Improving Design for Manufacturing Implementation in Knowledge Intensive Collaborative Environments

An analysis of organisational factors in aerospace manufacturing

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***Abstract*— Today, the manufacturing industry is under pressure to be able to rapidly come up with innovative designs and produce them in much shorter timeframes in order to keep up with growing customer demands and quickly gain new business. One of the ways used to achieve shorter time to markets for new product developments is by using design for manufacturing (DFM) methods to reduce time and energy going into resolving manufacturing based defects. It is also more vital in today's manufacturing industry to make use of DFM methods much earlier in the product development lifecycle in order to prevent potentially known quality defects from happening and save on costs associated with late design changes. This requires enabling a more systemic feedback cycle of production data for the creation of DFM knowledge repositories as well as overcoming some wider knowledge sharing barriers across the organization. This investigation focuses on how the communications of manufacturing knowledge from production data is affected by factors within the overall organization. The investigation is one of the few that consider the influence of organizational factors on the communication of engineering knowledge as well as the related knowledge sharing barriers. The project is carried out empirically with a large UK based aerospace manufacturing company by gathering data primarily from observations and interviews. This paper presents the findings followed by discussions for improving DFM Knowledge Management in the aerospace industry.**

Keywords—Knowledge Management; Design for Manufacture; Aerospace Industry; Manufacturing.

I. INTRODUCTION

Today, industries have begun acknowledging the benefits of Knowledge Management (KM) approaches that can make the use of the large amounts of data generated within the business much more effective. Similar approaches like cloud computing and the internet of things (IoT) can improve accessibility to information networks, and centralize data sets in manufacturing activities in order to make use of it in decision making [1]. Data representation, data automation, data mining and data analytics technologies improve the management of manufacturing knowledge particularly related to process planning and decision making in the middle and late design development stages [2, 3]. Virtual systems propose using simulated computer generated environments and software interface to manage knowledge based on the representations of real life process capability feedback [4]. Examples of this include the ability to monitor, control and optimize manufacturing processes via simulating process variables remotely from any computer network. Artificial intelligence is an area within virtualization of systems that is up and coming - promising the ability to support manufacturing decision making by collecting data. The data is then analyzed using intelligent learning systems capable of making useful conclusions from the manufacturing processes by learning from former process variabilities and presenting the thresholds to the engineers [5, 6].

Additionally a wide range of research focusing on manufacturing flexibility has been recently introduced [7] in literature. It aims to respond better and quicker to changing markets and customer requirements. Similarly, agile and dynamic supply chain literature mainly propose methods that improve business management to accommodate unforeseen commercial and operational changes. Cultural and managerial aspects of business management have appeared in literature aiming to improve working practices particularly for organizing teams that can work better in unexpected product changes that occur in the late manufacturing stages.

It is also more critical now to acknowledge that more complex products are becoming harder to manage and communicate especially due to extended enterprises manifestation. Researchers and the industry feel a strong need to adapt these new approaches to more complex knowledge intensive environments. Collaboration technologies, IT technologies like Cloud Computing, Web 2.0, and Industry 4.0 have evolved to improve decision making and centralization of project information for geographically dispersed teams, multi-disciplinary teams and to better integrate Product Lifecycle Management [8].

With all these progresses in the literature, there is still a serious need of research that consider any remaining organizational factors that may still hinder collaboration in knowledge intensive environments for improving design for manufacturing (DFM) implementation.

This paper considers the management of DFM knowledge based on real-life manufacturing data at a large UK based manufacturer of aerospace products. A need for a complete systematic knowledge feedback cycle from the production line to the engineering teams is identified. The organizational factors that may obstruct this cycle are investigated by carrying out a series of interviews, focus group discussions and observational studies at the collaborating company. The main findings of the organizational factors that affect KM are presented followed by discussions and recommendations.

The project confirms that not only the utilization of the latest systems, and IT tools to organize and manage knowledge feedback to the required engineering teams is required - but this needs to be combined with an understanding of some communication barriers in order to enable an improved feedback approach of any embedded DFM knowledge for engineering to implement.

II. Motivation

Many of the challenges of the aerospace industry are greatly driven by the increased complexities of products, organizations, and manufacturing activities [9]. In this industry, an avionic product can consist of several complex subsystems assembled together. Each of the subsystems could consist of several hundred components - each component goes through an extensive design development stage to qualify it for meeting extra-ordinary performance requirements, functional requirements, manufacturing quality requirements and other key specifications. Managing the knowledge within this entire process is considered much more complex than any other manufacturing sector.

