

Design for Verification in the Context of the Light Controlled Factory

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Abstract *“Design for Verification” is a novel DFX philosophy that considers the holistic verification aspects of complex, high value products throughout their life cycle that directly influence rules for assembly, integration and production processes as well as the end product functionality and experience. In this paper, the design for verification is placed in the context of the Light Controlled Factory, an innovative concept that denotes future factories with distributed and embedded metrology for verification as well as metrology-enabled manufacturing and assembly. Design for verification research and practice for complex high-value manufacturing has been lacking due to the inherent knowledge gap between design and production within large scale industries. Increasing product complexity and the rapid evolution of engineering knowledge has created a necessity for high fidelity products manufactured using adaptable and reconfigurable manufacturing systems for ensuring competitive costs and the implementation of state of the art technologies. This evidently places heavy emphasis upon real time metrological verification for both manufacturing and assembly systems as well as the product itself. This paper reviews the standard definitions of verification and the design for X concept within the holistic engineering design process to reveal the necessity for design for verification and then progresses to provide a coherent analysis and classification of these activities from preliminary design, to design in the digital domain and the physical verification of products and processes within the context of the Light Controlled Factory. The scope of the paper includes aspects of system design and demonstrates how complex products are verified in the context of their production and assembly processes.*

1. Introduction

Design for excellence, or X (DfX) encompasses a vast range of both specific and generalised guidelines to aid designers in meeting particular criteria in order to cost effectively, achieve an optimal final product configuration and work toward design

for six sigma (DFSS). The purpose of DFSS is to control design variation by ensuring that all the functional requirements of a design can be maintained at plus or minus six times the standard deviation for each component [1]. The DfX guidelines which reside within the overall DFSS theory can be divided into subcategories for the different phases within the product life cycle, summarised as: Development phase, Production phase, Utilization phase and Disposal phase [2]. Within aerospace manufacturing, these design phases are often treated as succinct and separate phases during development due to the fact that engineers often specialise within a single field or discipline. Design for verification (DfV) is a concept which spans across the all four phases and is of course a vital aspect of the first two phases (development and production) that are within the scope of this paper, highlighting the importance of tolerancing and critical feature design upon the assembly and verification requirements. Research under the Light Controlled Factory (LCF) (EPSRC grant EP/K018124/1) has proposed a new planning and implementation hierarchy of design and production processes that holistically detail the stream of engineering phases which lead to right first time manufacturing.

New levels of competition among high value manufacturers have forced industries to revolutionise attitudes towards their customer focused service approaches. Increased demand and market volatility must be dealt with, coupled with product customisation and short time to market. The needs for design adaptability, reusability and the ability to develop products and services for the ecommerce era as well as the issues of dealing with design complexity have been recognised across the top management levels of high value manufacturing industries. An example of this is the steady rise in commercially available spacecraft which was once limited to governments due to the high cost and available technology. The global interest in space travel and exploration has opened up the market to private companies introducing increased levels of competition forcing spacecraft manufacturers to drive down cost and improve product functionality, aesthetics and efficiency [3].

In order to maintain market standing and be successful in the modern global market, industries with high value manufacturing facilities are becoming increasingly reliant upon digital simulation and optimisation to enhance, improve and sustain factory wide lifecycle operations for improved product design, robustness, customisability, reusability and efficiency. Planning in the digital domain can significantly reduce costs through holistic resource scheduling and pre-programming of manufacturing and shop floor operations.

Verification within the aerospace industry is essential but it is currently very costly and time consuming. Verification of a product as an on-line process can often cause long delays and be carried out in a less than satisfactory manner with respect to the methodology of data collection, metrology system capability and environmental consideration compensations. Components within aerospace assemblies can contain large freeform surfaces and often do not include readily available features which can be used as datum points for metrological verification. Metrology system operators are usually forced to indirectly create a frame of reference for measurement or perform a best fit algorithm depending on the instrument being used. These processes can be highly unreliable and unrepeatable leading to a lesser degree of confidence within measurement data and ultimately a lesser degree of confidence in product conformance to specifications and quality. In order to eliminate these issues, designers can integrate key features to act as datum reference points which are stable and repeatable, providing a solid foundation for both a metrology reference system and a critical assembly point [4]. This philosophy has been widely adopted within *tooling* design due to the close link with metrology within assembly processes. However, this verification via metrology philosophy is still lacking exposure within complex high value product design, which typically places heavy emphasis upon product performance, functionality and aesthetics with minimal consideration of how product specifications might be verified, during or post production [5].

