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Evaluation of the applicability of design for six sigma to metal additive manufacturing technology

Cindy Sithole*, Ian Gibson, Sipke Hoekstra

Department of Design, Production and Management, University of Twente
Faculty of Engineering Technology, Enschede, The Netherlands

* Corresponding author. Tel.: +31-534-893-466: E-mail address: c.sithole@utwente.nl

Abstract

Design for Six Sigma has been applied in traditional and conventional manufacturing technologies to enhance both products and manufacturing processes. It has yielded great results and proven to be a key driver for quality improvement using Six Sigma strategy. Design for Six Sigma uses an organized methodology for designing new products and processes using statistical tools to minimize defects and process deviations.
Modern manufacturing technologies such as Additive Manufacturing are complex and require a lot of consideration in terms of selected process parameters that affect part quality. The quality of the resultant parts in additive manufacturing is influenced and affected by the design of the parts to be fabricated, the build process and the chosen process parameters. Quality deviations in additive manufacturing can be observed within a batch of similar parts and from batch to batch production. Due to the complexity of Additive Manufacturing technology and its application, defect reduction remains a key barrier towards further acceptance in highly regulated industries.
This paper aims to evaluate the applicability of design for Six Sigma principle to Additive Manufacturing. It seeks to outline how Design for Six Sigma can be applied to Additive Manufacturing to reduce variability and which tools can be used to enhance the quality of the resultant parts. The study critically reviews best practices for Design for Six Sigma to evaluate its applicability to modern manufacturing.

Keywords: Design for Six Sigma, Additive Manufacturing, Quality, Variability

1. Introduction

Technological advancement in manufacturing is imperative for competitive advantage in today's global competition. Advancements in manufacturing technologies has many benefits, among which are design flexibility, material productivity and production of highly customized products at short lead times. Due to these benefits, organizations are somehow compelled to upgrade their manufacturing systems to modern technologies in order to compete globally. However, many challenges still exist with modern manufacturing technologies and give rise to a need to evaluate existing systems and develop new models and tools for effective manufacturing planning and monitoring to leverage on the benefits of modern manufacturing[1]. Modern manufacturing technologies such as Additive Manufacturing (AM) are complex and contain many process factors that have significant effects on resulting products. Further, AM presents some specific challenges and issues that lead to quality discrepancies. Discrepancies in AM subsequently affect product performance and may lead to product failure[2]. According to El Maraghy and colleagues[1], the complexity of modern manufacturing technologies enforces difficulty in operations management and are pricey. Understanding that change is inevitable, existing quality improvement systems such as Design for Six Sigma (DFSS), Six sigma, lean principles and other process improvement models should be evaluated for suitability and applicability to modern manufacturing technologies in order to improve industrial adoption. DFSS is a methodology that utilises statistical tools to design products and processes that are capable of meeting customer requirements in a more efficient and reliable manner[3,4]. DFSS combines proven

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improvement methods and tools from Six Sigma and system development techniques to provide innovative process improvements[5]. It is a cost-effective approach for improving products and process performance by reducing quality deviations from the design stage. DFSS has been applied in traditional and conventional manufacturing technologies and across other manufacturing sectors to enhance both products and industrial processes[4,5]. It has yielded great results and proven to be a key driver for quality improvement using Six Sigma strategy.

This study aims to evaluate the suitability of DFSS to modern manufacturing and its applicability for process improvement through the reduction of product variation and increased productivity. It focuses on additive manufacturing technology (AM), which is currently transitioning towards increased industrialization. It outlines how DFSS can be applied to additive manufacturing to reduce variability and also outlines tools that can be used to enhance the quality of the resultant products. The study critically reviews best practices for DFSS to evaluate its applicability to modern manufacturing. This paper firstly looks deep into DFSS and applicable tools, secondly covers additive manufacturing as a modern technology and lastly evaluates the applicability of DFSS to AM as an industrial manufacturing technology.

