Quality linkages in complex production systems with causal ambiguity

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Abstract

A structured conceptualization method, concept mapping, is used to visualize the conceptual domain of quality linkages in a complex, small-volume production system of a premium automotive OEM. Concept maps are created to define clusters of sources of quality problems and rate their impact on product quality based on tacit knowledge of experts (engineers) of the production system. Dissemination of tacit knowledge in causally ambiguous production systems is critical to improve quality of managerial decisions. For implementing the results of concept mapping, an action plan was created.

Keywords: Quality Management, Causal Ambiguity, Concept Mapping

Introduction

Lippman and Rumelt (1982) describe causal ambiguity as the degree to which decision makers understand input-performance linkages when creating and managing complex processes. In complex manufacturing systems with correlated stages, interdependencies, uncertainties and, consequently, with many sources of causal ambiguity, it is critical to identify quality linkages that affect the quality of the final product (Zantek et al., 2002). One of the central drivers of performance in complex social systems, like modern production systems, or supply chains, is the behaviour of individuals, groups, or the whole organization (Gino and Pisano, 2008). This is also the case for quality management, where an increasing number of authors specifically investigate behavioural factors in their studies (Cho et al. 2017; Zeng et al. 2015). Soft factors, such as organizational learning and knowledge creation, are critical factors in most areas of operations management and, for that matter, in quality management.

Mukherjee et al. (1998) defined two types of learning in an organization: conceptual and operational. Operational learning is focused on implementing and observing factors in an operative setting and drawing conclusions directly from experiences of problems in processes and solving those issues to achieve short-term goals. Conceptual learning, on the other hand, is more related to the assessment of cause and effect relationships and the design of abstract concepts. They concluded that conceptual learning is better suitable to analyse more important factors of organizational learning and firm performance. The more valuable long-term goals are changing attention for measured variables, and knowing the specific impact of factors on process variability and quality. This ensures more efficient and effective quality improvement based on a deeper and broader understanding of causalities compared to short-term operational problem solving. They specifically consider behavioural factors, organizational behaviour, dynamic complexity and ambiguity when comparing those two forms of learning in terms of quality improvement. A more conceptual focus is therefore necessary to explore quality linkages in complex production systems with causal ambiguity.

Choo et al. (2007) distinguish between two forms of learning, similar to those of Mukherjee et al. (1998), exploratory learning and exploitation learning. Exploitation learning, like operational learning, is focused on the application of methodological elements in an operative setting by using explicit knowledge. Exploratory learning is aimed to create novel ideas and innovative solutions based on tacit knowledge and contextual elements (soft issues). While methodological elements contain metrics, tools and stepwise problem solving approaches to facilitate standardized and explicit quality programs, contextual elements include soft issues, like leadership and trust to boost tacit knowledge creation through empowerment. More innovative solutions for quality problems based on tacit knowledge also produce more durable competitive advantages because they are more difficult to imitate (Winter, 1987). This makes tacit knowledge also a more valuable resource for a company, according to the resource based view (RBV) of the firm (Barney, 1991), and should be the focus of learning and knowledge creation in quality management.

Knowledge creation and dissemination of tacit knowledge from an individual to tacit knowledge of the group is called socialization in the knowledge creation framework of Nonaka (1991). While methods to create and disseminate explicit knowledge (e.g. simulation, regression, value stream maps, fishbone diagrams, etc.) are relatively straight-forward, it is not so transparent with tacit knowledge. Anand et al. (2010) mention practices like brainstorming, or nominal group technique (Bartunek and Murninghan, 1984) for socialization of tacit knowledge in their study on the role of tacit knowledge in Six Sigma projects. They argue that it might be difficult to capture and apply tacit knowledge, especially in cross-functional teams that come together for a short-term project without significant cohesion and relationships among group members. It takes substantial amount of experience and soft skills to facilitate tacit knowledge dissemination among group members to find and implement potential “winner” process improvements that could create long-term competitive advantages for the firm.

To facilitate tacit knowledge creation in causally ambiguous production systems, we apply a `structured conceptualization' methodology (Trochim and Linton, 1986), called concept mapping, to create a 2D representation of the problem domain as seen by a management team and a team of experts. We analyse quality linkages in a small-volume, batch production system of a premium automotive OEM facing high degree of demand variability and causal ambiguity. Concept mapping has been used extensively in program management, for example, to assess the conceptual framework of staff’s views of a supported employment program for persons with severe mental illness (Trochim et al., 1994) - and, very scarcely, in operations management - for example, to show how management views the benefits of acquiring an ISO 14001 environmental certification and contrast it with the views of experts (Vastag and Melnyk, 2002).

