A DELPHI STUDY OF MANUFACTURING COMPLEXITY

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ABSTRACT

The purpose of this study is to identify the types and sources of internal manufacturing complexity and to define each type of manufacturing complexity. A Delphi study was performed including 81 experts form a variety of industries and job-positions in small to large businesses. The study conducted 5 rounds to reach consensus. When consensus was achieved, there was overwhelming support for four sources of complexity with a total of 11 sources being identified and defined. The most strongly supported sources of manufacturing complexity were process variability (in quality or quantity), product variety, non-standard product designs, and product design. This study used non-academic experts, anonymous to each other to identify sources of complexity familiar to them from their industrial experience. The results of the study can be used to begin the process of identifying what the sources of complexity are so that managers can consider how to avoid and reduce complexity when they make operations decisions.

INTRODUCTION

The adjectives simple and complex are often used when describing things like organisms, mechanisms, and organizations. In the area of management, one of the principles of the lean operations philosophy is to “simplify” systems in order to increase productivity and throughput, and to shorten cycle times. Simplifying implies that production systems have a level of complexity, one that might be altered by actions taken by the organization’s management. Some research has been conducted on aspects of a manufacturing system that were believed to be part of the complexity of a system. Examples of this include, Smunt and Ghose (2016), Song and Zhao (2009), Frizelle and Woodcock (1995), Kekre and Srinivasan (1990), and Benton and Srivastava (1985, 1993). However little has been done to identify a group of factors that create or add to the complexity in a manufacturing system. This is the first logical step needed to give direction for further study of manufacturing complexity. This study seeks to understand the sources of internal manufacturing complexity and whether manufacturing complexity can possibly serve as a fundamental construct that can be used to develop theories in many research streams in operations management.

Complexity has been examined in many different fields but it has not been a central research topic in operations management possibly because it is not clearly defined and it is not clear how the concepts of complexity can increase our understanding of operations. Complexity is often treated as important environmental variable in management strategy (e.g., Kim and Lee, 1993) and supply-chain management (e.g., Bozarth, 2009; Wan et al., 2012) research.

This research study focuses on internal manufacturing complexity since this area is most affected by decisions made by plant managers. It does not examine external manufacturing complexity (i.e., the complexity due to the firm's environment). For example, managers may elect to purchase one large machine instead of five smaller machines, which can change the internal manufacturing complexity of their facility. Managers cannot control the changes in demand for products nor the enactment of new legislation imposing new regulations, both of which can affect external manufacturing complexity.

This study uses a Delphi panel to examine manufacturing complexity to create a basic understanding of the internal sources of complexity in manufacturing. The purpose of the study was to create a basis for further studies of how managerial decisions contribute to manufacturing complexity. This will allow researchers to determine what elements of internal manufacturing complexity actually exist in practice; to determine how practitioners define each element of manufacturing complexity; to compare practitioner's definition of complexity to that of academics; and to rank the importance of the different types of complexity as perceived by practitioners. By understanding what things makes a system more or less complex, then future research can occur investigating their impact on performance and how changing them affects performance. This will provide managers with rationale for why reducing complexity helps performance and what things to change.

The next section reviews the literature to identify existing conceptual definitions of the various types of internal manufacturing complexity. The third section discusses the research methodology providing details about the Delphi study. The fourth section presents the findings and suggests different avenues for future research. The fifth section discusses the implications of the results. The final section concludes by identifying limitations to the study and future research opportunities.

BACKGROUND

Complexity

For any theory to provide clear insights and allow conclusions, it must be built with clear formal conceptual definitions (Wacker, 2004). Here relevant definitions regarding complexity and manufacturing complexity are presented.

To help define complexity Simon (1962) stated is that complex systems have a large number of parts, whose relationships are not simple. Gell-Mann (2002) defines effective complexity as the "length of a highly compressed description of the regularities of the entity under description." (p. 1) These definitions are similar. If a system has many parts, but all of them are arranged in a repeating sequence, then according to the first definition the complexity is low because the relationships are simple and the second definition agrees that the complexity is low because it takes few words to describe the regularities (e.g., 10 identical machines arranged in a sequence). Pippenger (1978) points out that a system with simple parts may be complex if the relationships are not simple. This also agrees with Gell-Mann's definition since non-simple relationships require longer descriptions of their regularities. In his discussion of measuring complexity, Lofgren (1977) identified numerosity, the number of items in a system, and intricacy, the relationships of the parts that make up a system, as two elements of complexity. According to Klir (1985), the *states* that a system element can attain is a third element of the definition of complexity. The state of a system element is the condition or mode of that element, e.g. on or off. System elements can relate to each other through its state and the states of the other system elements at a given point in time, thereby contributing to the complexity of a system.

Manufacturing Complexity

Based upon these definitions we recognize that manufacturing's systems are complex. They have many parts or elements and the relationships of these elements are not simple. Manufacturing systems can have many products, materials, machines, employees, and departments. These "parts" of a manufacturing system also have non-simple relationships. For example, one set of relationships may be that employee A cannot process certain materials on machine 1 unless they have first been processed on another machine. We also find that the parts with the system also change states, as according to Klir's defitnion. Even when there is regularity (i.e., an established sequence) in the use of these resources, the description will be long if the sequence differs even slightly for the different items produced and system elements (machines, personnel) change states irregularly.