2. Design for Six Sigma (DFSS) approach

DFSS is an organized approach that uses tools, training and measurements to design products and processes that meet customer requirements at a Six Sigma quality level [4]. Six Sigma quality level means that a process produces a total of 3.4 defect per million opportunities (DPMO) that exist in the production environment [6]. The total DPMO of 3.4 is equal to 99,99% process performance[7]. DFSS begins with defining the problems that affect meeting customer requirements and understanding the objective of the product by using the voice of the customer (VOC) tool[8]. From the problem definition, the critical quality characteristics of the products are outlined using parameter diagrams and a quality function deployment matrix (QFD) [7,8]. A proper problem definition affecting customer requirements and understanding of its elements is critical for the successful application of DFSS. DFSS follows a five step methodology (figure 1) known as Define, Measure, Analyze, Design and Verify (DMADV).

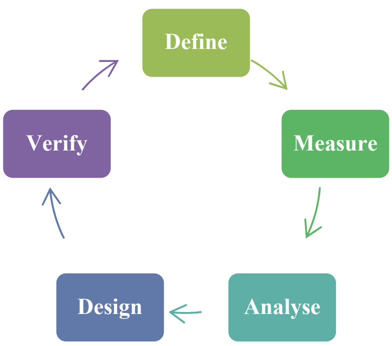

Fig. 1. DFSS typical approach.

This methodology is used to improve technological effectiveness and performance of products from the design phase[10]. Although there are other methodologies that can be applied in design for six sigma such as Identify, Design, Optimize and Validate (IDOV) or Design, Characterize, Optimize and Verify (DCOV), the standard and widely used methodology is DMADV[9]. This Methodology is applied when a new process is required and in process redesign. It is aimed at improving the manufacturing process. Figure 2 shows the flow chart and activities that are necessary for applying DFSS to a software and hardware manufacturing technology. The methodology for applying DFSS involves project charter establishment. The project charter elaborates the purpose and the focus of applying as well as the process flow to be followed during the implementation. It also outlines the tools to be used based on the required information.

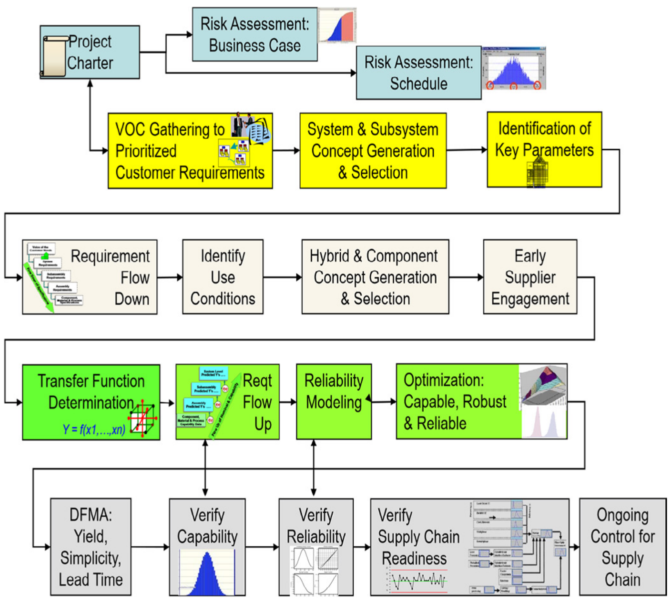

Fig. 2. DFSS DMADV process flow[11].

As observed from figure 2, clear understanding of the customer requirements is very critical for performance and productivity improvement in manufacturing. Traditional and new quality tools are used during the application of DFSS to better understand the process, translate the customer requirement and to analyze the capability of the process to meet the outlined specifications. Table 1 below summarizes some of the critical tools applied in DFSS along with their deliverables.

Table 1. DFSS deliverables and tools [11]

DFSS Deliverable	DFSS Tool
Identified Customer Requirements	Customer Selection Matrix &, Kano Analysis
Identified Critical Parameters	QFD , Design FMEA
Manufacturable design - simplicity and yield	DFMA Workshop
Documented Risk Analysis	Design FMEA
Identified Critical Parameters,	1st Principles Modelling, Regression, Comparative Methods &DOE
Initial Tolerance Analysis	RSS, Monte Carlo

Predicted Reliability or Availability	Fault Tree Analysis, System Reliability Modelling/Prediction
Optimized Critical Parameters	Robust Design, (DOE), ANOVA
Updated Tolerances Analysis	Updated CPM Scorecard
Control Plans for Critical Parameters	SPC, Poka Yoke implementations
Reliability Assessment	Reliability Evaluation
Process Capability	Cpk (CPM) results from pilot or early production,

The tools presented in table1 can be applied across all kinds of businesses to improve quality and organisational performance. The above tools are also used based on the nature of the problem and the objectives of DFSS. The quality tools are used to study the process capability and the process limitation to determine process improvement. The next section discusses additive manufacturing as a modern technology.

