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Identification of complexity cost factors in manufacturing companies

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Abstract

Complexity tends to be arguably the biggest challenge of manufacturing companies. As the demand from the customers increases in volume and diversity, the number of finished products and components increases as well. This increasing product complexity has a direct effect on the production processes. This research focuses on the relation between product and process complexity. Complexity cost factors are identified and categorized under the industrial standard APQC for process classification. Then, this categorization is used as a tool for identification of complexity cost factors in seven companies. The results from this research are evaluated and future work is discussed.

Keywords: Process Complexity, Product Complexity, Complexity Cost Factors

Introduction

Complexity is a field of increasing interest during the latest years, both for researchers and practitioners. Recent surveys show that the main concern of 1,500 chief executive officers (CEOs) is the increasing complexity, which is considered to be the biggest threat for an organization (IBM, 2015). A survey performed in over 100 companies from more than 10 industrial sectors revealed that 84% of the companies consider complexity as a key cost factor, and that lack of transparency over complexity costs leads to inefficient management of complexity (ATKearny, 2009). Complexity is three-dimensional, as it rises in products, processes and organizational structure, and there is an interconnection and a strong impact among these three types of complexity (Wilson and Perumal, 2009).

Complexity in the products leads to complexity in operations (Blecker et al., 2006). In this article we mainly focus on costs implications from product complexity on production, delivery and sales order handling (Samy and ElMaraghy, 2012a). Additionally, we neither consider other implications like on time delivery, time of delivery, quality, ability to introduce new products, nor the process step of product development. In order to make an in depth analysis, only parameters addressing costs are taken into account (Wang et al., 2011). Aiming to quantify the impact from product complexity we need to relate a specific product assortment with a specific number of

components and number of finished goods and quantify the impact from reducing or increasing the number of components or number of finished goods on the costs of a specific process step. A CCF is a factor that describes how product complexity (e.g. number of finished goods) has an impact on the costs of a specific process step. Examples of CCFs are setup times in production, scrap of materials in setup of machines, sales order handling, inventories of finished goods, and freight of finished goods to warehouses.

The assessment of product profitability and cost behavior (Wan et al., 2012) has been discussed in terms of managing complexity product- and process- wise (Danese and Romano, 2004) (ElMaraghy et al., 2013). Hence the purpose of this paper is to identify and classify possible CCFs in manufacturing companies. Then, CCFs are grouped and categorized under the APQC industrial standard of process classification (APQC, 2015), in order to provide an overview and a practical approach for identification in a specific company. These factors identified are further to be used for analyzing and quantifying costs caused by complexity in manufacturing companies. The results of this research contribute to the development of an approach for managing complexity in manufacturing companies, in addition to product variety control and optimization of production processes.

Theoretical Background

In order to define the conceptual framework of this research, a literature review is performed. The main key words for searching are “complexity cost factors”, “product complexity”, “process complexity” and “complexity cost drivers”. The reason for introducing the term “driver” is the fact that early in the review process, it has been noted that many articles use this term within the same meaning as others use the term “factor”, such as Perona and Miragliotta (2004) and Schaffer and Schleich (2008). However, both words when used in the articles reviewed refer to facts that cause, stimulate and increase complexity.

The second part of the literature review focuses on identifying a framework of classification of processes. The reason for using such a framework is to obtain an overview of the processes in a manufacturing environment, in order to enable comparison among organizations and categorize the CCFs under the relevant processes. The industrial standard APQC provides such a process classification (APQC, 2015). The reason for selecting the APQC standard as a classification framework is that it describes all the processes in every industrial environment; as a result it can be applied to any manufacturing company.

To begin with, five areas of complexity are identified by Foster and Gupta (1990): product design, procurement, manufacturing process, product range, and distribution. Rommel et al. (1993) identifies and calculates the complexity costs for the business processes, by using a case study in the automobile manufacturing. The research concludes with the cost structure and the break-down of complexity costs to different processes. 15-20% of the total costs are complexity costs, which are allocated to several business processes, such as inventory, production, logistics and sales.

Blecker et al (2004) discuss the relations between mass customization and complexity. Mass customization principles are investigated from two different perspectives. On the one hand, when applied as a pure customization strategy, they increase the product variety, which results in high planning and scheduling complexity. On the other hand, as customer ordering decoupling point moves towards the front-end, then mass customization reduces product configuration and inventory complexity.