In the manufacturing unit - producing exterior body parts for luxury sports cars - there are several correlated stages with various and highly variable inputs per process (e.g. machines, material). Product performance in terms of quality is a competitive priority for the business unit and for similar production systems (Schmenner and Vastag, 2006). The goal is to identify the most important inputs and solutions to improve quality performance within the whole value stream of the production system. Currently, quality costs are high because of many changes in machine parameters to ensure proper quality levels and due to increased investments in quality assurance and measurements. Still a significant number of products must be scrapped or reworked due to lack of data and holistic insight into quality linkages over the whole value chain. The paper aims to present an action plan for quality improvement by defining and structuring the problem domain and quality linkages of the manufacturing system based on tacit knowledge of the expert team by using concept mapping.

The following parts describe the methodology of concept mapping, followed by the explorative case study within the manufacturing unit. Next, the results are summarized, then theoretical and practical insights are discussed.

Methodology

One of the most difficult and important steps in planning is the initial conceptualization, which ultimately determines the success of all following steps. Concept mapping can be used whenever a group of people should develop a conceptual framework for evaluation or planning and the content of the maps is entirely determined by the group. Each map is a pictorial representation of the groups thinking and displays their ideas regarding a specific topic, shows relationships between those ideas and their relative importance (Trochim, 1989). The methodology consists of six steps followed in this study:

Step 1: Preparation

This step includes the selection of participants and the decision on the specific focus of the conceptualization. Participants in this study are members of the management and operative experts from several departments (production, quality assurance, and engineering) who are responsible for quality performance of the system. The scope of the analysis are quality linkages between all process steps, from metal sheet to finished exterior car body part, like doors, hatches, bonnets, etc.

Step 2: Generation of Statements

A prompt and statements should be created to represent the conceptual domain of the topic of interest – e.g. “one source of quality problems is: …” This part is very similar to a traditional brainstorming approach and as many statements as possible should be created to ideally represent the entire conceptual domain of the topic. There is a focus on high quantity of different statements and there should be no criticism regarding the legitimacy of statements as long as they fit into the previously defined areas of focus. All participant were encouraged to contribute as many statements as they could come up with regarding sources of quality issues at the manufacturing unit.

Step 3: Structuring of Statements

In this step all statements are sorted and ranked by the participants. Unstructured card sorting can be used to sort statements and put them into clusters. Response scales (e.g. Likert) are used to rank the importance of the statements. In this research participants were given a card for each statement which they had to sort into piles in an order that made sense for them. They further had to rate each statement based on its influence on quality problems with one meaning that it causes only a few light problems, and five meaning that it causes many severe quality problems. All results were then entered in a similarity matrix to summarize how many times each statement was grouped together with any other statement for all participants. The average rating of each statement was calculated to give an overview of the importance of each statement based on the judgments of the experts.

Step 4: Representation of Statements

Three tasks are necessary to graphically represent the conceptual domain based on the similarity matrix from step three. The first task is the creation of a point map which locates each statement as a separate point on the map, with statements being placed closer to each other, if they were sorted into the same pile more frequently. To accomplish this, nonmetric multi-dimensional scaling of the similarity matrix is conducted to create the point map. This technique takes a proximity matrix and represents it as distances between the original items in the matrix (Trochim, 1989) – most of the time as a two-dimensional solution to make it easier to interpret. The second task is a hierarchical cluster analysis to group the points on the point map into clusters. The X-Y coordinate data from the multidimensional scaling is used to group points into any number of clusters. The difficulty in this task is the decision on how many clusters are optimal to give a viable and meaningful solution because, in general, any number of clusters is possible. The final task is to overlay the clusters with the average rating from the participants to obtain a cluster rating map that visualizes all the information from the third step to give a full representation of the conceptual domain to be interpreted.

Step 5: Interpretation of Maps

Several maps that provide different views of the same structure can be created in the fifth step, with different clusters to be analysed by the participants. The goal is to find a mutually acceptable solution which makes sense for all participants, with the right number of clusters and proper labelling of all clusters. Then, cluster ratings can be compared among clusters and the concept domain is fully mapped based on the available information.

Step 6: Utilization of Maps

The final step is to use the maps for evaluation or planning purposes. In this paper the maps are used to develop an action plan for the selection of future quality improvement projects within a continual improvement process.