3. Additive manufacturing as a modern technology

Modern manufacturing technologies involve advanced computerised systems for product fabrication and overall production control. Further, they require computer based analysis and so are also more broadly known as computer-integrated manufacturing systems [12].

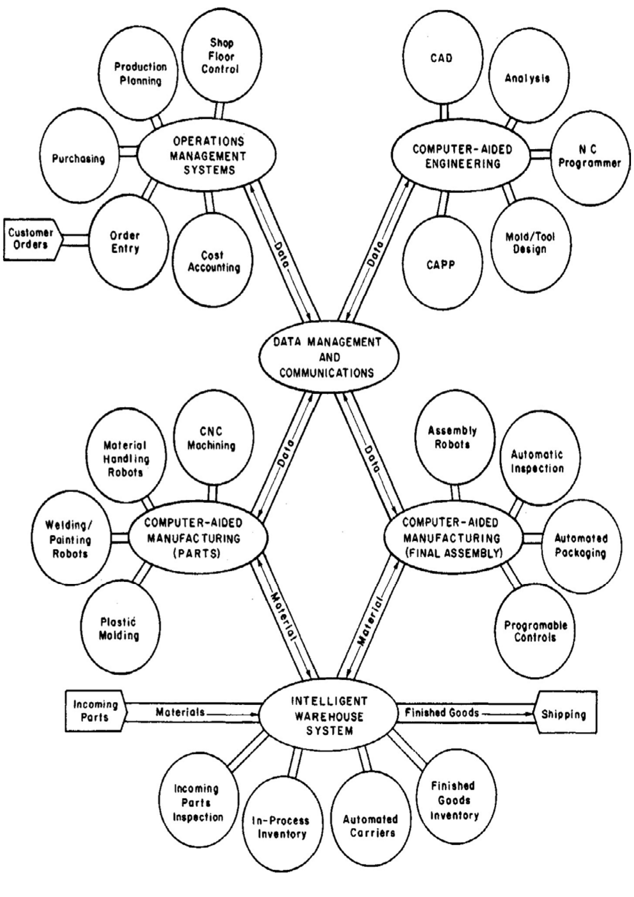

Fig.3. Computer-integrated manufacturing technologies[12]

As observed on figure 3, computer-integrated manufacturing systems are comprised of computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided inspection (CAI), computer-aided production planning (CAPP) and material handling[12]. All these technologies and systems are integrated to form a significant part of what is commonly referred to as industry 4.0 (I4.0).

Additive manufacturing, also known as three-dimensional (3D) printing, is one manufacturing technology that is a key focus for integration into I4.0. AM has evolved from its original purpose of prototype production towards functional parts manufacturing and is increasingly influencing everyday engineering design and innovation[13]. AM technology consists of producing products generally by material addition in layers, where the layers are the cross-section of the final product from a CAD model[14]. Additive manufacturing combines both software data processing which is then later converted or translated into processible information for product fabrication. AM process applications have increased in various industries due to its technological capability advantages including design and manufacturing of free-form products without the need for complex tooling[15]. Although AM has expanded and provides many potential benefits as a modern manufacturing technology, it poses quality challenges and requires strict process monitoring. AM is mostly competent to manufacture products with high quality. However, it is still difficult to print without any form of defects in the final products[16]. AM, like most modern manufacturing technologies, is complex and requires a lot of consideration in terms of selected process parameters that affect part quality. Bandyopadhyay and Traxel[13] state that defects are common in AM technology and inconsistency can be high in resulting product properties.

Quality challenges in AM are accelerated by lack of knowledge on how to recognise defects early in the process and how to repair them as they occur[13]. The quality of the resultant parts in additive manufacturing is influenced and affected by the design of the parts to be fabricated, the build process and the chosen process parameters[17]. The design proficiencies of AM consist of software that permits the prediction of product processing and parameters settings. Greater understanding is therefore required in order to reap the full benefits of AM[13]. Understanding of the relationship between the process parameters and final part process is required in AM to allow the advancement of the technology [13].

