Optimizing order fulfillment using design for six sigma and fuzzy logic*

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Abstract. Supply chain management aims to add value across the supply chain and customer service is now a major strategic issue. Supply chains are complex and subject to variables of forecast, supply, process, and transportation which can lead to problems such as the bull whip effect, product lateness, damaged goods and stock outs. A key issue facing companies today is how to monitor and control performance across the chain. This paper presents Design for Six Sigma (DFSS), which focuses on customer requirements from the onset, as an effective methodology for monitoring and controlling supply chain variables, optimizing supply chain processes and meeting customer's requirements. By applying DFSS methodology to the key supply chain process of order fulfillment, a customized representation of detailed activities of order fulfillment processes is demonstrated providing key performance indicators. A theoretical transfer function for predicting the performance of the perfect order incorporating fuzzy set theory provides a way of monitoring supply chain performance.

Keywords: Supply chain management (SCM), supply chain strategy, performance measurement, customer service management, design for six sigma (DFSS), order fulfillment, perfect order and fuzzy set theory

1 Introduction

Supply chain strategy focuses on developing competitive advantage through supply chain related capabilities and linking them to the overall business strategy. Through appropriate supply chain management this allows decisions to be made between competing demands on the supply chain that support the overall business objectives.

Supply chain strategy can be viewed as the pattern of decisions related to the eight processes that make up supply chain management (see Fig. 1); "customer relations management, customer service management, demand management, order fulfillment, manufacturing flow, supplier relationship management, product development and returns management"^[24, 27]. Whilst there is concern that SCM as an academic discipline lacks consensus on what defines SCM^[5, 32] this article takes this definition:

Definition 1. *Supply chain management is the integration of key business processes from end user through original suppliers that provides products, services, and information that add value for customers and to other stakeholders. [23] as the most encompassing and customer centric.*

SCM is now seen as a way to determine competitive advantage which had previously been achieved through practices such as Just in Time (JIT), Total Quality Management (TQM), and business process re engineering (BPR). With product and technological standardization and commoditization there is now greater competition around price^[4, 10] and ensuring value to customers across the chain is high.

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While there is acknowledgment of the potential benefits to be gained there is minimal uptake of strategic and integrated supply chain management across industries and a dearth of research available of companies who have successfully applied strategy and integration to their supply chain to competitive advantage^[9, 10, 20, 21, 26]. The companies that are cited for successful integrated SCM are limited, Proctor and Gamble, Wal Mart, Hewlett Packard, Dell Computer, Sun Micro Systems, and Seven Eleven Japan^[18]. The few empirical studies that have been undertaken describe the fact that end to end transparency of the supply chain is not a reality and that in most cases integration only spans to one tier up and downstream from a firm^[29]. Partial integration rather than holistic integration is advocated by some^[2]. Generally the literature describes a theoretical ideal which is not backed by empirical evidence^[13] with calls for more understanding of the diversity of supply chain management and managerial approaches and mechanisms for dealing with integration. Taking incremental steps towards integration can lead to competitive gains and focusing on key supply chain processes can be a starting point for improved performance and collaboration between chain members. DFSS which considers the requirements and constraints from all stakeholders as voice of the customer (VOC) at the design onset, and applies a systems engineering approach to functionally decompose the design as per requirement is a promising methodology to employ for supply chain design. One of the difficulties in managing a supply chain is their complexity, having to deal with multiple market segments^[28] with each segment a system in itself, but having to closely interconnect with dependant sub systems and integrate with the noise and conditions imposed by market dynamics. The potential problem associated with the design and the development of such systems is the organization and management of system complexity without compromising the customer requirements. Where other supply chain designs are generic in nature, DFSS allows the flexibility for individual circumstances. Where general supply chain metrics are being put forward [15] DFSS methodology provides a means of creating specific targeted metrics and a way of isolating where quality improvement efforts should be focused. The process of order fulfillment has been highlighted as a key metric for supply chain integration^[8]. The customer's order triggers the supply chain processes into action involving the activity of all the other supply chain processes through the various functions within a firm. It is often the only interface with customers making it a core supply chain process for meeting customer requirements.