Table 1, summarizes what the literature has identified as potential sources of manufacturing complexity. In most instances, these elements were theorized as to their role in complexity of manufacturing systems, but a few did attempt to include some of the elements in a measure of system complexity. For example, Frizelle & Woodcock (1995) incorporated the number of machines, product mix, queue lengths, and machine status in their proposed entropic measure of static manufacturing complexity. Orfi et al. (2011), proposed number of components, component commonality, routing commonality, and product structure complexity are key factors of complexity.

Other research used these elements of manufacturing complexity to study its effect on system performance. As one example, Park and Kremer (2015) studied the manufacturing complexity caused by product variants. They found that manufacturing complexity had a negative impact of lead-time and cost for systems that make-to-stock but not for those that were made-to-order. Smunt and Ghose (2016) found that routing commonality, something they viewed as alleviating manufacturing complexity, affected mean flow time and flow time variability. From this review, we find several potential items that may instigate or add to the complexity in manufacturing system. We are curious to the overlap that will occur from elements from our literature review and what this study of practitioners will reveal.

METHODOLOGY

The Delphi Technique

A Delphi method was selected to help identify the sources of manufacturing complexity in an effort to create a basis for future studies. It provides a way to have an iterative group process that leads to consensus regarding a topic or situation that is not well-defined (Okoli and Pawlowski, 2004; Linstone and Turoff, 2002). It is a structured, scientific approach for study opinions from a group of experts. The interactions are controlled and anonymous so that deeper reflective thinking occurs and peer-pressure and group-think is avoided (Martino, 1983).

It is appropriate because this is an exploratory study where this issues cannot be directly analyzed (Meredith et al, 1989) due to the very nature of complexity. The Delphi Techniques was developed by the RAND Corporation in the 1940s and has been used in a vast number of research studies (McKenna, 1994).

Table 1 Studies using Elements of Manufacturing Complexity

Complexity Element Proposed/Studied	Author (Year)
Product variety	Park & Kremer (2015), Wan et al. (2012), Huang & Inman (2010), Bozarth, Warsing, Flynn & Flynn (2009)
Product mix	Khurana (1999), Deshmukh Talavage & Barash (1998), Calinescu et al. (1998), Bozarth & Edwards (1997), Anderson (1995), Frizelle & Woodcock (1995), Cooper Sinha & Sullivan (1992), Kekre & Srinivasan (1990), Kotha & Orne (1989)
Number of components	Orfi, Terpenny, & Sahin-Sariisik (2011), Huang & Inman (2010), Bozarth, Warsing, Flynn & Flynn (2009) , Calinescu et al. (1998), Frizelle & Woodcock (1995), Foster & Gupta (1990)
Component commonality	Orfi, Terpenny, & Sahin-Sariisik (2011), Huang & Inman (2010), Song & Zhao (2009), Wacker Miller (2000), Vakharia, Pamenter, & Sanchez (1996), Guerrero (1985), Collier (1981)
Product structure complexity	Orfi, Terpenny, & Sahin-Sariisik (2011), Fry, Oliff, Minor, & Leong (1989)
Product complexity	Khurana (1999), Ittner & MacDuffie (1995), Kotha & Orne (1989)
Queue length	Frizelle & Woodcock (1995)
Rounting Commonality	Smunt & Ghose (2016) , Orfi, Terpenny, & Sahin-Sariisik (2011), Monahan & Smunt (1999), Bozarth & Edwards (1997)
Number of machines	Deshmukh Talavage & Barash (1998), Calinescu et al. (1998), Frizelle & Woodcock (1995)
Number of operations	Deshmukh Talavage and Barash (1998)
Set-up time	Calinescu et al. (1998)
Layout	Calinescu et al. (1998)
Lot Sizes	Calinescu et al. (1998)
Machine status	Frizelle & Woodcock (1995)

Selection of Experts

The value of a Delphi study is that it uses experts, so selecting the experts is crucial to success of the Delphi study. The validity of the opinions received is directly related to expertise of the panel (Turoff, 1975). The experts for this study were operations managers, plant managers, manufacturing managers, industrial engineers, quality managers and production planners working in a cross section of industries selected to assure comprehensive coverage of the concepts of internal manufacturing complexity.

An email list of MBA graduates who took employment in manufacturing was obtained from the MBA office of southeastern university. Another group of individuals employed in manufacturing throughout the U.S. were also contacted. These contacts were garnered through prior business relationships with the researchers or membership in organizations having manufacturing professionals. These individuals were contacted via e-mail and invited to either participate in the study or to nominate another individual who would be knowledgeable about manufacturing complexity at their plant. To reduce bias two sets of individuals were contacted, some form each list.

The emails solicitation provided the names and email addresses of 146 individuals considered to be experts about manufacturing complexity. These individuals were then contacted via email. The first email sought demographic information about the experts and confirmation that they would participate in the Delphi study. Of those contacted, 81 agreed to participate in the study. As is shown in Table 2, there was a substantial diversity in the participants' job, education, and experience as well as differences in their organization's size and manufacturing process type. The job functions represented clearly support that the participants can be considered experts. Their expertise is further supported since most participants having substantial career experience, meaning the context and understanding of operations is demonstrated to be mature. The breadth of organization size and process type will permit the results to be more generalizable because they represent a range of manufacturing organizations.