2. Design Verification and Validation

During the manufacturing phase for components and or assemblies, a critically important stage to ensure product quality is the verification and validation process. Verification and validation processes aid in the assessment of process capability so that refinements can be made throughout the manufacturing lifecycle to improve and enhance product quality. The purpose of verification and validation is to enable the final product to meet all required design specifications and ultimately ensure that the product is fit for purpose. Verification can be termed generally as a quality control process, used during the development phase to specify if a product, service, or system adheres to specifications, regulations or general conditions initially imposed [6] [7]. Alternatively, design validation is a process to collate evidence to eliminate doubt in product or service specification conformance. This being said, verification and validation can be, and are still used interchangeably or as a combined, succinct process [8] [9].

ISO 9000 focuses upon quality management and how evidence can be accumulated in an effective manner so that conformance to product specification can be coherently established and maintained [10]. The distinction between

verification and validation according to ISO has been broadly defined. Verification is a process which assesses a product's conformance to physical specifications, i.e. GD&T (Geometric Dimensioning and Tolerancing) [11]. This is the reasoning behind verification being closely linked to metrology within the LCF definition, as metrology is usually deployed for measurement of physical specifications. Validation is a process that assesses a product's ability to fulfil its intended purpose, i.e. conducting finite element analysis (FEA) to predetermine structural integrity [12].

Maropoulos et al. [3] defined a new framework for design verification and validation within engineering in the CIRP Annals Keynote paper as seen in Figure 1: A New Framework for Engineering Design Verification and Validation [3]. Maropoulos et al. categorised design verification and validation into four succinct phases with sub stages for three of the four phases. The scope of the research focus of this paper is highlighted by the three red rings within Figure 1: A New Framework for Engineering Design Verification and Validation which collectively form the basis for the DfV philosophy defined and outlined in this paper.

GD&T [11] is a symbolic language which was developed to aid designers in communicating product specifications in a coherent and standardised manner. GD&T specifications aim to minimise non-conformance by defining clear parameters for permissible product variation by fully capturing the intent of the designer and providing a methodology for verification whilst communicating the functionality of the product. GD&T is also used for design validation through tolerance stack up analysis to determine if multi-part assemblies will correctly assemble when the expected variation of the parts at the various manufacturing processes inevitably occur. Whilst the standards relating to GD&T have been very beneficial to production and metrology engineers worldwide, there is still a lack of a clear process for designing a holistic instrument specific verification capability into the design of the product itself.

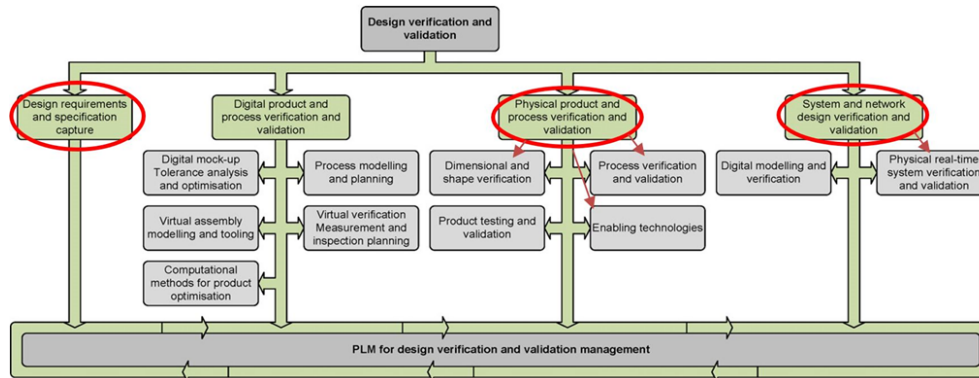


Figure 1: A New Framework for Engineering Design Verification and Validation

3. Design for Excellence

The success of the DfX concept was achieved through integrating small, focused engineering teams to achieve holistic DfX approaches ensuring that parts are designed with manufacturability and ease of assembly, with interchangeable parts. The concept of standardised and interchangeable components designed for large scale assembly was popularised by the requirement for the mass production of weapons by figures such as Lieutenant General Jean-Baptiste Vaquette de Gribeauval in 1765 and Honore Blanc in 1778 [13] [14]. In 1801, Eli Whitney successfully demonstrated this concept before the United States Congress which led to the standardisation of all United States equipment. This was a large leap towards modern manufacturing although Eli Whitney himself did not manage to achieve a manufacturing process capable of producing the interchangeable parts [15].