Wildemann (2001) performs an empirical study in manufacturing industries, regarding how the number of product variants affects the unit costs. Two types of industries are examined, with traditional and segmented and flexible automated plants. The results have shown that with the double number of product variants in the production program, the unit costs would increase about 20-35% for industries with traditional manufacturing systems. At the same time, in segmented and flexible automated plants, the unit costs would increase about 10-15%.

In tandem with these results, Khurana (1999) categorizes various production processes, such as job shops, flow shops, assembly and continuous processing, by assigning levels of product and process complexity.

Another distinction among complexity factors is their predictability and controllability. Gershwin (1994) categorizes as controllable activities maintenance, setup changes and calibration, while activities that increase complexity, though are unpredictable, could be failures, vendor non-delivery and worker absence.

The following tables (1-5) provide an overview of the results from the literature review. Each table describes the CCFs related to a process group, as described in the APQC standard. Under each CCF, the authors working with it are listed. When the names are in bold, it means that the article provides with quantification methods. When parenthesis follows the name of the authors, it represents that there is empirical evidence, such as case-study (CS), survey (S) or numerical example (NE).

Table 1 - Plan for and align supply chain resources

<i>No of components</i>
<i>No of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012b (CS), Garbie & Shikdar, 2011b (NE), ElMaraghy et al., 2012 (CS)
<i>State of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012b (CS)
<i>Type of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Garbie & Shikdar, 2011b (NE), Samy & ElMaraghy, 2012a (CS)
<i>Material flow pattern:</i> ElMaraghy et al., 2014 (CS), Samy & ElMaraghy, 2012b (CS), Thyssen et al., 2006 (CS), Garbie & Shikdar, 2011b (NE), Hayes & Clark, 1985, Urbanic & ElMaraghy, 2006 (CS), Khurana, 1999
<i>No of finished goods</i>
<i>No of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012b (CS), Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011b (NE), Samy & ElMaraghy, 2012a (CS), Schaffer & Schleich, 2008 (CS)
<i>State of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)
<i>Type of material handling systems:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Garbie & Shikdar, 2011b (NE), Samy & ElMaraghy, 2012a (CS)
<i>Material flow pattern:</i> ElMaraghy et al., 2014 (CS), Samy & ElMaraghy, 2012b (CS), Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011a (CS), Garbie & Shikdar, 2011b (NE), Schaffer & Schleich, 2008 (CS), Rathnow, 1993 (CS)

Table 2 - Procure materials and services

<i>No of components</i>
<i>No of suppliers:</i> ElMaraghy et al., 2012, Hu et al., 2008, Perona & Miragliotta, 2004 (CS), Jacobs, 2013
<i>Location of suppliers:</i> Hu et al., 2008

<i>No of finished goods</i>
<i>Location of suppliers:</i> Hu et al., 2008
<i>No of suppliers:</i> Garbie & Shikdar, 2011a (CS), Garbie & Shikdar, 2011b (NE), Perona & Miragliotta, 2004 (CS), Jacobs, 2013
<i>Cost of sourced components:</i> Foster & Gupta, 1990 (CS)