Table 2 Demographics of Participants

Job Function	
Industrial Eng.	10
Engineering Mgr	9
Manufacturing Mgr	13
Operations Mgr	6
Plant Mgr	7
Prod. Control Mgr	1
Other	11

Education	
High School	1
Tech. School	2
College	33
Masters	18
Ph.D.	1
No Response	2

Experience	
Less than 5 years	5
5 to 10 years	18
More than 10 years	34

Employees	
< 100	8
100 – 4999	22
500 – 1,000	14
> 1,000	11
Unknown	2

Process Type	
Assembly Line	8
Batch	12
Continuous	6
Flow Line	8
Group Technology	12
Job Shop	11

The Study Procedure

The Delphi procedure used in this study was based on Scheibe et al.'s (1975) work. There are four distinct phases in this Delphi process. The first phase is exploration. The second phase is understanding how the experts view the issue. The third phase explores any disagreements by bringing out the reasons for the disagreements. The fourth phase feeds back the analyzed evaluations to the experts.

The Delphi study was conducted entirely using the internet which has been a supported methodology, e.g. in Lummus et al. (2005). All contact was via e-mail. Questionnaires were posted on a non-public webpage. The only way to access the page was with a coded hyperlink to that page included in the e-mail. There was a unique access code for each participant so that multiple submissions could not happen. The codes were generated and assigned randomly so that the identity of the participant was anonymous.

At the beginning of each round, an e-mail soliciting participation was sent with the hyperlink to the webpage for that round. The first page contained instructions and any definitions that were deemed critical for the participant to understand prior to starting the questionnaire. After a designated amount of time had elapsed, follow-up e-mails were send to the participants who had not responded asking them to consider participating in that round. After each round, the results were analyzed and summarized. The results were shared with the participants along with a new questionnaire that solicited further response from participants after they introspectively consider the response from the group. Five rounds were conducted. Participation in the five rounds is shown in Table 3.

Table 3 Participation by Delphi Round

Round	Total Contacted	Total Participating	Total Withdrawing
1	81	57	-
2	81	47	2
3	79	54	-
4	79	49	-
5	76	41	3

Questionnaire Development

Although a list of sources of manufacturing complexity and definitions already existed in the literature, it was not provided to the participants in advance so as not to influence their opinions (Scheibe et al., 1975). The first round of the study was to explore the concept of internal manufacturing complexity and to allow time for a variety of opinions to emerge (Linstone and Turoff, 2002). This exploration helps prevent the loss of information that might otherwise occur if there was a push to consensus.

The first round consisted of two sections. The first collected the demographic information summarized in Table 2. The second section began with a guiding definition of complexity and then asked the experts to name and describe the sorts of things that create manufacturing complexity in their facility. This open-ended question was used hoping to produce a long list of the types of complexity encountered in manufacturing operations (Dalkey, 2002).

The questionnaires for subsequent rounds were developed after analyzing the results of the previous round. The objective was to provide participants with meaningful feedback so that group can move to consensus on the elements of manufacturing systems that cause complexity.

RESULTS

Round 1

The list of elements of ***internal*** manufacturing complexity received from the open-ended question was then reviewed by the researchers, and content analysis was used to objectively, systematically and quantitatively consolidate the information (Holsti, 1969). Formal rules and procedures were developed and employed to allow another analyst using the same data to develop similar conclusions. The researchers attempted to apply these rules consistently to all content (e.g., the researchers do not favor comments with which they themselves agreed) in order to achieve theoretical relevance.

First, the researchers independently developed a list of keywords to describe each statement submitted by the Delphi panel. Interpretation of the actual words was allowed. For example, one expert may have talked about batch size, while a second expert talked about order quantity rules for production. Initially, each researcher chose whether to identify these comments using the key word batch size or order quantity rules. If the researcher feels that there was more than one thought in an expert's comments, more than one key word was listed for the comment. While doing this, each idea was categorized by the researcher as being either associated with internal or external complexity. The researchers then reviewed these keywords together and discussed differences and similarities in their lists. The descriptions provided by the Delphi panel were then used to create formal definitions for each type of manufacturing complexity as shown in Table 4.

Round 2

The creation of Table 4 was the end of the exploratory phase of the Delphi study. The second phase was to develop an in-depth understanding (Linstone and Turoff, 2002) of how the experts viewed ***internal*** manufacturing complexity. In the e-mail opening Round 2, the researchers explained their decisions in refining the Delphi panels' responses in Round 1. The participants were given the definitions of internal manufacturing complexity in Table 4 and they were asked to review and revise the definitions as appropriate and finally to select the top 10 types of the sources of internal manufacturing complexity. To prevent presentation bias in the rankings, the internal complexity list was randomized for each participant. This review and ranking process is similar to other uses of the Delphi study (e.g., Jolson and Rossow, 1971). The suggestions for changes to the definitions were analyzed using content analysis as described in Phase 1.

The definitions that were revised are shown in Table 5. The summarized results of Round 2 of the top 10 sources of complexity are given in Table 6. Twenty definitions were presented to the Delphi panel, so the median was 10.5. The percent selecting the median was 42.6%. The median less 15% was selected to remain in the study, resulting in having 15 types of internal manufacturing complexity retained for Round 3 of the study.