Arguably, the first successful implementation of part interchangeability within mass production was achieved by Marc Isambard Brunel (father to Isambard Kingdom Brunel) in 1803, shortly after Whitney presented to the U.S. Congress in 1801. This was during a time when the Napoleonic war was at a climax and the Royal Navy was rapidly expanding capability with a requirement for wooden pulley blocks. M. Brunel, working in collaboration with the esteemed Henry Maudslay, revolutionised the industry with a force of 45 purpose-built machines capable of carrying out 22 processes, able to produce three different sized pulley blocks. The processes involved marking the blocks and using features for alignment and creating datums, both showing and proving the integrated necessity for the concept of design for manufacture – DfM [16] [17].

With the advances in manufacturing technologies such as milling machines and turret lathes, the concept of part inter-changeability, and the associated but still

largely undefined design for manufacture concept, spread throughout numerous manufacturing industries during the late 1800's including the locomotive, steam engine and sewing machine manufacturers. This paved the way for the introduction of the moving assembly line which was brought into fruition by the sponsorship of Henry Ford within the assembly process of the Ford T in 1913 - although general assembly lines can be dated back much further, even to the 11th century. Following the success of Ford's moving assembly line, the concept was widely adopted throughout many industries, satisfying the pressing requirement for assembly processes to keep up with the increasing capabilities of machine tools introduced through the industrial revolution and afterwards [18] [19].

It was not until more recently with the increase in computational power and software capability that assembly evaluation methods were created to rate assemblies and estimate time schedules and costs incurred such as the Design for Assembly method (DfA) by Geoff Boothroyd in 1977 or the Assembly Evaluation Method (AEM) by Hitachi in 1986 which were both crucial elements within the creation of the Design for Excellence (DfX) philosophy [20].

The DfX concept, often interchangeably referred to as Design for Excellence, has been developed to aid designers through an entire product design process from conception to market release [21]. DfX has been recognised as one of the most beneficial design approaches in order to implement state of the art engineering solutions [22]. DfX has long been established and has steadily evolved to accommodate changing market requirements and technological advances. DfX has been described by Bralla as the "knowledge base to approximate the product design to the maximum of its desirable characteristics such as high quality, reliability, maintainability, safety, ease of use, environment constraints, reducing the lead times for sales, reducing manufacturing costs and product maintenance" [20]. As previously stated within the introduction, DfV can be considered as an element of DfX and when considered within the context of the LCF, its scope is targeted at the development phase and the production phase. Within Table 1: DfX Classification and Definition the DfX concepts are tabulated within their respective phases to provide an overview of where DfV will reside. Within the development phase, DfX components such as DfTest, DfReliability and DfQuality will all be encompassed and support by DfV with embedded design rules and assurance checks. The components such as DfAssembly and DfManufacture within the Production Phase link between the two phases through DfV.

Table 1: DfX Classification and Definition

DfX Classification [2] [20]

<u>Development Phase</u>	Design for Safety
	Design for Clarity
	Design for Simplicity
	Design for Short Time to Market
	Design for Reliability
	Design for Test
	Design for Quality
	Design for Minimum Risk
<u>Production Phase</u>	Design to Cost
	Design to Standards
	Design for Assembly
	Design for Manufacturability
	Design for Logistics
	Design for Electronics Assemblies
	Design for Low-Quantity Production
<u>Utilisation Phase</u>	Design for User-friendliness
	Design for Ergonomics
	Design for Aesthetics
	Design for Serviceability
	Design for Maintainability
<u>Disposal Phase</u>	Design for Environment
	Design for Recycling
	Design for Active Disassembly
	Design for Remanufacturing

4. Design for Verification - Motivation, Scope and Definition

As illustrated within the Design for Excellence section, the scope of DfV is contained within the defined DfX phases: Development phase and Production phase, shown within Figure 2: DfV within the Context of DfX.

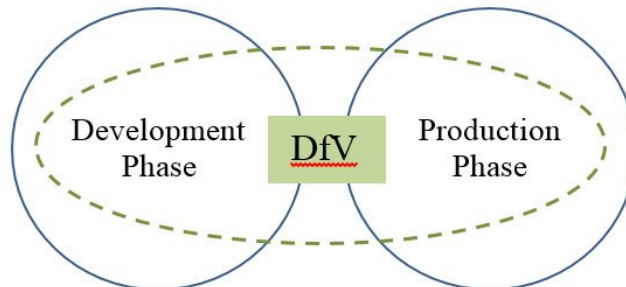


Figure 2: DfV within the Context of DfX

Verification is a key necessity for any structural assembly to ensure quality and product conformance and is present in many forms. The design for verification (DfV) concept proposed within this paper aims to close the gap between the design development phases and the manufacturing and assembly stages. A systematic and well-engineered structural design will optimise tolerances to ensure critical interfaces meet their key characteristics to perform specific functional requirements whilst simplifying assembly processes, which is managed through DfA and DfM. This, however, disregards the critical process of verification that is frequently left as an afterthought. It is by verification that a supplier can prove product conformance and ensure quality to the customer which is why it is essential that verification processes are considered early on in the design phase as a key requirement, and special features or hard datums are designed into structures in order to permit verification data acquisition by accessible, instrument specific, reference points.