Table 3 - Produce/Manufacture/Deliver product

<i>No of components</i>
<i>Capacity utilization :</i> ElMaraghy et al., 2012, Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006
<i>Assembly:</i> ElMaraghy et al., 2012, Hu et al., 2008, ElMaraghy et al., 2014 (CS), Samy & ElMaraghy, 2012b (CS), Thyssen et al., 2006 (CS), Blecker & Abdelkafi, 2006, Samy & ElMaraghy, 2012a (CS), Khurana, 1999
<i>Tools:</i> Hu et al., 2008, Samy & ElMaraghy, 2012b (CS), Deshmukh et al., 1998 (NE), Urbanic & ElMaraghy, 2006
<i>Operator:</i> Hu et al., 2008, Urbanic & ElMaraghy, 2006 (CS), Gershwin, 1994
<i>No of machines:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), ElMaraghy et al., 2014 (CS), Samy & ElMaraghy, 2012b (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Perona & Miragliotta, 2004 (CS), Samy & ElMaraghy, 2012a (CS), Urbanic & ElMaraghy, 2006 (CS)
<i>Type of machines:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Garbie & Shikdar, 2011b (NE), Samy & ElMaraghy, 2012a (CS), Urbanic & ElMaraghy, 2006 (CS)
<i>State of machines:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)
<i>No of buffers:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS), Samy & ElMaraghy, 2012b (CS), Khurana, 1999
<i>Type of buffers:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)
<i>State of buffers:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)
<i>Failure:</i> Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012b (CS), Hayes & Clark, 1985, Urbanic & ElMaraghy, 2006 (CS), Gershwin, 1994
<i>Set up:</i> Thyssen et al., 2006 (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Benjaafar et al., 2004, Hayes & Clark, 1985, Urbanic & ElMaraghy, 2006 (CS), Gershwin, 1994
<i>Change-over:</i> Thyssen et al., 2006 (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Benjaafar et al., 2004, Hayes & Clark, 1985, Urbanic & ElMaraghy, 2006 (CS), Gershwin, 1994
<i>Waiting times:</i> Thyssen et al., 2006 (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Hayes & Clark, 1985, Urbanic & ElMaraghy, 2006 (CS), Gershwin, 1994
<i>Batch size:</i> Thyssen et al., 2006 (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Benjaafar et al., 2004
<i>Capital costs (rent/heating):</i> Thyssen et al., 2006 (CS), Perona & Miragliotta, 2004 (CS)
<i>Production lines:</i> ElMaraghy et al., 2012, Kuzgunkaya & ElMaraghy, 2006 (CS), Hu et al., 2008, Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006, Deshmukh et al., 1998 (NE), Jacobs, 2013
<i>Job shop:</i> Deshmukh et al., 1998 (NE), Khurana, 1999

No of finished goods

Capacity utilization: ElMaraghy et al., 2012, Hu et al., 2008, Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006

Assembly: ElMaraghy et al., 2012, Hu et al., 2008, Samy & ElMaraghy, 2012a (CS), Blecker & Abdelkafi, 2006, Samy & ElMaraghy, 2012b (CS), Schaffer & Schleich, 2008 (CS)

Tools: Hu et al., 2008, Samy & ElMaraghy, 2012b (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE)

Operator: Hu et al., 2008

No of machines: Kuzgunkaya & ElMaraghy, 2006 (CS), ElMaraghy et al., 2014 (CS), Samy & ElMaraghy, 2012a (CS), Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Samy & ElMaraghy, 2012b (CS)

Type of machines: Kuzgunkaya & ElMaraghy, 2006 (CS), Garbie & Shikdar, 2011b (NE), Samy & ElMaraghy, 2012a (CS)

State of machines: Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)

No of buffers: Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS), Samy & ElMaraghy, 2012b (CS)

Type of buffers: Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)

State of buffers: Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012a (CS)

Failure: Kuzgunkaya & ElMaraghy, 2006 (CS), Samy & ElMaraghy, 2012b (CS)

No of processes: Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011a (CS), Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006, Deshmukh et al., 1998 (NE), Jacobs, 2013, Schaffer & Schleich, 2008 (CS)

No of production lines: ElMaraghy et al., 2012, Wang et al., 2011, Kuzgunkaya & ElMaraghy, 2006 (CS), Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011a (CS), Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006, Deshmukh et al., 1998 (NE), Perona & Miragliotta, 2004 (CS), Schaffer & Schleich, 2008 (CS), Hayes & Clark, 1985

Manufacturing strategy: Garbie & Shikdar, 2011b (NE), Blecker & Abdelkafi, 2006, Wiendahl & Scholtissek, 1994

Resources: Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE)

Job shop: Deshmukh et al., 1998 (NE)

Capital costs (rent/heating): Perona & Miragliotta, 2004 (CS)

Table 4 - Manage logistics and warehousing

No of components

Transportation and handling within the production site and warehouse: ElMaraghy et al., 2014 (CS), Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Samy & ElMaraghy, 2012a (CS)

Product assortment in inventory: Thyssen et al., 2006 (CS), Jacobs, 2013

Scrap: Perona & Miragliotta, 2004 (CS)

Location of warehouses: Hayes & Clark, 1985

<i>No of finished goods</i>
<i>Product assortment in inventory:</i> Li, 2007 (NE), Sivadasan et al., 2002 (S), Perona & Miragliotta, 2004 (CS), Jacobs, 2013 , Benjaafar et al., 2004)
<i>Warehouses:</i> Garbie & Shikdar, 2011a (CS)
<i>Inventory:</i> Garbie & Shikdar, 2011a (CS), Perona & Miragliotta, 2004 (CS), Foster & Gupta, 1990 (CS), Benjaafar et al., 2004 , Blecker et al., 2004
<i>Transportation and handling within the production site and warehouse:</i> Garbie & Shikdar, 2011b (NE), Deshmukh et al., 1998 (NE), Perona & Miragliotta, 2004 (CS), Samy & ElMaraghy, 2012a (CS)
<i>Identification system:</i> Garbie & Shikdar, 2011b (NE)
<i>Scrap:</i> Perona & Miragliotta, 2004 (CS)
<i>Administrative costs:</i> Rommel et al., 1993 (CS), Wiendahl & Scholtissek, 1994