This paper is organized as follows; the steps for DFSS for service design are described with the order fulfillment process identified as critical to customer requirement (CCR). The order fulfillment sub processes and key performance indicator's (KPI's) are identified and the order fulfillment variables as key process input variables (KPIV's) and key process output variable (KPOV) is identified, showing 'perfect order' as one of the CCRs. A transfer function is then developed for the perfect order and a membership function assigned to measure the gap between the current performance and the perfect order. The presented transfer function of "perfect order" is formulized and refined using fuzzy logic. Finally conclusion and limitations will be discussed and further recommendations will be made.

2 Design for six sigma

There are two major improvement methodologies under the six sigma umbrella. DMAIC (Define, Measure, Analyse, Improve and Control) is used for continuous improvement of already existing products/processes and DFSS is used for designing new product/processes. DFSS is often used when the existing processes do not satisfy the customers or are not able to achieve strategic business objectives [12]. DMAIC has been presented as an adjunct to SCOR which lacks quality improvement initiatives and metrics beyond level one^[3] and has been applied at Samsung where it was modified for supply chain process improvement^[33]. DFSS has successfully been implemented for product design in a number of leading manufacturing firms such as Motorola, GE, Allied Signals, Honeywell, and Seagate, while a lack of examples is found of designing services within a supply chain^[17]. Six sigma is a highly disciplined, data-oriented, top-down approach which explicitly links the tactical and the strategic. Statistical techniques are used in a systematic way to reduce variation and improve processes, with a strong focus on results [22].

Today the design of services within the supply chain in many industries exhibit deficiencies like modest levels of quality, ignorance of customer wants, and too much complexity. Such shortcomings add a considerable amount of non-value added activities to SCM and can mainly be attributed to the lack of a systems design

Fig. 1. Supply chain business processes^[?]]

methodology. Additionally there are several sources of variation in the service delivery processes which need to be considered while conceptualising a solution. Implementation of DFSS has successfully delivered quality products to customer satisfaction for many industries^[17] and the potential exists for it to deliver the same results for supply chain design. DFSS activities are classified into four major phases, namely; Identify, Define & Design, Optimize and Validate (IDDOV/IDOV). Going through these phases each CCR is presented as a function (transfer function) of a number of KPIVs, which can be used to predict the performance level of the CCR.

The following sections present a brief introduction to the sequence of major activities covered under IDOV phases of DFSS in designing a supply chain as shown in Fig. 2.

2.1 Identify

The foundation of a product or service begins with setting the expectations or specifications. DFSS focuses on determining what customers require, and then translating it into product/service specifications in the “identify phase”. The major activity in this phase, as illustrated in Fig. 2, is the collection and translation of often vague and abstract customer requirements also known as VOC. Using tools like Quality Function Deployment (QFD), VOC is translated into design specifications termed as CCRs, comprehensible to the supply chain development/design team^[6]. While QFD is the major tool in Identify phase, there are other tools that may be used, such as kano model, pareto analysis, affinity diagram, brainstorming and benchmarking^[30].

2.2 Design

After having translated the VOC into engineering terms as CCRs, the supply chain development/design team has the task of proposing and evaluating conceptual solutions to address the above CCRs. Using of the

Fig. 2. Activities for supply chain design through dfss

'functional design' approach of systems engineering and, multiple functional system models (or conceptual solutions) are proposed in this phase. Each solution is presented as a hierarchy of functional subsystems without going into engineering design details. The functional concept designs are evaluated to narrow down solution options. Measurement metrics and methods to inspect the design are to be verified prior to detail designing.

Having narrowed down the number of conceptual solutions, requirements are followed down from top to lowest hierarchical level of the functional system models. As a result of this exercise, the team is able to translate the high level system CCRs to lower level KPIVs. Using engineering practice and methods like design of experiments, mathematical and statistical simulations, and regression analysis predictive transfer functions are developed to relate the CCRs to KPIVs^[30].

2.3 Optimize

Performance of real world products/services is always shadowed with variation. DFSS therefore, stresses predicting and optimizing the probability of the design to meet the required targets (CCR) given environmental variation, manufacturing variation, and usage variation. Statistical analysis and optimization of the design is necessary to achieve a robust product/service design.