Case Study

The case study was conducted at the BU of the automotive OEM during the first quarter of 2018. The production system consists of five stations with grouped equipment. Small batches of a broad product mix are produced, and parts are transported between stations in specialized containers as depicted in Figure 1. The press and laser workstations are producing components which are then assembled at several assembly stations. The aluminium and stainless-steel parts are then cured in a furnace in specialized furnace fixtures to ensure geometry and form of the final product. At the end, products are "finished" to ensure proper surface quality of all external car body parts. Quality checks could potentially be done between any process step but are costly and time consuming because surface, geometry and stability of parts are critical for quality of the final product.

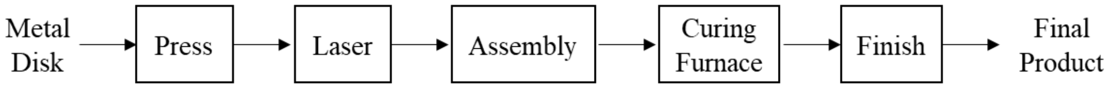

Figure 1 – Simplified value stream of the business unit

Nine experts participated in several brainstorming sessions to generate statements regarding the sources of quality problems within the BU. The experts group included people from production, quality and engineering who were responsible to ensure and analyse quality levels throughout the entire value stream. After removing duplicates and cleaning up the list, 41 statements were generated which are summarized in Table 1. The study was conducted in German, then translated by the authors and verified with English-speaking experts of the manufacturing system to ensure translational validity.

Table 1 - Brainstormed statements with average ratings

1	Dirty metal discs	3,60
2	Pressing tools not clean enough	3,60
3	Varying surface qualities after assembly	2,90
4	Finish work not according to defined standards	2,50
5	Low-cost concepts for containers	3,40
6	Quality team too small (not enough capacity)	2,90
7	Manual handling at press (no robotic linkage between pressing operations)	3,20
8	High quality variability in press due to press tool construction problems	3,50
9	Employee errors (missing components, wrong sequence of components inserted into fixture)	3,20
10	Bad positioning in pressing tool and fixture	3,30
11	Bad metal discs and purchased parts	3,10
12	Unstable processes	4,00
13	Bad external production (e.g. external laser cutting)	2,80
14	Old part numbers (long time in storage and between two production steps, parts become obsolete, FIFO problems)	3,30
15	Many joining technologies (welding, riveting, press joining, etc.)	2,90
16	Old and obsolete metal discs end up in production	3,50
17	Bad fixture settings (e.g. curing fixture)	3,30
18	Not enough information regarding part changes (missing change management)	3,20
19	Bad packaging (e.g. wooden pallets for metal discs)	3,00
20	Missing sample parts or sample parts are not used to check for quality issues	2,80
21	Containers are in bad condition (missing container TPM)	3,00
22	Transport damages, bad storage system, too many transports, difficult routes for forklifts	2,70
23	Many fixture changes and general characteristics of small-scale series production (many products, low quantity, high complexity)	3,00
24	Dirty fixtures	3,30
25	Low-cost concepts for pressing tools, only improved prototype tools in series production	3,90
26	Lack of KPIs for production stability (e.g. OEE, OWE and min/max boundaries)	2,50
27	Lack of influence / participation of manufacturing during concurrent engineering phase	3,33
28	Missing risk assessments	3,30
29	Missing quality measurements regarding metal disc quality (breaking stress test, oiling)	3,00
30	Weak inspection during production, almost no gauge sampling, not enough visual checks and defective parts are passed on to the next process step	4,20
31	“Forgotten” parts within production (prototypes, optimization parts, etc.) become obsolete and must be scrapped (no control in SAP)	2,60
32	Missing TPM	2,80
33	External storage of pressing tools (temperature and weather conditions not optimal)	2,70
34	Variable raw material quality causes frequent adjustments of machine parameters (“playing around” with parameters)	3,20
35	Missing part numbers cause confusion (common parts, e.g. screws, bolts, can be mixed up)	2,70
36	No Poka-Yoke to prevent against forgetting to insert components, bad positioning in fixtures and parts can still be processed until the end	3,20
37	Bad positioning / movement of parts in fixture	3,11
38	Missing information / communication with customers regarding quality and performance	3,10
39	Missing information / communication with planning department in concurrent engineering phase regarding quality and performance characteristics during ramp-up	3,30

40	No integrated quality information over the whole process chain (from metal disc to final assembly	3,40
41	Employees do not follow specific quality assurance processes	3,70