Table 5 - Markets, customers, and capabilities

<i>No of components</i>
<i>No of orders:</i> Thyssen et al., 2006 (CS), Perona & Miragliotta, 2004 (CS)
<i>Order size:</i> Perona & Miragliotta, 2004 (CS), Cooper & Kaplan, 1998
<i>No of finished goods</i>
<i>No of orders:</i> Sivadasan et al., 2002 (S), Blecker & Abdelkafi, 2006 , Perona & Miragliotta, 2004 (CS), Rathnow, 1993 (CS), Wiendahl & Scholtissek, 1994
<i>Demand:</i> Sivadasan et al., 2002 (S), Garbie & Shikdar, 2011 (NE), Deshmukh et al., 1998 (NE)
<i>Information flow:</i> Sivadasan et al., 2002 (S)
<i>No of customers:</i> Garbie & Shikdar, 2011a (CS), Perona & Miragliotta, 2004 (CS), Rathnow, 1993 (CS)
<i>Order size:</i> Perona & Miragliotta, 2004 (CS), Cooper & Kaplan, 1998
<i>Order taking process:</i> Blecker et al., 2004

As it can be seen from the tables above, the main sources of complexity in products are the number of variants and components. These factors indicate aspects of the product that are responsible for increasing complexity in the business processes. Specific process steps identified are the flow of materials, variety in the production lines, machinery, warehouse and distribution, customers' service and order handling process. In detail, batch size, set up time, waiting time, tools and flow shops are the main factors related to production and machinery. With reference to delivery, CCFs identified are number of vendors, lead times and delays. Logistics and warehouses gather also various CCFs, such as number and size of warehouses, locations, capacity, variability of inventory and handling processes in the warehouses. Through these factors complexity costs can be quantified.

It should be mentioned that in the literature review, some of the CCFs are quantified or/and tested in cases. In addition to that, the level of detail, regarding the quantification method and the data required vary significantly among the different articles. However, these two aspects (quantification methods and data acquisition) are not considered in this current work.

Research methodology

This paper examines the existing literature on complexity management, and compares the CCFs identified in the literature review to those identified in case studies. Firstly, the various approaches of analyzing complexity by academia and practitioners are examined and discussed. Then, the factors for quantifying complexity, both from the literature and the case studies, are identified and then categorized. Therefore, an integrated framework, linking complexity in both products and processes is used, and is

built upon the industrial standard for process classification, in order to enable classification of the CCFs.

Seven companies have been used as case studies. Each company has been researched for a 5 month period, so that it would be possible to collect and analyze the required data. In all cases, CCFs were identified and evaluated. This in depth analysis allows relatively high validation of the acquired information (Yin, 2003). Then, the CCFs identified in the case-studies are also classified.

The APQC industrial standard is used for that purpose (APQC, 2015). Since this classification framework describes all the processes in an industrial environment, it can be applied to all the companies examined. The purpose of categorizing the CCFs under the APQC framework is to enable a cross-examination and comparison among different manufacturing industries and allow for generalizability of the research method. This categorization also serves a direct comparison between the factors discussed in the literature and those identified in the case-studies.

Case studies

In order to test the suggested methodology and provide empirical evidence, seven companies have been examined as case-studies. All companies are in the manufacturing industry, however they produce different products and they differ in size. The reason for selecting these companies with such diversity is to compare the CCFs across organizations, to get a better understanding in tandem with setting the limitations of this research. The following table describes the main characteristics of the seven companies.

Table 6 - Overview of case-studies

Company	Product	No of employees / size	Production strategy	Number of product variants
A	Medical devices, sensor cassettes	2400	CTO	120
B	Pumps	500	ETO (MTO, CTO)	2736
C	Analytical instruments	1200	CTO	40
D	Commercial vacuum cleaners	5200	CTO	350
E	General Building Insulation products	7800	CTO	175
F	Mattresses	274	CTO	3714
G	Frozen food	1000	-	666

At this point, it should be noted that Company G is not in the manufacturing sector, as it produces frozen food. However, it is included in this study as the main processes, such as logistics and distribution, management of vendors and suppliers, warehouse management, and handling processes are similar to those for companies operating in the manufacturing industry.