2.4 Validate

At the final stage validations are performed to check that the process is complete, valid and will meet requirements in practice. It involves verification of the design to ensure that it meets the set requirements;

assessment of performance, reliability, capability, etc. At this stage prototyping/ simulation may be used to test the product/service operation. If this stage suggests that the design of the product/service does not or may not meet the required capability, then it is necessary to retract back through the earlier stages of design or optimize. If the validation results are satisfactory, development of a process control plan for the mean and variance of CCRs^[30] are initiated.

3 Implementation of dfss steps to supply chain design.

As depicted in Fig. 3, the aforementioned DFSS methodology is used to tabulate activities leading to detail the design of a supply chain core process. The overall supply chain is represented by 8 core processes^[24]. Each core process presents a complex system in itself. Since each core process requires a dedicated design effort, in this study the key core process 'order fulfillment' (OF) is selected.

Fig. 3. 'order fulfillment' design activity flow.

3.1 VOC

VOC can be initiated from both the internal and external customers of the supply chain. The supply chain development/design team identifies the customers potential needs, enlists and prioritizes their expectations through data collected from customer interviews, focus groups, surveys, complaint data and enhancement request or through market research. Using tools like QFD, cause & effect (fishbone), system and service process structure, VOC are used to iteratively derive design specifications. Fig. 4 contains a first level QFD which identifies order fulfillment as a CCR with Fig. 5 showing a fishbone analysis of order fulfillment.

Fig. 4. A first level qfd for scm

Fig. 5. A fishbone analysis of order fulfillment

3.2 Voc translation

From a first level QFD, as depicted in Fig. 4, the major variables (how's) to be controlled are on time delivery, quality (undamaged deliveries), and quantity (meet demand quantity). A further analysis of the supply chain structure is carried out below to link the above variables to supply chain system hierarchy. Fig. 6 represents a structure of supply chain showing order fulfillment amongst other core processes.

Unlike product design, services within a supply chain are best represented by the flow of activities addressing each core process. Arranging 'order fulfillment' as a sequence of activities and using the outcomes surfacing from the above steps, the design can list KPIV's and KPOV's at each 'order fulfillment step'. Fig. 7 presents a process flow for 'order fulfillment' with major KPIV's and KPOV's listed for each step.

Fig. 6. A customised representation of detailed activities of ccr order fulfillment

Fig. 7. Order fulfillment process flow with kpiv's/kpov

3.3 CCR-order fulfillment

As depicted in Fig. 7, the Order fulfillment process can be described by a sequence of sub-processes, such as Order entry, order processing, Start manufacture, Fill order, delivery, Customer receipt, and Post delivery activities. DFSS can be used to develop performance targets related to CCR's of these sub-processes. Through brainstorming, the supply chain development/design team lists the KPIV's shown under each process step. KPOV's for each sub-process are also determined and listed on top of the process flow.

The overall KPOV for the order fulfillment process is best described as the "perfect order". Its elements on-time delivery, quantity of delivered order and quality of delivered order, as identified in the KPIV's, make the "perfect order" the key metric for monitoring the order fulfillment variables of forecast, supply, process and transportation.

The Perfect order is represented as the Equation

$$PerfectOrder = f [Delivery Time (DT), Quantity Delivered Qty), Quality (Qual)] \quad (1)$$

A marginally short or over order or a slight decline in the delivered quantity, or slight delayed/early delivery may raise alarm if the factors are measured in specific metrics. In real world metrics to measure the performance or customer's level of satisfaction from the "perfect order", DT, Qty, and Qual is a subjective matter. Therefore the above equation (transfer function relating Perfect Order to DT, Qty and Qual) is optimized with use of fuzzy logic.

4 Application of fuzzy logic to transfer function

A transfer function is a mathematical representation of the relationship between the input and output of a system or a process. It facilitates the DFSS optimization of process output by defining the true relationship between input variables and the output. Optimization in this context means minimizing the requirement variability and shifting its mean to some desired target value specified by the customer. The transfer function presented in Equation 1 of "perfect order" is formulized and refined with the use of fuzzy logic. Usually transfer functions resulting from DFSS implementation are expected to have a mathematical representation. However, in this research the refined transfer function is presented as sets (sequences) of fuzzy logic rules evaluated using the fuzzy logic toolbox in MATLAB.

