliers work closely with manufacturing teams.	14b. In IPDD, suppliers work closely with the design and development teams.
15a. In LM, close relationship between suppliers and manufacturing teams is essential in improving quality, reducing manufacturing cost, and shortening delivery time.	15b. In IPDD, close relationship between suppliers and design and development teams is essential in improving design quality, reducing design cost, and shortening design and development time.

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Table 2. Survey Items for Comparison of LM and IPDD Factors
(1=strongly disagree, 5=strongly agree) (Continue)

16a. In LM, new technologies such as robots are integrated into manufacturing system after process analysis and simplification has been performed.	16b. In IPDD, new technologies such as IT and CAD are integrated into the design and development process after process analysis and simplification has been performed.
17a. LM utilizes 5S practices to organize, clean, and sustain the workplaces.	17b. IPDD utilizes 5S practices to organize data and design team members for easy access to timely information to conduct NPD activities.
18a. In LM, standardization of parts and components is a critical component of the system.	18b. In IPDD, standard method of doing activities such as data collection and organization is a critical component of the process.
19a. In LM, due to the principles of elimination of wastes, process activities contain high value added content	19b. In IPDD, simultaneous communication among team members, NPD process contain high value added content.
20a. In LM, elimination of wastes and respectful treatment of people are the two main principles.	20b. Similar to LM, the main principles of elimination of wastes and respectful treatment of people are applicable to IPDD.

As shown in Table 3, overall the respondents strongly agreed with the statements regarding similarities between LM and IPDD factors. The mean ratings for about 70% of the factors for both LM and IPDD are above 3.80. Specifically, out of twenty hypotheses, the respondents agreed that there is a high degree of similarities between LM and IPDD for all except three hypotheses H3, H6, and H8.

For H3, the mean ratings for LM and IPDD are respectively 4.34 and 3.81. This means although the respondents understood that short set-up and fast transition time are the main requirements of successful LM and IPDD, the relationship between short set-up and LM was much stronger. This is a reasonable result because an average manufacturing manager has longer experience with LM than IPDD. They clearly understood that successful LM requires small lot-size and small lot-size requires short set-up time. However, due to their shorter experience with IPDD and because IPDD is primarily an information processing process, the links between small batches of information and fast transition time is not clear.H6 hypothesizes the relationships between small lot-sizes and quality improvement for both LM and IPDD. For this test, the mean ratings for LM and IPDD are respectively 3.43 and 3.89. This indicates for an average manager it is easier to recognize the relationship between PDD and quality improvement than the relationship between LM and quality improvement.

The higher rating for IPDD is perhaps due to continuous and two way communication among design team members, which encourages early detection of the design problem. The LM result is also consistent with the literature because although total quality management and quality improvement are fundamental requirements of successful LM, an average manufacturing manager has difficulty to understand this relationship. The relationships between small lot-size and reduced manufacturing cost in LM and the relationship between small batches of information and reduced development cost in IPDD are examined in H8.The mean ratings for LM and IPDD are respectively 3.58 and 3.94. For the same reasons as H6, this means for an average manager it is easier to understand this relationship in IPDD than LM. The LM result is interesting and also consistent with the literature because reduced manufacturing cost in LM is primarily due to elimination of wastes, a fundamental principle of LM, and an average manufacturing manager has difficulty to see this relationship.

Table 3. Comparison of LM and IPDD Factors (1=strongly disagree, 5=strongly agree)