During the content analysis of Round 2 responses, it was noted that there was a point of disagreement among the Delphi experts concerning scheduling. Three distinct views about scheduling emerged among the experts. One group suggested that choosing an inappropriate scheduling system created complexity. The second group viewed the scheduling task itself as complex. The third group emphasized that a good schedule reduced complexity.

Table 4 Initial Elements of Internal Manufacturing Complexity with Definitions

Term	Definition
Business Management	Business Management creates internal manufacturing complexity by: • lacking accountability of personnel in all/some positions • requiring a process change or program implementation without sufficient resources or infrastructure • having corporate policies that prevent investment in required technology • failing to update standards that are used for budgeting and control • lacking communication and coordination among functional groups
Workforce Management	Workforce Management creates internal complexity due to: • the need to train the workforce • insufficient communication between multiple shifts • the difficulty of having to schedule workforce • the difficulty of determining the size of the workforce required to support manufacturing.
Traceability	There is an internal or external requirement to identify material and processing history of the products produced. This creates complexity because of the need to gather, record, and save information.
Work Flow Disruption	This occurs when the planned workflow is changed because: • rework is required • scrapped production necessitates the starting of new, expedited orders • equipment failure, material shortages, etc. creates delays
Set-up Time	Creates internal complexity when long-setup times or the need for frequent setups either: • consume excessive amounts of capacity, or • necessitate large batch sizes
Process Variability in either quality or quantity of output	Process variability can be due to the lack of standard operating procedures, tolerance stacking, or machine variation. It is often difficult to find the root cause of the process variability.
Variety of the internally produced components	Creates complexity by affecting material handling, capacity scheduling and workflow management
Inventory Management	Creates complexity when the inventory records are inaccurate and when the inventory has special storage requirements (e.g., product segregation), limited shelf life and when it is hard to set good target levels.
Scheduling	Creates complexity when limited resources (e.g., bottlenecks) have to be allocated to multiple needs to meet due dates.

Product Variety	The number of end products (product line breadth). It creates complexity by increasing the number of items to manage (i.e., inventory control and scheduling) in the shop and/or in the supply chain. Product variety results in an increased number and variety of manufacturing processes that must be managed.
Maintenance Management	The scheduling of preventive maintenance, the stocking of the tooling and spare parts, the management of breakdown repairs and equipment upgrades.
Non-standard Product Design	The use of different components or raw materials to perform the same function within the product. This creates complexity in inventory control of raw material and components, and in processing.
Number of Routings	The total number of flow paths in the facility. This creates complexity for scheduling and workflow management.
Number of Steps in the Routing	The number of operations and their sequencing. This creates complexity in the scheduling of labor and equipment and the tracking of inventory
Number of Processes	The total number of processes in a facility. This creates complexity, since a larger number of manufacturing processes require more technical knowledge.
Process design	Decisions such as the number and type of machines, the level of machine standardization, the sophistication of the control and monitoring systems, and the assignment of tasks and/or labor to work centers. Process design creates complexity when there is a mismatch between the machine and process capability, flexibility and capacity and the market demands and other requirements. Process design can also affect material flow.
Process Type Variety	Significant differences between equipment that performs similar functions. This creates complexity by requiring increased training, maintenance and quality procedures to be in place.
Product Design	Decisions about tolerance specifications, tolerance stacking, standardization of components, choice of raw materials, function of components and degree of process difficulty. Product design creates complexity by making products hard to assemble and affecting the degree of difficulty of the processes.
Non-standard Product Design	Use of different components or raw materials to perform the same function within the product. This creates complexity in inventory control of raw material and components, and in processing.
Number of Routings	The total number of flow paths in the facility. This creates complexity for scheduling and workflow management.
Number of Steps in the Routing	The number of operations and their sequencing. This crates complexity in the scheduling of labor and equipment and the tracking of inventory.
Process design	At a high level this consists of decisions that match the process type to the market requirements (e.g., volume and variety). The choice of process type leads to a choice of facility layout, and technology selection. Also, the environmental requirements (e.g. temperature and humidity) for the selected processes are important.

Table 5 List of Elements of Internal Manufacturing Complexity from Round 2

Term	Definition
Business Management	Business Management creates internal manufacturing complexity by: • Not requiring accountability of personnel in all/some positions • requiring a process change or program implementation without sufficient resources or infrastructure • having corporate policies that prevent investment in required technology • failure to update standards that are used for budgeting and control • failing to facilitate communication and coordination among functional groups • Difficulty of determining the size of the workforce required to support manufacturing.
Workforce Management	Workforce Management creates internal complexity by: • not properly managing the need for training and cross-training • not ensuring that there is sufficient communication among multiple shifts • the procedures and work • rules used to schedule the workforce
Process Variability in either quality or quantity of output	Process variability can be due to the lack of standard operating procedures, tolerance stacking, or machine variation. It is often difficult to find the root cause of the process variability.
Variety of the internally produced components	Creates complexity by requiring different processes which may affect material handling, capacity scheduling and workflow management.
Inventory Management	Creates complexity when: • the inventory records are inaccurate • when the inventory has special storage requirements (e.g., product segregation) • when the inventory has limited shelf life • when it is hard to set good target levels.
Scheduling	Is the advance planning of capacity consumption at each work center, workstation or machine. A poor quality schedule increases shop floor complexity, by affecting material handling, capacity scheduling and workflow management of limited resources (e.g., bottlenecks), which have to be allocated to multiple needs to meet due dates.