4.1 Fuzzy logic - a brief introduction

Fuzzy logic^[34] describes subsets where the transition between full membership and non membership is gradual rather than abrupt. Most groups of objects in the real world have a fuzzy nature not having precise criteria for membership, e.g. functions can assume values between 0 and 1 depending on the degree of membership of the element in the set which gives the advantage of being able to formalize judgment without resorting to an artificial process of making precise judgment. In other words, partial membership means an element can fully belong to a set, partially belong, or not belong at all. Fuzziness seeps into most human perception and fuzzy logic copes with these uncertainties and incomplete understanding, helping to deal with parameters that are difficult to express in a quantitative or numerical measure^[11].

Qualitative measures often need to be translated into quantitative measures. For example, the qualitative measure of customer responsiveness can be translated into the quantitative measures of fill rate, product lateness, and lead time^[7]. Essentially vague and subjective information often found in the fuzzy supply chain environment of variability, complexity and constraints make it a difficult environment to control and improve. Therefore modeling with fuzzy set theory is a useful performance monitoring tool to incorporate.

A literature review of papers related to SCM and fuzzy logic show fuzzy logic has been applied for analysing and monitoring performance of suppliers^[25], developing models for strategy related performance outcomes^[14], the use of fuzzy set and weighted averages for SCM, intangible and tangible performance measurement^[14], screening suppliers^[31], combined with QFD to improve logistics processes and customer satisfaction^[4], and in a multicriteria decision making procedure for assessment of supplier performance^[16].

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic (major stages being fuzzification, rule evaluation and aggregation, and defuzzification). The mapping of defuzzified results onto the problem situation then provides a basis from which decisions can be made. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type^[11].

The two types differ in the way output is determined. In the Mamdani-type, after the aggregation process the output membership function of the output variable (Fig. 12) is a fuzzy set, while a Sugeno-type uses a constant value (singleton) as the output membership function. The first two parts of the fuzzy inference process, fuzzifying the inputs and rule evaluation and aggregation are exactly the same. The main difference between Mamdani and Sugeno is that the Sugeno output membership functions are either linear or constant^[19].

Since performance or satisfaction level of a perfect order cannot be judged in terms of discrete values, a Mamdani-type inference system is selected for evaluating and aggregating the fuzzy rules in this case. The steps for assessing the "perfect order" using the fuzzy inference system are fuzzification, rule evaluation and defuzzification.

4.2 Fuzzification

The fuzzification process is performed during run time and consists of assigning membership degrees between 0 and 1 to the crisp inputs of delivery time, quantity and quality.

4.3 Rule evaluation

The rule evaluation process consists of using the fuzzy value obtained during fuzzification and evaluating them via the rule base in order to obtain a fuzzy value for the output. The rule evaluation follows the form of **if** (condition x) and (condition y) **then** (result z) rules are applied. Basically the use of linguistic variables and fuzzy IF-THEN- rules utilize the tolerance for imprecision and uncertainty mimicking the ability of the human mind to summarize data and focus on decision-relevant information and are generated from expert knowledge.

4.4 Defuzzification

The fuzzy inference system using Mamdani's fuzzy implication rule determines the appropriate fuzzy membership value. The defuzzification process consists of combining the fuzzy values obtained from the rule evaluation step and calculating the reciprocal in order to get one and only one crisp value that the output should be equal to. The output 'order' is evaluated in relation to the crisp value and translated into linguistic terms (see Tab. 4).

4.5 Fuzzification of perfect order transfer function

Fig. 8 depicts the empirical transfer function from equation (1) as a fuzzy logic system with inputs and output being fuzzified using appropriate membership functions. The following sections narrate each component of the system.

Fig. 8. Graphic layout of transfer function in fuzzy format.