As products are becoming increasingly complex, global knowledge is increasing, and customers are being given a broader range of choice than ever before; customisation and product personalisation are becoming inherently unavoidable within high value manufacturing. To enable such variation, increased levels of flexibility and manufacturing systems reconfigurability are becoming ever important. The ability for manufacturing systems to quickly and cost effectively adapt and react to evolving customer requirements is a key necessity within industries, globally. For this reason, real time metrological verification has become one of the main focuses in the pursuit to achieve this goal. Advanced, optical based metrology systems, such as laser trackers and photogrammetry systems, have been the enabling technologies for creating adaptive and flexible manufacturing systems due to their inherent ability to globally provide real time, automated, high accuracy measurement information over large volumes.

5. DfV in the Context of the Light Controlled Factory

The pursuit of the research under the Light Controlled Factory (LCF) project funded by EPSRC (grant EP/K018124/1) is to optimise the selection, deployment and use of metrology systems for advanced manufacturing and assembly system commissioning, certification and real time verification of both processes and products. The stages and activities of the LCF factory-wide metrology network has been defined as shown in Figure 3: The Light Controlled Factory Metrology Network Definition. This section will detail how the DfV concept has been incorporated into the LCF Metrology Network as the backbone for successful right first-time manufacturing and how its integration is fundamental to the overall philosophy of the Light Controlled Factory.

DfV needs to be considered as early as stage 1 of the LCF metrology network definition, as shown in Figure 3: The Light Controlled Factory Metrology Network Definition. Understanding and codifying a product, based upon critical feature specification is a preliminary task in the determination of verification procedures and assembly planning within the digital domain. A high level Geometric Dimensioning and Tolerancing (GD&T) analysis of the product can provide valuable information as to the implementation of suitable metrological capability as and when required. The GD&T analysis will also provide an overview of the assembly requirements with respect to part-to-part relationships in order to establish a philosophy for the assembly and metrology process. This in turn assists in defining the requirements for a flexible, adaptive assembly tooling system. To fully design a modern assembly system, knowledge of the environment and factory layout will shape the constraints placed upon the assembly system as well as the available metrology hardware. This stage forms a crucial part of the design for verification process through the early stage metrology planning arising from initial requirements, which can assist designers in defining realistic tolerances for components and assemblies.

The second phase of the LCF metrology network model characterises the environment and the factory floor for future detailed process planning. Digital CAD models of the factory layout with the associated real world environmental data for thermal modelling and compensation are key to successful preplanning in the digital domain. By this second stage the designer has a process plan for manufacturing and product assembly and a detailed map of the manufacturing technology resources required for the application specific processes. Thermal and

force modelling of the factory equipment such as machines, jigs and tools, specify the temporal constraints active upon optimal assembly periods. The DfV process identifies all external, factory-wide environmental factors which may effect the fidelity and quality of components and assemblies and then develops appropriate, metrology enabled and computational techniques for the mitigation of respective impact during the manufacturing and assembly stages. Such factory environment factors can include the tide altering gravitational fields near coastal areas, thermal gradient present in large factories and the cyclic variation of factory air temperature that influences the thermal stability of machines and tools,, to name a few. DfV ensures environment specific best practice measurement confidence and product conformance.

The third phase of the LCF metrology factory model focuses on individual manufacturing and production stages for the fabrication and assembly processes that belong to the second DfX phase. The production and assembly processes are analysed with respect to the design tolerances for product integration, functionality and aesthetics. Appropriate metrology systems are identified and down-selected, considering cost, measurement uncertainty, measurement times, metrology system usability and integrity and physical measurement range. Good product and process design considers not only product function, but the real world process capability including the capability of metrology systems to ensure confidence in verification of tolerances and manufacturing processes.. The process specific instrument selection considers a range of parameters that in the case of large volume metrology includes factory environment such as the air temperature, pressure, relative humidity and carbon dioxide content, as well as the number of measurements required, the measurement range, the tolerances allocation and other constraints such as line of sight.. At this stage, if there are no available instruments to fully meet the requirements for verification of the product design, a feedback loop to the design stage is implemented for the reconsideration of the product's specifications. It is nonsensical for designers to allocate tolerances which are impossible to verify within the real world which creates a trade-off between cost, product functionality and time to market.