Round 3

As suggested by Linstone and Turoff (2002), the third phase explored the experts' disagreements and sought to understand why the experts disagreed and to create consensus definitions. To do this, the participants were sent the revised definitions along with a list of the 15 types of internal manufacturing complexity that were retained from Round 2. The participants were asked to select the top eight types of complexity and to review the definitions again and to suggest any changes they felt were appropriate.

Table 6 Round 2 Selection Results

% Selecting	Source of Complexity
68.1	Process Variability
63.8	Workforce Management
63.8	Work Flow Disruption
57.4	Product Design
51.1	Business Management
51.1	Scheduling
48.9	Product Variety
46.8	Facility layout (Process Design)
42.6	Inventory Management
42.6	Non-standard Product Design
42.6	Number of Processes
38.3	Process Type Variety
36.2	Set-up Time
34.0	Technology selection (Process Design)
27.7	Variety of the internally produced components
23.4	Maintenance Management
23.4	Number of Routings
23.4	Number of Steps in the Routing
8.5	Traceability
4.3	Environmental requirements (Process Design)

The cover page for Round 3 also addressed the issue of scheduling since it was not clear why so many participants felt that scheduling was a major cause of complexity. According to the Delphi process, participants reading the perceptions of all three groups about why scheduling might or might not be a source of complexity may lead them to reconsider their understanding of the relationship between scheduling and manufacturing complexity.

All of the participants accepted the definitions provided at the beginning of Round 3. The summary of the participant's votes about the top eight sources of complexity is given in Table 6. Note that the participants did not rank the sources of complexity (i.e., 1, 2, 3…) but simply selected the top eight sources of complexity from the list of 15. The lists presented to the participants were randomized to avoid bias. Comparing Table 6 to Table 5 shows that seven of the top eight from Round 2 remained in the top eight most selected sources of complexity Round 3. This was interpreted as an indication that consensus was emerging among the participants.

The bottom four complexities in Round 2 were the same four that were on the bottom of those retained from Round 3. These four sources of internal manufacturing complexity (i.e., set-up time, variety of internally produced components, technology selection or process design and process type variety) were eliminated from further Rounds.

Table 7 Round 3 Results

% Selecting	Source of Complexity
78.7	Process Variability
59.6	Non-standard Product Design
57.4	Work Flow Disruption
57.4	Scheduling
57.4	Product Design
55.3	Workforce Management
49.0	Business Management
48.9	Product Variety
40.4	Facility layout (Process Design)
38.3	Inventory Management
38.3	Number of Processes
31.9	Set-up Time
31.9	Variety of the internally produced components
29.8	Technology selection (Process Design)
27.7	Process Type Variety

Round 4

In Round 4 the experts were asked to rank the 11 remaining sources of complexity. To help a consensus emerge, the experts were given the results from Round 3 (Table 7). The experts were also asked to explain why they selected their first and second choices.

The results from the Delphi experts are summarized in Table 8. The mean ranking of the sources of internal manufacturing complexity were used to measure the degree to which consensus was being achieved. After sorting the sources by the mean ranking, the percent of responses ranked in the top five was calculated. From this it appeared that there was consensus on the most important sources. Process variability, product variety, non-standard product design, scheduling and product design all appeared in the top five over 50% of the time. There was a substantial difference between the fifth ranking source, product design (55%), and the sixth rank source, work flow design (39%).

Table 8 Round 5 Results

Source	Mean	Rank	% of Time Ranked in Top 5
Process Variability	4.00	1	**69%**
Product Variety	4.76	2	**61%**
Non-standard Product	5.35	3	**57%**
Scheduling	5.31	4	**59%**
Product Design	5.49	5	**55%**
Work Flow Disruption	5.84	6	39%
Number of Processes	6.67	7	33%
Business Management	6.86	8	39%
Inventory Management	6.92	9	31%
Workforce Management	7.35	10	27%
Facility layout	7.47	11	31%

A content analysis was conducted of the expert's reasons for selecting process variability as either the 1st or 2nd greatest cause of internal complexity. The experts indicated that process variability creates complexity because it means key output parameters are not predictable (e.g., yield, quality, lead time) and the source of the process variance may be difficult to identify and/or eliminate.

According to the experts, product variety was selected either as the 1st or 2nd cause of internal complexity because product variety increases the number of things (e.g., inventory) and activities (e.g., setups) that must be managed.

The content analysis revealed that nonstandard product design was selected as the 1st or 2nd source of internal complexity because nonstandard product designs contribute to or create some of the other sources of complexity. For example, nonstandard product designs increase the number of activities (e.g., setups, tools) to be managed and they create nonstandard work processes which leads to waste through mistakes and rework.

There was a single expert comment regarding product design. That expert indicated that the simplicity or complexity of the design determined whether the manufacturing process would be more or less complex.

Round 5

To achieve consensus, Round 5 provided the ranked listing the 11 sources of ***internal*** manufacturing complexity. Participants were also shown a summary of the rationale provided by the panel for the top four complexity elements from Round 4. The remaining complexity elements were presented in the order they were ranked in Round 4. Participants could voluntarily view the rationale for the ranking of the last seven elements by "clicking" on the source of complexity. In this way, the experts were given two types of feedback: 1) a detailed rational for the top four complexity elements and 2) the current consensus about the relative ranking of the complexity elements. This was done to achieve closure in the ranking of the complexity elements.