4.5.1 Delivery time

Order delivery time is measured and evaluated based on a range from the number of days earlier or later than the promised/expected delivery date. The categories in the measure are: 'fail', 'very early', 'acceptable early', 'optimum', 'acceptable late', 'late' and 'very late' performance, see Tab. 1. Any delivery earlier or later than four days fails and is rejected. 'Very early delivery' is considered to be unacceptable due to inventory requirements of space and labour and associated inventory costs. 'Very Late' delivery can lead to delays in

production which affects downstream members of the chain and leads to longer production/process cycles, customer dissatisfaction and loss of future sales. This impacts on business and financial outcomes and is unacceptable. Both indicate urgent action is required to improve performance.

‘Acceptable early’ and ‘acceptable late’ indicate that the supplier is not able to deliver on the expected time but within an acceptable time frame and requires performance improvement in the near future. ‘Optimum’ standard indicates that the supplier is performing well. Furthermore, Fig. 9 shows the fuzzy sets delivery time that represents the standard in degree of membership. For the fail standard, the degree of membership is 0, while the optimum standard has a degree of membership of 1. The rest of the standards are represented within the range 0 to 1 degree of membership with the boundaries between the standards graded. This provides the fuzzy set sensitivity to the membership function by providing degrees of closeness to the required value of the perfect order.

Fig. 9. Input variable “delivery time”

Table 1. Delivery time measurement

Fuzzy	Linguistic Term	Range (Days)
1	Fail	More than -4
2	Very Early	From -4 to -2
3	Early	From -3 to -1
4	Acceptable Early	From -2 to 0
5	Optimum	From -1 to 1
6	Acceptable Late	From 0 to 2
7	Late	From 1 to 3
8	Very Late	Form 2 to 4
9	Fail	More than 4

4.5.2 Quantity

Order quantity is measured and evaluated based on the range of the percentage of the quantity ordered. The categories in the measure are: ‘Very low’, ‘low’, ‘acceptable low’, ‘optimum’, ‘acceptable high’, ‘high’ and ‘very high’. Any order quantity between 10 – 20% less or greater than the required order is considered ‘very low’ or ‘very high’ and is unacceptable. Any order quantity between 5 – 15% less or greater than the required order quantity is considered as ‘low’ or ‘high’ which is alarming and requires urgent attention. ‘Acceptable low’ and ‘acceptable high’ is any order quantity between 0 – 10% less or greater than the required

order quantity indicating that the order is acceptable but highlights need for improvement, see Fig. 10. Any order quantity 5% less or greater than the required order quantity is considered Optimum, as shown in Tab. 2.

Fig. 10. Input variable “order quantity”

Table 2. Quantity measurement

Fuzzy	Linguistic Term	Range (% of delivered Quantity)
1	Fail	More than –20%
2	Very Low	From –20% to –10%
3	Low	From –15% to –5%
4	Acceptable Low	From –10% to 0%
5	Optimum	From –5% to 5%
6	Acceptable High	From 0% to 10%
7	High	From 5% to 15%
8	Very High	From 10% to 20%
9	Fail	More than 20%

4.5.3 Quality (quality of products in order)

Quality value is measured based on the defect rate of the delivered order quality. There are three categories of the delivered order quality, namely, ‘poor’, ‘good’, and ‘excellent’ as shown in Tab. 3. Any defect rate equal or greater than 5% is considered ‘poor’ and rejected. Any order defect rate less than or equal to 1% is considered ‘excellent’. The range between ‘excellent’ and ‘poor’ is considered ‘good’. ‘Good’, while acceptable, shows that the quality standard needs to be improved aiming towards achieving ‘excellent’. For the ‘poor’ standard, the degree of membership is zero, while the ‘excellent’ standard has a degree of membership of one. The rest of the standard is presented within the range 0 to 1 degree of membership. The boundaries between the standards are graded which provides the fuzzy set sensitivity to the membership function by providing degrees of closeness to the required value of the perfect order. See Fig. 11.

4.5.4 Order output

Any value for order output between the values of 0 and 0.29 will cause the order to be rejected, between 0.30 and 0.49 indicates that the order is poor and needs major attention and action. Although the order value from 0.50 to 0.69 indicates acceptance of the order it shows a high gap from the optimum and the processes

Fig. 11. Input variable “order quality”

Table 3. Quality measurement

Fuzzy Set	Linguistic Term	Range (% of Defects)
1	Poor	Below -4%
2	Good	From -1% to -3.5%
3	Excellent	Above -1%

and performance needs significant improvement. Order value between 0.70 and 0.89 indicates a low level of satisfaction aiming to close the gap towards optimum. An order output value between 0.90 and 1 indicates that the order is fulfilling the requirements and requires the processes to be monitored and maintained. See Fig. 12 and Tab. 4.