The Design for Verification procedure then involves the detailed measurement and verification planning within the digital domain for successful implementation, optimisation and configuration that correspond to stages 4 to 7, as shown in Figure 3. The digital verification and validation of manufacturing processes requires detailed instrument dependent measurement planning and uncertainty analysis. As shown in Figure 3, the instrument specific uncertainty models that are integrated with CAD/CAE form a holistic planning and validation environment. The realisation

of the DfV concept benefits the production process further downstream within stages 8, 9 and 10 when the metrology systems are used for tool commissioning and product verification. The LCF metrology network definition holistically incorporates all verification aspects of the manufacturing process to ensure right first time production.

As shown in Figure 3, the application of product and process verification via metrology generates valuable knowledge and rich data arising from the deployment of metrology for the evaluation of engineering specifications of design and the measurement of process capability. These knowledge and data can be used for the specification of DfV rules and constraints that can be codified and applied by designers and manufacturing engineers alike during product design and process planning. In order to increase the impact and effectiveness of DfV, it is always important that DfV rules and procedures are applied as early in the design lifecycle as may be feasible, which is the design specification and requirements capture stage, as shown in Figure 1. This as early as possible application approach for DfV corresponds to the design development phase of classical DfX and links well to the first three stages of the LCF metrology network as shown in Figure 3. Hence, the first three stages of the LCF metrology network provide the foundation for the DfV concept within the design development time-cycle.

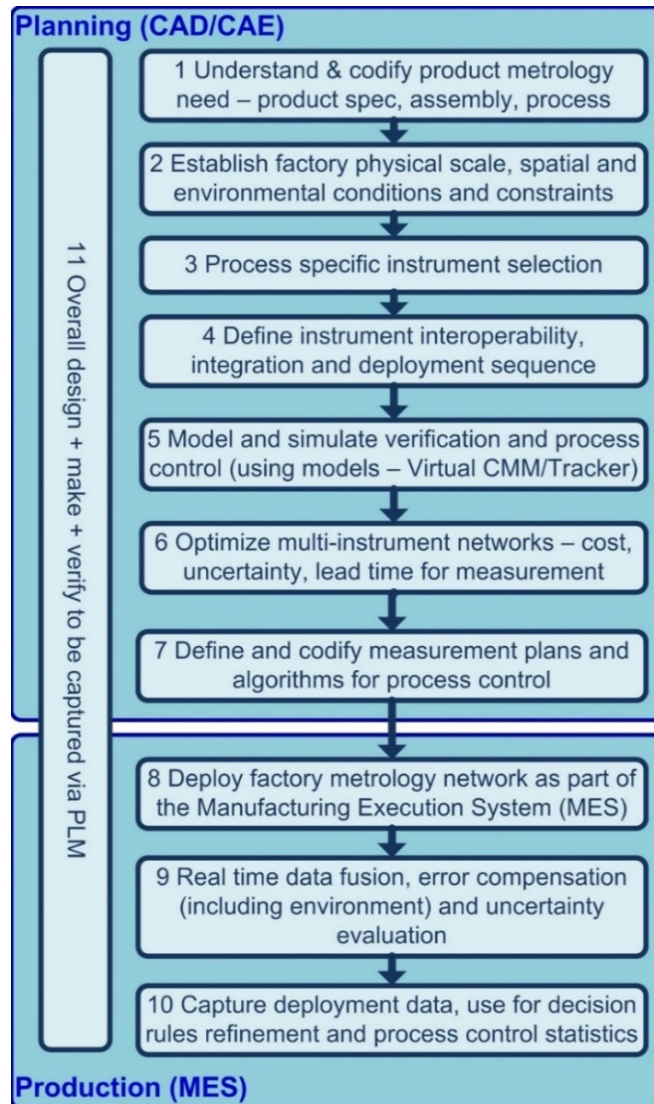


Figure 3: The Light Controlled Factory Metrology Network Definition

6. Concluding Comments

Definitions of verification have been explored and the authors have shown the necessity for developing Design for Verification (DfV) within DfX and proposed a methodology for its implementation.. Design for verification is a vital ingredient of design development and its rules, algorithms and implementation methodology are directly linked to knowledge and data arising from product and process verification

via the deployment of metrology. In this context, DfV is intrinsically linked to the theory and implementation process of the Light Controlled Factory that is a new concept for the factories of the future that will have embedded verification capability via the widespread deployment of optical metrology systems for parts verification and process capability enhancement. In order for DfV to be most effective, it is vital that its application starts as early as possible during design and process planning and the process is an integral element of the future Light Controlled Factory network of functions and implementation processes.

7. Acknowledgement

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