Table 9 Comparison of Rounds 4 and 5

Complexity Element	Rank	Mean	Std. Dev.	Rank	Mean	Std. Dev.	Δ Rank	Δ Mean	Δ Std. Dev.
Process Variability	1	2.30	1.94	1	4.00	2.52	0	(1.70)	(0.58)
Product Variety	2	2.70	1.99	2	4.76	3.17	0	(2.06)	(1.18)
Non-Std Prod. Design	3	3.78	2.35	3	5.35	3.56	0	(1.57)	(1.21)
Product Design	4	4.78	2.57	5	5.49	2.84	+1	(0.71)	(0.27)
Scheduling	5	5.08	1.66	4	5.31	2.68	-1	(0.23)	(1.02)
No. of Processes	6	6.23	1.99	7	6.67	3.20	+1	(0.45)	(1.20)
Workflow Disruption	7	6.65	2.03	6	5.84	2.91	-1	0.81	(0.88)
Inventory Mgmt.	8	7.48	2.24	9	6.92	2.66	+1	0.56	(0.42)
Business Mgmt.	9	8.58	2.26	8	6.86	3.28	-1	1.72	(1.02)
Plant Layout	10	8.75	1.80	11	7.47	2.97	+1	1.28	(1.17)
Workforce Mgmt.	11	9.70	1.87	10	7.35	2.77	-1	2.35	(0.89)

After analyzing the results of Round 5, the researchers felt that the expert's opinions have converged. Table 9 presents a comparison of the results from Rounds 4 and 5. The rankings of the elements of complexity changed very little. Additionally, the mean rankings were all lower for the top five, especially for the top three – process variability, product variety and non-standard product design. Also, the variation in rankings also decreased for every element, signifying a move towards consensus.

In order to resolve the rankings further, the percentage of times that a source of complexity was ranked first or second was calculated as reported in Table 10. In both cases, the top five complexity elements by mean rank (Table 9) matched the complexity ranked order in Table 10. Process variability was ranked as the 1st or 2nd largest source of internal manufacturing complexity by 70% and was ranked as one of the top five by 95% of the respondents. Product variety was ranked as the 1st or 2nd source by 56.5% of respondents and in the top five sources of complexity by 92.5% of the respondents. Nonstandard product design was ranked as the 1st or 2nd source by 37.5% and in the top five by 80% of respondents, while product design was ranked 1st or 2nd source by 17.5% and in the top five by 67.5% of respondents. Scheduling remained in the top five sources of complexity, but was only ranked as the 1st or 2nd source by 5% of respondents.

Table 10 Rank Order by percentages for Round 5

Complexity Element	% ranking as 1 or 2	% ranking in top 5
Process Variability	70.0%	95.0%
Product Variety	57.5%	92.5%
Non-Std Prod. Design	37.5%	80.0%
Product Design	17.5%	67.5%
Scheduling	5.0%	60.0%
Workflow Disruption	5.0%	27.5%
Business Mgmt.	5.0%	7.5%
Inventory Mgmt.	2.5%	22.5%
No. of Processes	0.0%	37.5%
Plant Layout	0.0%	5.0%
Workforce Mgmt.	0.0%	5.0%

DISCUSSION

This Delphi study of internal manufacturing complexity identified the most critical sources of internal manufacturing complexity, that is, complexity that results for decisions made within the operation. Definitions were developed for each element of complexity from a content analysis of the Delphi expert's feedback. Eleven sources of complexity remained from an initial list of 22 with five of these having strong support by the end of the study. The top five, in order, are process variability (in quality or quantity), product variety, non-standard product designs, product design, and scheduling.

The results of the research lead to several practical implications. The top source was process variability, which leads to poor quality that impacts subsequent processes or unpredictability in the quantity that will be yielded from processes. In either case, the unplanned results of these necessitate some additional effort by the system to alleviate or rectify the situation. This finding corresponds to emphasis on reducing variation advocated in the lean manufacturing philosophy. Managers should plan investment to study and improve their manufacturing processes to avoid the unpredictability due to this variability which leads to rework, scrap, initiation of new manufacturing orders to fulfill requirements, or overproduction (unneeded use of capacity) all of which are recognized as waste in lean manufacturing.

The second source of complexity is product variety. Our experts indicated this increases the number of end-products and materials that need to be managed with regards to inventory control and production scheduling, and can increase the number of processes that must be managed. Managers are advised to carefully consider adding new products to the product line. The impact of these additions can add more than the accounting cost of production in that there may be a non-proportional increase in the management needed to mitigate the unpredictability brought on by the added complexity in these areas. This also supports the use a focused factories or workcells.

Non-standard product designs, the third-rated complexity element, results from having one product having a design where equivalent components are not identical, thus necessitating a different processing method. The different process requirements for a manufacturing order is not known or accounted for during planning and scheduling, but becomes evident only in the midst of the processing of the production order. It is surprising that this is an item that resounded so strongly within the group. It must be more common than one would expect that there is an impactful difference between components being functional equivalent and being interchangeable. Management should carefully consider the tradeoff between the cost savings or supply flexibility gained and the complexity added when accepting non-identical components as equivalent.