Fig. 12. “order” output ranges

4.6 Fuzzy evaluation rules

Tab. 5 demonstrates the 147 rules following the format “if (condition x) and (condition y) then (result z)” corresponding to the combinations of input conditions. For example: if quality is “poor” and if delivery time is “very early” and if quantity is “low” then order is “reject”. The rules are determined through expert knowledge and are further refined following real life application and appraisal which will either confirm them or require them to be modified.

Table 4. Ranges for “order” output and linguistic value

Linguistic Value	Scores
Optimum	0.90 1.00
Satisfied	0.70 0.89
Acceptable	0.50 0.69
Poor	0.30 0.49
Reject	0.00 0.29

Table 5. Fuzzy rules for quality “poor”, “good” and “excellent”

Quality “Poor”							
Quality \ Delivery time	Very Early	Early	Acceptable Early	Optimum	Acceptable Late	Late	Very Late
Very Low	Reject	Reject	Reject	Reject	Reject	Reject	Reject
Low	Reject	Reject	Reject	Reject	Reject	Reject	Reject
Acceptable Low	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Optimum	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Acceptable High	Poor	Poor	Poor	Poor	Poor	Poor	Poor
High	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Very High	Reject	Reject	Reject	Reject	Reject	Reject	Reject

Quality “Good”							
Quality \ Delivery time	Very Early	Early	Acceptable Early	Optimum	Acceptable Late	Late	Very Late
Very Low	Poor	Poor	Poor	Poor	Poor	Poor	Reject
Low	Poor	Acceptable	Acceptable	Acceptable	Acceptable	Poor	Reject
Acceptable Low	Poor	Acceptable	Acceptable	Acceptable	Acceptable	Poor	Reject
Optimum	Acceptable	Acceptable	Acceptable	Satisfied	Acceptable	Poor	Reject
Acceptable High	Poor	Acceptable	Acceptable	Acceptable	Acceptable	Poor	Reject
High	Poor	Poor	Acceptable	Satisfied	Acceptable	Poor	Reject
Very High	Poor	Poor	Poor	Acceptable	Poor	Poor	Reject

Quality “Excellent”							
Quality \ Delivery time	Very Early	Early	Acceptable Early	Optimum	Acceptable Late	Late	Very Late
Very Low	Reject	Poor	Poor	Acceptable	Acceptable	Poor	Reject
Low	Poor	Poor	Acceptable	Acceptable	Acceptable	Poor	Reject
Acceptable Low	Poor	Acceptable	Acceptable	Satisfied	Acceptable	Poor	Reject
Optimum	Acceptable	Acceptable	Satisfied	Optimum	Satisfied	Poor	Reject
Acceptable High	Poor	Acceptable	Acceptable	Satisfied	Acceptable	Poor	Reject
High	Reject	Poor	Acceptable	Acceptable	Poor	Poor	Reject
Very High	Reject	Poor	Poor	Poor	Poor	Reject	Reject

4.7 Fuzzy solution results

A continuum of fuzzy solutions for equation (1) is presented in Fig. 13 using the fuzzy tool box of Matlab. The three inputs can be set within the upper and lower specification limits and the output response is calculated as a score that can be translated into linguistic terms. In this instance the order output of 0.714 indicates “satisfied” linguistically from Tab. 4.

A further graphical representation as a response surface for the order is presented in Fig. 14, 15, 16. However, given the limitation of Cartesian axes only two of the three input variables can be selected to map the resulting variations in the output (order). In Fig. 14 the perfect order achieves a maximum score at peak of quality and when the order is delivered to the targeted quantity. As the quality drops, the order score gradually drops too. As long as the quality is towards the higher end, any drift from the order quantity has relatively less effect on the order score.