The statements were then sorted by the participants in an additional session to create the similarity matrix, showing how many times each statement was piled together with any other statement by the participants. Each participant also received a list with all statements to rate them on a 5-point Likert scale as described in the previous chapter. Monotonic two-dimensional scaling using the Kruskal Method (Kruskal and Wish, 1978) was conducted in the SYSTAT 13.2 statistical software to create the point map. With a stress score of 0.138, the stress level is relatively low compared to other concept mapping applications which indicates a good fit (Kane and Trochim, 2007). An R^2 of 0.898 further supported the fit of the point map. The points were clustered with a K-means clustering based on Euclidean distances (again in SYSTAT 13.2) to group points into different clusters. The solution with eight clusters seemed most representative for the researchers and the experts with a clear relationship of points within each cluster. Each cluster was then appropriately labelled, and the average ratings were added to complete the cluster rating map as seen in Figure 2.

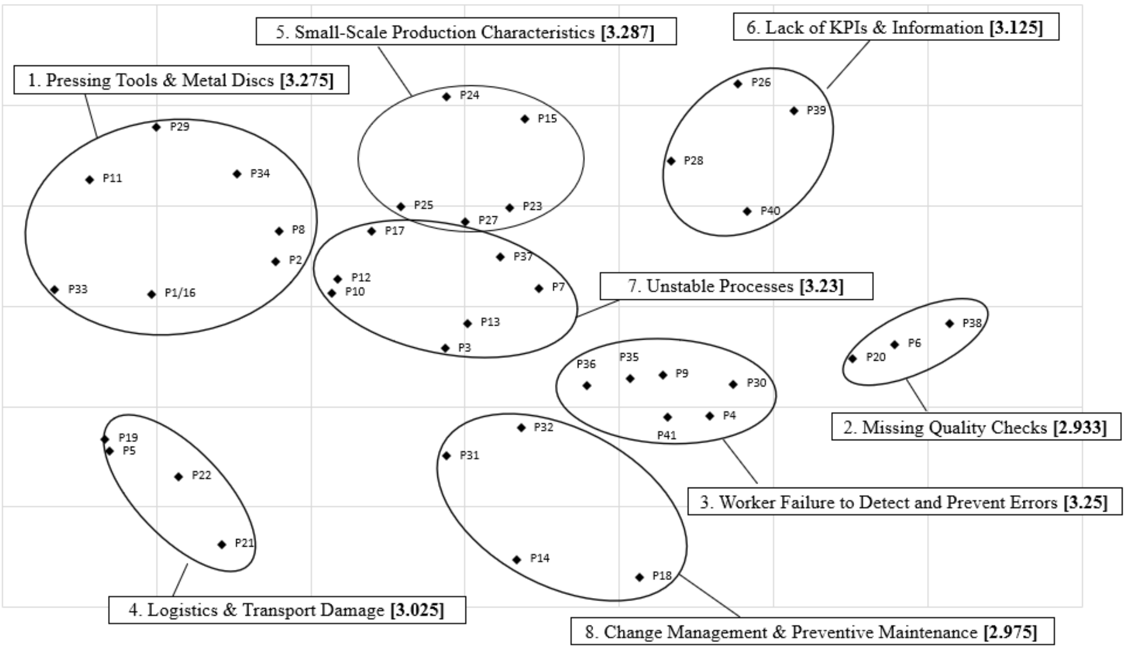

Figure 2 – Cluster Rating Map with 8 clusters and average ratings

Results

The concept map combines similar problems into clusters of statements (ranked by their perceived importance) and show connections and importance ratings. This visualization method is based on expert knowledge and aims to reduce causal ambiguity in decision making regarding quality management. The first cluster contains quality issues regarding the pressing department and raw materials (especially metal discs). It has the second-highest rating of 3.275 (Figure 2) and is therefore a critical factor of quality. This is understandable, because it is responsible for all components used in the assembly system and can negatively affect all following process steps. A critical aspect of this cluster is to ensure that the raw materials and tools coming into the production system have the right quality and are prepared (cleaned) to function at the highest level.

The second and sixth clusters can potentially be grouped together because both are about missing information due to a lack of quality checks (cluster two) and general lack of KPIs and information (cluster six). They are relatively less important (3.125 and 2.933, respectively) and contain all points associated with the work and capacity of the quality department, including risk assessment, communication with customers regarding quality and the like. This culminates in a general lack of integrated quality information over the whole value stream and related KPIs. Another critical cluster (three) deals with worker failures to detect and prevent quality errors on time with an average rating on 3.25 for all points in that cluster. Lack of proper training and finish work falls into this cluster, alongside with weak quality controls by the workers and handling errors.