The models developed in this work are based on metal AM technology that is focused on industrial use, like the MetalFab1 machine, developed by Additive Industries in Eindhoven, Netherlands. With a 400mm square work plate, it is capable of batch production, where numerous identical parts can be fabricated in a single build. Due to varying heat transfer effects, each part on the plate will require different optimum conditions. By changing the build orientation or machine parameters (like laser power, scan spacing and scan speed) for example, each part being built can be fine-tuned so that they arrive at some defined optimum conditions based around geometrical tolerances or mechanical properties (like surface hardness or compression modulus). It is also well understood that varying properties can result from changes in the part geometry, occuring during the accumulation of multiple layers and their changing of cross-sectional area. Further fine-tuning of build parameters can also be carried out as the build progresses in height. Whilst AM is considered as a technology suitable mainly for customised or individula parts, there are an increasing number of companies looking at metal AM in particular for large batch production of medical or aerospace parts due to the advantages in creating complex forms.

It is very important to understand the nature of production in order to solve existing challenges in modern manufacturing technologies. The undersatnding of the nature of production and the applied technology assist in determining the limitations and the capabilities of the manufacturing process. The next section evaluates the applicability of DFSS to additive manufacturing as a modern manufacturing technology.

4. Evaluation of Design for Six Sigma for additive manufacturing

Additive manufacturing technology involves both sofware and hardware processes to manufacture physical parts. The CAD model data is usually sent to a simulation software to assess the printability of the parts and identify possible errors before sending to the printing machine. AM machines contain specific softwares that control hardwares which are process specific[18]. Having said that, all AM machines are manually assembled. This could explain why variation is experienced from machine to machine in AM as outlined by E.Fraizer[19]. Furthermore, AM production is largely dependent on the geometry of the input part design and overall closed-loop process control is currently not available. Because of this environmental variations can be observed within a batch and from batch to batch production. The application of DFSS to AM should take into account the nature of production and product requirements. The application of DFSS to AM is to eliminate product post-processing by reducing process limination from the design phase to improve cost from the design phase of the technology[20]

Based on literature, DFSS can be applied in any industry including the software environment[7,8,12]. Modern manufacturing technology often requires computer based analyses due to the nature of production[8]. Analytical models can be used to determine noise factors such as product to product variation, dimensional deviations, and other changes in properties of the product and/or process and are important for initiating DFSS improvement in modern manufacturing[21].
Moreover, quality improvement in AM can be achieved in three parts, namely, deviation analysis, deviation correction and deviation prevention[22], this manner of quality improvement recognised in AM requires a systematic approach to cater for technological deviations on an industrial scale. It is imparative to note that in all these fragments of quality improvement in AM, deviation should not be expected to be linear due to many factors that possibly have a non-linear influence on the resulting part quality[22]. All these quality improvement aspects of AM can be achieved using DFSS methodology through the application of the tools listed in table1 and their deliverables. The DFSS principle (DMADV) is used when product improvement is required in order to achieve high quality from the customer point of view[10].

Understanding of the DFSS approach, the applicable tools and the critical aspect of product definition practically assist in resolving the quality issues early in the process[11]. The application of DFSS to modern manufacturing technologies involving software and hardware systems such as AM requires an understanding and translation of customer specification first from the software and then to the hardware in order to properly gain an insight of the critical quality features required[11]. Although it is apparent that DFSS can be applied to modern technology a clear framework outlining how it can be applied should be developed. The next section discusses how DFSS can be applied to AM as a modern technology .

New models and techniques including machine learning and mathematical algorithms for improving product quality in modern manufacturing has been developed through intensive reseach[23]. However, most of the research focusing on quality improvement in modern manufacturing, especially AM, is still carried out in laboratory environments and disregard the industrial relevance of the techniques for improving quality in AM[22]. A systematic approach that will cater for quality improvement of resulting parts in a batch and batch to batch production in AM is possibly required. The DMADV approach is embedded with the principle of reducing variation and defects in resulting product by redesigning the process[24].

4.1 Application of DFSS To Additive Manufacturing

In AM, everytime a new product is fabricated, the process must be adjusted and optimised to cater for the design and specification of the product thereof[25]. This means that the process must be optimized before manufacturing. Keeping the key fragments of quality improvement of AM in mind, the application of DFSS in AM focuses on deviation prevention which is centred on establishing optimal process parameters and analysing possible error sources in an AM process[22]. The optimal process parameters are established by outlining the critical to quality elements of both the product and the process. This process is carried out during the define phase of DFSS by using the Critical to Quality trees[5,3].