	LM		**IPDD**			
Factor	**Mean**	**SD***	**Mean**	**SD***	**P-Value**	**Correlation**
1. Layout	3.92	0.85	3.62	1.08	0.140	0.74
2. Flow	4.08	1.03	4.06	0.96	0.640	0.83
3. Set-up	4.34	0.70	3.81	0.96	0.003	0.47
4. Lot-size	3.85	0.88	3.55	1.03	0.100	0.65
5. Quality at source	4.23	0.77	4.28	0.74	0.300	0.69
6. Quality Improv.	3.43	0.90	3.89	0.85	0.000	0.32
7. Inventory	4.22	0.80	3.96	0.85	0.150	0.62
8. Manufacturing cost	3.58	0.80	3.94	0.67	0.001	0.45
9. Delivery	4.26	0.75	4.31	0.72	0.280	0.75
10. Customer respons	4.22	0.73	4.24	0.70	0.480	0.79
11. Teamwork	3.98	0.81	3.83	0.90	0.360	0.76
12. Flexibility	3.86	0.93	3.72	0.96	0.330	0.65
13. Team scheduling	3.72	0.78	3.76	0.78	0.240	0.82
14. Suppliers	3.77	0.79	3.82	0.83	0.350	0.77
15. Suppliers & teams	4.23	0.72	4.02	0.70	0.390	0.73
16. Technology	3.53	0.96	3.68	0.94	0.072	0.69
17. 5S Practices	4.30	0.92	4.12	0.84	0.310	0.71
18. Standardization	4.22	0.87	3.84	0.88	0.320	0.67
19. Value added	4.28	1.12	4.13	0.98	0.160	0.72
20. Overall	4.56	0.93	4.29	0.96	0.140	0.73

* SD = Standard deviation

The overall impact of lean principles on LM and IPDD is examined in H20. It is obvious that the data supports the hypothesis as the mean ratings for LM and IPDD are respectively 4.56 and 4.29 indicating strong agreement with the statements that the

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main principles of waste elimination and respectful treatment of people in LM can also be applied in IPDD.

The last column of Table 3 shows correlation coefficients between LM and corresponding IPDD factors. The correlation coefficients in Table 3strongly support the above analysis. With the exception of three hypotheses H3, H6, and H8 other coefficients are greater than 0.60 indicating a high degree of linear association between LM and IPDD factors.

The performance hypotheses (H21-H25) state that by utilizing IPDD approach, LM companies are able to design new products with fewer design changes, faster, more often, with less development cost, and less manufacturing cost than conventional companies.

Table 4 provides useful statistical information regarding PDD performances for LM and conventional companies. The average number of design changes for conventional and LM companies are respectively 5.36 and 3.28, a quality improvement of 63%. The average development time for conventional and LM companies are respectively 37.52 and 24.73 months, an improvement of 52%. For development competency, the average time between introduction of new products for conventional companies is 49.46 months and 32.72 months for LM companies, an improvement of 51%. Table 4 also indicates that LM organizations enjoy a 45% reduction in PDD cost and 36% reduction in manufacturing cost. From the last column of Table 4, it is clear that the hypotheses are strongly supported by the data as the p-value for all five hypotheses is less than 0.005.

Table 4. NPD Performances for Conventional and LM Companies using IPDD

Factor	Mean Conventional	Mean LM	p-value
Number of design changes	5.36	3.28	0.004
Development time (Months)	37.22	24.73	0.003
Development competency (Months)	49.46	32.72	0.005
Development cost	144.60*	100*	0.005
Manufacturing cost	135.75*	100*	0.005

* Data reported in terms of percent improvement

8. Conclusion

The focus of this article was to demonstrate possible links between LM practices and IPDD. First, comparison and analysis of a number of factors showed remarkable similarities between LM practices and IPDD. Second, a set of twenty paired hypotheses was used to test similarities between LM practices and IPDD factors. Statistical results strongly support the hypotheses regarding similarities between LM and IPDD for majority of factors. Specifically, out of twenty hypotheses, the respondents agreed that there is a high degree of similarities between LM and IPDD for all but three hypotheses.

The last pair of hypotheses that examines the overall impact of LM principles is especially important. Statistical results strongly agreed that the main principles of waste elimination and respectful treatment of people in LM is also applicable to IPDD. The correlation coefficients between LM and IPDD factors also supported the same result. Third, statistical results also indicate that compared with conventional companies, LM companies are able to develop new products with 63% better quality, 52% less development time, 45% less development cost, and 36% less manufacturing cost. Also frequency of new product introduction is 51% faster than conventional companies.

In summary, statistical results of the article show strong links between LM practices and IPDD. Managerial implication of the research is that successful implementation of LM principles goes much beyond inventory reduction and frequent deliveries. For LM organizations, success in IPDD is the result of knowledge and technology transfer from their LM system into their product design and development process.

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