Fig. 15 depicts the order behavior in relation to variations in quantity and delivery time. Unlike Fig. 14 (quantity-quality-order), order scores protrude as a plateau above the remaining surface. A delayed delivery

Fig. 13. Shows the rule viewer of the fuzzy inference system for the linguistic description and the corresponding membership values for an order output = 0.714 indicating “satisfied” from tab. ??.

reduces the order score drastically as contrast to early delivery. Again as before quantity effects are relatively less marked. The maximum score for the order occurs when both the quantity and delivery time are at target, which is indicated as a spike.

Fig. 16 presents the order response surface with quality and delivery time as input variables. The relatively smooth surface depicts the order score to be diminished significantly with delays in delivery time. An early order with poor quality still has the chance of being revised. A delayed order no matter how exact in quantity and best in quality may be of no use to the customer; therefore delays show maximum effect in contrast to early ones, even though other factors are poor.

5 Discussion and concluding remarks

Unlike product design where the final deliverable is a tangible product, the supply chain can be presented as an intangible component of service design (i.e. covering a work plan to meet supply targets, management of information flow, decision making, etc) with the tangible component being the practical implementation of the service design (actual hardware like logistics, transportation, information infrastructure, etc). This research

Fig. 14. Output surface of the fuzzy inference system for quality and quantity

Fig. 15. Output surface of the fuzzy inference system for quantity and delivery time

presents the use of DFSS methodology to design the service i.e. intangible component of the supply chain. Nevertheless, the same methodology can also be extended to design/selection of aforementioned tangible components in an iterative manner. Since DFSS methodology was developed and matured for product design, a direct implementation to supply chain design was not possible. However, a customized adaptation of the same to a supply chain was presented in Fig. 2 and followed for this research.

After having collected, translated and mapped the VOC on the system design, the predictive model or transfer function is a step of key importance to predict the system performance in terms of KPOV's by varying independent KPIVs, as presented in Equation (1). Conventionally in the product design arena, transfer functions or predictive mathematical models are developed using methods like engineering knowledge, physical principals, design of experiments and regression. However, in this case, keeping the fuzzy nature of categorizing supply chain performance level, fuzzy logic was used to develop the transfer function and provide a means of putting quantitative value on qualitative measurement.

The methodology described in this paper can be applied to diverse supply chain processes. It provides the flexibility to tailor make process control and accommodate changing needs as they arise. This makes DFSS an adaptable methodology for monitoring and controlling performance in a complex and variable supply chain environment. Real cases application and further research is called for across supply chain processes, and

Fig. 16. Output surface of the fuzzy inference system for quality and delivery time

from different positions within the chain. The process of order fulfillment was the focus of this paper as it is considered as a core supply chain process involving the activity of all the other supply chain processes through the various functions within a firm and has been highlighted as key metric for supply chain integration. Further research should address the strategic outcomes of improved collaborative performance that the methodology could potentially deliver.

References

- [1] Fuzzy logic toolbox user's guide (for use with matlab). 2005.
- [2] A. Bask, J. Juga. Semi-integrated supply chains: Towards the new era of supply chain management. *International Journal of Logistics: Research and Applications*, 2001, **4**(2): 137–152.
- [3] P. Bolstorff. Putting it all together. **in:** *Chief Logistics Officer*, vol. 10, 2003.
- [4] E. Bottani, A. Rizzi. Strategic management of logistics service: A fuzzy qfd approach. *International Journal of Production Economics*, 2006, **103**(2): 585–599.
- [5] K. Burgess, P. Singh, R. Koroglu. Supply chain management; a structured literature review and implications for future research. *International Journal of Operations & Production Managements*, 2006, **36**(7): 703–729.
- [6] P. Buss, N. Ivey. Dow chemical design for six sigma rail delivery project. **in:** *Proceedings of the 2001 Winter Simulation Conference*, 2001.
- [7] D. Chan, K. Yung, A. Ip. An application of fuzzy sets to process performance evaluation. *Integrated Manufacturing Systems*, 2002, **13**(4): 237–246.
- [8] K. Croxton. The order fulfillment process. *The International Journal of Logistics Management*, 2003, **14**(1): 19–32.
- [9] C. Defee, T. Stank. Applying the strategy-structure-performance paradigm to the supply chain environment. *The International Journal of Logistics Management*, 2005, **16**(1): 28–50.
- [10] D.Power. Supply chain management integration and implementation: a literature review. *Supply Chain Management: An International Journal*, 2005, **10**(4): 252–263.
- [11] D. Dubois, H. Prade. *Fuzzy Sets and Systems: Theory and Applications*. Academic Press, New York, NY, 1980.
- [12] G. Eckes. *The Six Sigma Revolution*. John Wiley & Sons, Chichester, 2001.
- [13] S. Fawcett, G. Magnan. Supply chain integration: rhetoric or reality? *International Journal of Logistics Management*, 2002, **32**(1): 339–61.
- [14] C. Felix, H. Qi, etc. A conceptual model of performance measurement for supply chains. *Management Decisions*, 2003, **41**(7): 635–642.
- [15] A. Gunasekaran, C. Patel, R. McGaughey. A framework for supply chain performance measurement. *International Journal of Production Economics*, 2004, **87**: 333–347.
- [16] N. Gunasekaran, S. Rathesh, etc. Optimizing supply chain management using fuzzy approach. *Journal of Manufacturing Technology Management*, 2006, **17**(6): 737–749.