Product Design increases complexity by either having more parts to assemble, or requiring processes that are more difficult to perform. Here we find a connection to technological complexity as purported by Khurana (1999). This points to the need to develop new processes together with new products. As products become more complex in the sense of requiring greater manufacturing difficulty using current processes, new or improved processes must be born to mitigate the added complexity. If the complexity from the product design is due to number of components and materials to assemble, this recommends the application of subassembly or modules within the product design which can be produced outside of the product assembly process, perhaps even outsourced.

An important objective of this study was to identify sources of internal manufacturing complexity are controlled to some degree by management decisions. This was clear from the definitions developed from the Delphi expert's feedback. Issues like workforce management and business management were ideas that have not been included as complexity factors in the literature as identified Table 2.

As with most studies, the conclusions must be contemplated with restraint. Although the pool of experts represented a variety in sizes of operations, levels of personal experience, professional background, and process type, there were only approximately 50 representatives (experts) all from a single country. It is also a study that is a "snapshot" at one point in industrial history. A different group at a different time (20 years from now) may yield different results.

Certainly we cannot claim that the list of the sources of internal manufacturing complexity are absolute or complete.

CONCLUSION AND FUTURE RESEARCH

A Delphi study was conducted to discover the sources of manufacturing complexity that are under the control of management. Definitions for the initial list of 22 sources of complexity were developed from a content analysis. In subsequent rounds, according to the Delphi process, the list was reduce to 11 with clarified definitions. Four of these sources of complexity achieve substantial support. These were:

1. process variability (in quality or quantity)
2. product variety
3. non-standard product designs
4. product design.

Manufacturing scheduling garnered strong support for it causing complexity, something that doesn't stand logically. The study attempted to determine the expert's rationale for this results and explain the incongruous finding without success.

Future research is needed to determine whether complexity may be a useful concept to use in examining manufacturing decisions and to classify these sources of complexity. Measurement of complexity may be beneficial as a tool for evaluating the relative performance of a manufacturing system and when making decision that can have either a positive of negative effect on the business.

Another challenge is how to measure some of these elements. For example, how is product design complexity to be measured? The definition indicates this is not only a function of the number of items to be assembled, but also the technical complexity of the processes necessary to assemble or fabricate the product.

Manufacturing complexity must play a role in operations performance. This study begins the process of identifying what the sources of complexity are so that managers can consider how to avoid and reduce complexity when they make operations decisions.

REFERENCES

Benton, W. C. and R. Srivastava (1985), Product Structure Complexity and Multilevel Lot Sizing Using Alternative Costing Policies. *Decision Sciences*, 16 (4), 357-369.

Benton, W. C. and R. Srivastava (1993), Product structure complexity and inventory capacity performance of a multi-level manufacturing system. I*nternational Journal of Production Research*, 31 (11), 2531-2545.

Bozarth, Cecil C., Donald P. Warsing, Barbara B. Flynn, and E. James Flynn (2009), The impact of supply chain complexity on manufacturing plant performance, *Journal of Operations Management*, 27 (1), 78-93.

Bozarth, C. and S. Edwards (1997), The impact of market requirements focus and manufacturing characteristics focus on plant performance. *Journal of Operations Management*, 15 (3), 161-180.

Calinescu, A, J. Efstathiou, J. Scirn, and J. Bermejo (1998), Applying and assessing two methods for measuring complexity in manufacturing, *Journal of Operational Research Society.* 49 (7), 723-733.

Casti, J. L. (1979), *Connectivity, Complexity, and Catastrophe in Large-Scale Systems.* Wiley, New York, NY.

Collier, D. A. (1981), "The Measurement and Operating Benefits of Component Part Commonality. *Decision Sciences*, 12 (1), 85-96.

Cooper, W. W., K. K. Sinha, and R. S. Sullivan (1992), Measuring complexity in high-technology manufacturing: indexes for evaluation. *Interfaces*, 22 (4), 38-48.

Dalkey, N. C. (2002). A Delphi Study of Factors Affecting the Quality of Life". in Linstone, H. A. and M. Turoff, *The Delphi Method: Techniques and Applications*, Addison-Wesley, Reading, MA, 387-401.

Deshmukh, A. V., J. J. Talavage, and M. M. Barash (1998), Complexity in manufacturing systems, Part 1: Analysis of static complexity. *IIE Transactions*, 30, 645-655.

Fisher, M. L. and C. D. Ittner, (1999), The impact of product variety on automobile assembly operations: empirical evidence and simulation analysis. *Management Science*, 45 (6), 771-786.

Foster, G. and M. Gupta, (1990), Manufacturing Overhead Cost Drivers Analysis. *Journal of Accounting and Economics*,12, 309-337.

Frizelle, G. and E. Woodcock (1995), Measuring complexity as an aid to developing operational strategy. *International Journal of Operation and Production Management*, 15 (5), 26-39.

Fry, T. D., M. D. Oliff, E. D. Minor, and G.K. Leongs (1989), The effects of product structure and sequencing rule on assembly shop performance. *International Journal of Production Research*, 27 (4), 671-686.

Gell-Mann, Murray (2002), Plectics: The study of simplicity and complexity. *Europhysics news*, 33 (1), 17-20.