As it can be seen from the table above, the companies vary in size and type of products they manufacture. The unit of analysis is the final variants that the companies offer to their customers. In order to ensure consistency among the different cases, all data is obtained from the ERP systems. The data is also discussed with the project managers, so as to certify that the research team has all the information needed and that the data acquired is up-to-date. Moreover, a research protocol is developed and followed in all cases, regarding data retrieval and processing, in order to ensure external validity

of the research. The following table provides an overview of the CCFs identified in each case. After each CCF, if identified in a case, brackets with the name of the company follow. When quantified, the name of the company appears in bold.

Table 7 - Categorization of CCFs in the case-studies under APQC standard

Product/ Process	No of components	No of FG
Plan for and align supply chain resources	No ,State, type of material handling systems material flow pattern	No, state, type of material handling systems material flow pattern [D]
Procure materials and services	Location of suppliers No of suppliers [G]	Location of suppliers No of suppliers [G] Cost of sourced components [C,D]
Produce/ Manufacture/ Deliver product	Assembly tools No, Type, state of machines No, type, state of buffers failure Production lines job shop waiting times operator [E] Capacity utilization [F] set up [D] changeover [E,F] batch size [E,F,G] capital costs (rent/heating) [G]	Assembly tools No, Type, state of machines No, type, state of buffers failure no of processes job shop operator [E] capacity utilization [D,F] No of production lines [D] manufacturing strategy [D] resources [D,E] capital costs (rent/heating) [D,E,G] Indirect production cost [A] Direct production [A,D] Overproduction [D]
Manage logistics and warehousing	transportation and handling within the production site and warehouse [B,G] product assortment in inventory [A,B,C,D,F,G] scrap [G] location of warehouses [D]	warehouses identification system product assortment in inventory [A,B,C,D,E,F,G] inventory transportation and handling within the production site and warehouse [A,D,E,G] scrap [A,E,G] administrative costs [A,D] Freight [A,D] Insurance [E] Shelf-life [G]
Markets, customers, and capabilities	no of orders [A] order size [A]	information flow No of customers no of orders [A] demand/sales [A] order size[A] order taking process [B,D,G]

As it can be seen from the table above, CCFs identified in the case-studies cover the same business processes as from the literature review. The main limitation to this research is the availability and validation of the data acquired. For that reason, the research team was not able to quantify all the CCFs identified.

Discussion and Conclusion

This research focuses on identifying and categorizing CCFs from the literature review and the case-studies under the APQC framework of process classification. Product complexity, measured in terms of number of components and number of finished goods, causes complexity to several process steps. By comparing the results from the literature review and the empirical evidence regarding product complexity, it can be seen that CCFs related to material handling systems have not been identified in the cases, as well

as factors related to machines, buffers and tools. On the contrary, in almost all cases have been identified and quantified CCFs in processes related to inventory, production and sales. In detail, CCFs related to the process group of logistics and warehouse, such as freight costs from the warehouse to the distribution centres, insurance costs of finished goods and their shelf-life have been identified and quantified in some of the cases, but not in the literature. This, points out the need of expanding the limits and depth of the literature research.

Factors related to markets and customers have been identified in the cases, yet not quantified. The same applies for material flow, where the lack of data did not enable the research team to quantify the complexity cost.

Summarizing the findings from the literature and the empirical evidence, the most common CCFs discussed in the literature and identified in the case studies are related to the number of components and variants kept in stock, machine utilization, batch sizes and changeover times. Furthermore, processes related to supply, logistics and distribution gather also numerous factors. In detail, transportation and handling within the production site and warehouse, number and size of orders, and number of suppliers are the “usual suspects”.

In overall, it can be seen that the factors discussed in the literature align with the factors identified in the case-studies. Additionally, the use of the APQC framework and the classification of the CCFs allow for cross-examination not only between the literature and the empirical evidence, but also among different companies.

The results indicate that the complexity in products, described by the number of components and finished goods, are the source of increasing complexity in processes, such as production and delivery. This research is a stepping stone in order to develop a concrete framework for managing complexity in the manufacturing sector. Data acquisition and validation, quantification methods and methods for application of the CCFs classification in different industries are future research fields.

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