The fourth cluster deals with logistics and transport damages but is not very important (3.025) based on the ratings of experts for all statements in this cluster. The fifth and seventh clusters, however, are highly important for quality within the system. They deal with the general characteristics of small-scale series production and unstable processes with a rating of 3.287 and 3.23, respectively. It is questionable if factors like low-cost concepts of pressing tools and a multitude of assembly technologies can be improved but they certainly have an influence on quality due to bad equipment and increased complexity. Clusters five and seven could also potentially be consolidated into one single cluster due to many relationships between statements and proximity in the point map. The position of the cluster for unstable processes is understandably at the centre of the point map because it influences many other inputs and was grouped together with many other statements by the participants. The last cluster contains points regarding change management and making sure that machines and materials are ready for production with the correct parts numbers and machine settings. It is relatively less important with an average rating of 2.975 with only four statements falling into this cluster.

The results of the analysis can be used to plan and allocate resources to improvement projects with the highest returns in terms of quality performance as perceived by the management team and team of experts. It can also help to define quality measurement strategies to ensure that the most susceptible process steps are secured with the highest rate of measurements. The maps are comprised of the collective experience and knowledge of the team of experts to fully map the conceptual domain of the problem area. Visualizing this tacit knowledge can significantly increase common understanding of the whole team regarding a matter of interest, thus, reducing causal ambiguity. An action proposal was created based on this information to make results of the analysis even more usable for the management team. The methodology was adopted from Friend and Hickling (2005) and it has been mentioned in the literature that this approach is always useful to increase the usability of OM/OR interventions (White, 2016). The method defines immediate decisions and future decision space for all relevant decision areas based on the current level of information and uncertainty related to different options.

Table 2 – Action Proposal

Decision Area	Immediate Decisions		Future Decision Space	
	Actions	Explorations	Deferred Choices	Contingency Planning
Pressing Tools & Metal Discs [3.275]	Improve raw materials quality Improve cleanliness	Find possibilities for better pressing tool concepts	-	-
Quality Checks [2.933]	-	-	Increase quality team & information	-
Worker Failure to Detect Errors [3.25]	Improve inspection processes and train workers to perform better Q-checks	-	-	-
Logistics & Transport [3.025]	-	-	Improve container construction and maintenance	-
Small-Scale Production [3.287]	Increase influence in engineering and construction phase	Find possibilities to make different technologies manageable	-	If necessary increase investments into pressing tools and equipment
Lack of Information [3.125]	-	-	Increase data collection and quality information	-
Unstable Processes [3.23]	-	Analyze sources of process instability	-	If necessary increase level of automation
Change Management [2.975]	-	-	Improve information flow regarding changing part numbers and obsolete material	-

The action proposal was created based on the cluster ratings and the average rating of each point within the clusters. Immediate actions were defined for the most important clusters, and specifically for points within each cluster. This results an extremely concrete set of decisions based on the concept mapping analysis and can be used by the expert for improved resource allocation and quality management. Some of the more important statements require further analysis and exploration to create better information on which further decision should be made. Other, less important, points are not completely dismissed and forgotten, but rather pooled in a future decision space to be re-evaluated in the future. This depends on the future state of the system and the outcome of immediate decisions and explorations. The goal is to continuously manage a relatively complete list of actions based on tacit knowledge of the expert team and allocate resources to the most important points in an efficient and effective way.

Theoretical and Practical Insights

King and Zeithaml (2001) found that intra-firm causal ambiguity (the lack of common understanding of cause and effect relationships between people within the organization) can severely reduce the performance of a business. Our study aims to reduce this form of causal ambiguity to efficiently and effectively improve quality in the production system of the automotive OEM to increase its competitiveness. This was the first attempt to fully conceptualize the quality domain of the BU and aims to support decision making regarding quality improvement and measurement efforts within process steps.

Using the results of the analysis to create action proposals is a key principle of concept mapping (Trochim, 1989) and was also mentioned by White (2016) to increase the relevance of OM interventions. This aid to detect causal relationships as described by the experts of the business unit can facilitate a continual improvement process, because the conceptual domain is analysed by the problem owners in their native language. Consequently, this kind of analysis has very high internal validity. Many small-volume batch production systems with high quality requirements (like premium sports car manufacturers) are facing similar problems of causal ambiguity and dynamics. We believe that our findings can be generalized to many of these settings, thus our analysis and the proposed methodology offer some degree of external validity as well.

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