Guerrero, H. H. (1985), The effect of various production strategies on product structures with commonality. *Journal of Operations Management*, 5 (4), 395-410.

Holsti, O.R. (1969), *Content Analysis for the Social Sciences and Humanities*. Addison-Wesley, Reading, MA.

Huang, N., & Inman, R. (2010). Product quality and plant build complexity. International Journal of Production Research, 48(11), 3105-3128

Ittner, C. D. and J. P. MacDuffie (1995), Explaining Plant-Level Differences in Manufacturing Overhead: Structural and Executional Cost Drivers in the World Auto Industry. *Production and Operations Management*, 4 (4), 312-334.

Jolson, M. A. and G. L. Rossow (1971). The Delphi Process in Marketing Decision Making. *Journal of Marketing Research*, 8, November, 443-448.

Kekre, S. and K. Srinivasan (1990), Broader Product Line: A Necessity to Achieve Success? *Management Science*, 36 (10), 1216-1231.

Kim, Yearnmin, and Jinjoo Lee (1993), Manufacturing strategy and production systems: an integrated framework. *Journal of Operations Management*, 11 (1), 3-15.

Klir, G. J. (1985), Complexity: Some General Observations. *Systems Research*, 2 (2), 131-140.

Kotha, S. and D. Orne (1989), Generic Manufacturing Strategies: A Conceptual Synthesis. *Strategic Management Journal*, 10, 211-231.

Khurana, A. (1999), Managing complex production processes. *Sloan Management Review*, 40 (2), 85-97.

Linstone, H. A. and M. Turoff *(2002). The Delphi Method: Techniques and Applications*. 2002, Murray Turoff and Harold A. Linstone.

Löfgren, L. (1977), Complexity of Descriptions of Systems: A Foundational Study. I*nternational Journal of General Systems*, 3, 197-214.

Lummus, R. R., Vokurka, R. J., & Duclos, L. K. (2005). Delphi study on supply chain flexibility. *International Journal of Production Research*, 43(13), 2687-2708.

Martino, J.P. (1983), *Technological Forecasting for Decision Making*. Elsevier: New York, NY.

McKenna, H.P. (1994), The Delphi technique: a worthwhile research approach for nursing? *Journal of Advanced Nursing*, 19 (6), 1221–1225.

Meredith, J.R., Raturi, A., Amoako-Gyampah, K., and Kaplan, B. (1989), Alternative research paradigms in operations. *Journal of Operations Management*, 8 (4), 297–326.

Monahan, G. E. and T. L. Smunt (1999), Processes with nearly-sequential routings: a comparative analysis. *Journal of Operations Management*, 17 (4, 449-466.

Park, K., & Kremer, G. E. O. (2015) Assessment of static complexity in design and manufacturing of a product family and its impact on manufacturing performance. *International Journal of Production Economics*, 169, 215-232

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & management*, *42*(1), 15-29.

Orfi, N., Terpenny, J., & Sahin-Sariisik, A. (2011). Harnessing product complexity: Step 1—Establishing product complexity dimensions and indicators. The Engineering Economist, 56(1), 59-79.

Pippenger, N. (1978), Complexity Theory. *Scientific American*, 238 (6), 114-125.

Russell, R. S. and B. W. Taylor (1985) An Evaluation of Sequencing Rules for an Assembly Shop. *Decision Sciences*, 16 (2), 196-212.

Scheibe, M., Skutsch, M., & Schofer, J. (1975), Experiments in Delphi methodology. 262-287.

Simon, H. (1962), The Architecture of Complexity. *Proceedings of the American Philosophical Society*.106 (6), 467-482.

Smunt, T. L., & Ghose, S. (2016). An Entropy Measure of Flow Dominance for Predicting Operations Performance. Production and Operations Management, 25(10), 1638-1657.

Turoff, M. (1975), "The Policy Delphi" in Linstone, H. A. and M. Turoff, *The Delphi Method: Techniques and Applications*, Addison-Wesley, Reading, MA, *84-101.*

Song, J. S., & Zhao, Y. (2009). The value of component commonality in a dynamic inventory system with lead times. Manufacturing & Service Operations Management, 11(3), 493-508.

Sum, C. C., D. O. Png, K. K. Yang (1993), Effects of Product Structure Complexity on Multi-level Lot Sizing. *Decision Sciences*, 24 (6), 1135-1155.

Vakharia, A. J., D. A. Pamenter, and S. M. Sanchez (1996), The operating impact of parts commonality. *Journal of Operations Management*, 14 (1), 3-18.

Veral, E. A. and R. L. LaForge (1985), The Performance of a Simple Incremental Lot-Sizing Rule in a Multilevel Inventory Environment. *Decision Sciences*, 16 (1), 57-71.

Wacker, J. G., & Miller, M. (2000). Configure-to-order planning bills of material: simplifying a complex product structure for manufacturing planning and control. Production and Inventory Management Journal, 41(2), 21-26.

Wacker, J.G. (2004), A Theory of Formal Conceptual Definitions: Developing Theory-building Measurement Instruments. *Journal of Operations Management*, 22 (6), 629-650.

Wan, Xiang, Philip T. Evers, Martin E. Dresner (2012), Too much of a good thing: The impact of product variety on operations and sales performance. *Journal of Operations Management*, 30 (4), 316-324.