- [17] B. Haik, D. Roy. *Service Design For Six Sigma*. John Wiley & Sons, New York, 2005.
- [18] L. Hau. Creating value through supply chain. *Integration Supply Chain Management Review*, 2000, 30–36.
- [19] J. Jang, C. Sun, E. Mizutani. *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence*. Upper Saddle River: Prentice Hall, 1997.
- [20] C. Joseph. Supply chain logistics initiatives research implications. *International Journal of Physical Distribution & Logistics Management*, 2005, **35**(3): 148–151.
- [21] J. Kim, K. Rogers. An object orientated approach to building a flexible supply chain model. *International Journal of Physical Distribution & Logistics Management*, 2005, **35**(7): 481–502.
- [22] B. Klefsjo, H. Wiklund, R. Edgeman. Six sigma seen as a methodology for total quality management. *Measuring Business Excellence*, 2001, **5**(1): 31.
- [23] D. Lambert, M. C. J. Pagh. Supply chain management: implementation issues and research opportunities. *The International Journal of Logistics Management*, 1998, **9**(2): 1–19.
- [24] D. Lambert, T. Pohlen. Supply chain metrics. *The International Journal of Logistics Management*, 2001, **12**(1): 1–19.
- [25] H. Lau, W. Pang, C. Wong. Methodology for monitoring the supply chain performance: a fuzzy logic approach logistics. *Information Management*, 2002, **15**(4): 271–280.
- [26] B. Leavy. Supply chain effectiveness: strategy and integration. *Handbook of Business Strategy*, 2005, **7**(1): 331–336.
- [27] R. Lummus, R. Vokurka. Defining supply chain management: a historical perspective and practical guidelines. *Industrial Management and Data Systems*, 1999, **99**(1): 11–17.
- [28] D. McKay. How a systems engineering education benefits supply chain managers. *Logistics Spectrum*, 2003.
- [29] J. Mouritsen, T. Skjott-Larsen, H. Kotab. Exploring the contours of supply chain management. *Integrated Manufacturing Systems*, 2003, **14**(8): 686–695.
- [30] Rath, Strong. *Design for Six Sigma*. Rath and Strong Publishers, Massachusetts, 2002.
- [31] B. Shore, A. Venkatachalam. Evaluating the information sharing capabilities of supply chain partners: A fuzzy logic model. *International Journal of Physical Distribution & Logistics Management*, 2003, **33**(9): 804–824.
- [32] J. Storey, C. Emberson, etc. Supply chain management; theory, practices and future challenges. *International Journal of Operations & Production Management*, 2006, **26**(7): 754–774.
- [33] H. Yang, B. Choi, etc. Supply chain management six sigma; a management innovation methodology at the samsung group. *Supply Chain Management; An International Journal*, 2007, **12**(2): 88–95.
- [34] L. Zadeh. A fuzzy set. *Information and Control*, 1965, **8**: 338–53.