During the establishement of the critical to quality elements, process parameters required to ensure the quality of the product are outlined and broken down into quality drivers and functional requirements [3]. The outlined requirements are then employed into the design process. Figure 4 provides a framework for implementing DFSS to AM for error prevention and it is complimentary to the flow chart presented in figure 2 for DFSS application. The outlined framework can be applied only before manufacturing and is coupled with other process optimisation techniques and quality improvement tools.

In the first phases of implementing DFSS, the Supplier, Input, Process, Output and Customer (SIPOC) diagrams and the Faliure mode and effect analysis (FMEA) tool are used[4]. These tools are considered important, the SIPOC diagram ensures that everyone understands the process and its fundamental elements while the FMEA is used to outline process risks, their occurance and detection[5]. Conducting these activities and understanding their effect consequences is benefial and can be considers vital during the AM process design.

After manufacturing the part deviation analysis and quality assurance must be conducted to validate whether the desired quality has been achieved or not and to ensure that the existing variation in the product is at acceptable levels. The analysis of the variation and deviation after manufacturing can be conducted using quality tools such as Control charts and Gage R&R[5]. According to Beltrán *et al.* [22], deviation analysis include inspection of the influence of process parameters and comparison of the theoretical values with the manufactured parts.

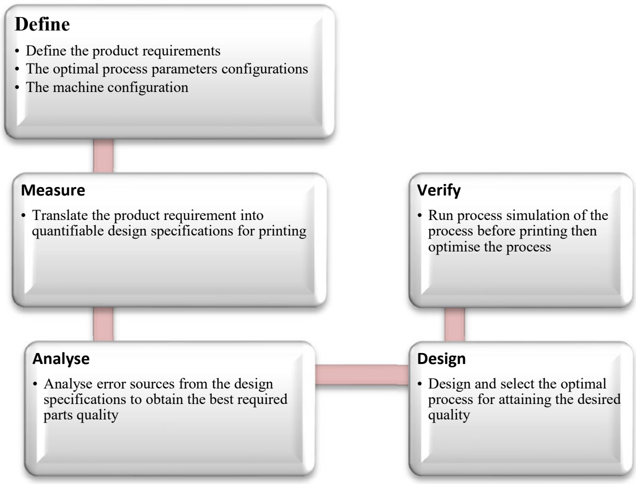

Fig.4. DFSS framework for AM

The deviation analysis process is followed by the deviation correction which is based on the nature of the observed variation and deviation. During deviation analysis and correction the define, measure and analyzing phases of DFSS remains and are integrated with the Improve and Control phases of Six Sigma[10]. The integration of DFSS and Six Sigma methodology allows for the standardization and proper documentation of the process.

The effects of applying DFSS to modern manufacturing has many benefits including defining process chains and in-depth understanding of the AM process technology[26]. The understanding of the technology will aid in the adoption of AM for industrial application which is currently a challenge and will also assist in improving the quality of AM product.

Conclusion

Design for six sigma is one of the quality improvement strategies that can be integrated into modern manufacturing for process and quality enhancement. Customer requirements are used to determine the process parameters and quality indicators for product manufacturing. Different operational tools are applied to generate more data for process analysis and measurement. Although the purpose of this paper was to evaluate the applicability of DFSS to AM, it also outlined the framework for implementing the technique to the technology. The outcomes of DFSS lies in the applied tools in the define stage and the understanding of the customer requirement during the measurement- phase.

Although design for six sigma is applied when the new process is require and to ensure that product requirements meet customer reqrequirements' the first time, it can be applied to an existing process since it provides infrastructure for six sigma application. Moverover, for AM technology it becomes relevant due to the production requirement of the technology. The AM technology requires process design optimization every time a new product is manufactured.

This paper looked at design for six sigma as an improvement strategy, it outlined the basics and tools of DFSS methodology and outline the basics of modern manufacturing.It outline how DFSS can be applied to to additive manufacturing.

Future work will involve the application of DFSS to metal additive manufacturing and the recording of its outcomes. A case study methodology, based around batch production of similar parts within a single build, will be used to implement the outline DFSS methodology and to study the consequence effect of applying the technique.

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