From the organizational point of view, a mixed team of engineer's aim to design the product to meet those customer's specifications as well as the design functionality and manufacturing requirements set at the start of the project [12]. At this stage, the product would have not been yet manufactured for any potential defects to arise or be avoided in the way the parts are specified. Additionally, a series of activities by different engineering disciplines take place in order to unify the design from different aspects such as production planning, DFM approaches, and the supply chain strategy. This also adds to the complexity of managing the knowledge required to specify the manufacturing processes for a successful product with a low or zero amount of defects. The knowledge required to do this is difficult to attain as it is purely gained from previous designs' exposures to manufacturing that result in a series of good design practices and specifications that avoid any known potential defects. It is very important to transfer some of this type of knowledge from previously manufactured products and create additional specifications that can result in a more successful new product.

The approach described above has already been explored in research in the domain of concurrent engineering, and integrated product design [14]. Sometimes referred to DFM methodologies, they aim to use the knowledge gained on previous problematic areas in manufacturing to design products that better and more successful in their manufacturing stages. DFM methodology is also a major contributor to corporate learning due to its ability to integrate the most recent solutions to common manufacturing issues in the designs of new products. Nevertheless, DFM methodology heavily relies on people and expert knowledge. In literature, it currently lacks a systematic approach by the use IT tools and falls short with ways of aligning it with organisational strategies. This research paper aims to fill in this gap by looking at the requirement for expert knowledge to be captured correctly, its transfer to the appropriate engineering teams, and how to manage it effectively for implementation in NPD from both technical and organisational point of views. This paper is a continuation of previously published work for this project found in El Souri et al [15].

III. Related Litereture

There has been a significant range of literature that looks at overcoming some of the challenges for improving knowledge management in knowledge intensive environments. The two main discipline areas absorbed for this paper are summarized below. This section aims to review the latest approaches in the field and highlights any shortcomings in their considerations of the organizational factors that limit their effectiveness.

[redacted] *Organizational Management*

Ever since Extended Enterprises started forming over two decades ago, it became no longer feasible to look at the manufacturing activities and process capabilities in isolation from the rest of the business. Methods that promote enterprise networking, improvement of data interchange, and knowledge integration across larger clusters of manufacturing resources operating under one business have become more critical to consider in manufacturing activities [16]. Although other methods are more established in the industry like Just in Time Production, Concurrent Engineering, World Class Manufacturing, Lean Production, & Benchmarking, they have not dramatically evolved to address the issue of making use of production data to generate DFM knowledge for NPD and any of the existing barriers to knowledge sharing in organizations. Traditional engineering and manufacturing organizations are rapidly moving towards knowledge based organizations – they must now consider how to make the most use of the data constantly being created in businesses for more effective DFM implementation.

One of the major challenges for a knowledge based organization, is managing all the digital information and the computer centered-processes and activities. Increased complexity, and the 'heterogeneous' of dealing with this digital information (or data) needs more addressing [17]. There are some proving practical approaches being implemented in industry (such as standardizing IT infrastructures, standardization for knowledge ontologies, and the introduction of IT visualizations) as they improve data interoperability and align the enterprise architecture across the various partners and business involved in single manufacturing projects [18]. However, there are still major limitations in those approaches that consider the overall organizational strategy to make the proposed systems work. There is a need for frameworks that can use technological systems for managing digital information alongside addressing how the business should integrate them across multiple manufacturing sites, multiple engineering teams, and multiple lifecycle management systems that all have different ways of running manufacturing lines.

On the other hand, dynamic and agile supply chains (in the supply chain discipline) propose more consumer-centric, information driven methods of operations in order to increase flexibility of manufacturing activities for multiple businesses within a single enterprise. The new methods developed in this domains have overcome some information sharing barriers by improve responsiveness to customers and adapting quicker to continuously changing markets than the traditional supply chain models used [9]. These approaches are more open to allocating their own resources to understand their partner's manufacturing processes. However, the strategies in this discipline have not yet been clear about how to unify the management of knowledge systemically particularly in the aerospace industry. Alternative methods such as predictive models and risk mitigation have shown a strong capability to build knowledge repositories from past experiences [10]; but remain top down approaches and have not featured any designs of knowledge feedback systems to engineering teams for mitigating potential defect risks.

[redacted] *Quality Management*

The literature that propose approaches within Quality Management (QM), production planning, and product maintenance have been widely analyzed but "remain treated by scientists and industrialists almost in isolation" from the overall product lifecycle management [11]. This is also the case with traditional quality management methods like Six Sigma, Total Quality Management, Continuous Improvement, Lean Manufacturing and World Class Manufacturing as they still face many limitations in regards to addressing the current industrial challenges particularly with the more recent challenge of 'big data'. Moreover, most research acknowledges that these QM approaches are more effective when they are interrelated and strategically carried out with a holistic view of the product life cycle management. Yet applications of this are very limited in literature that do not treat QM activities in isolation. Some new methods in QM have been found that use data from the inspection processes and feeding it back for the design engineering teams to carry out engineering changes [12]. It was not possible to find any research that looks at similar methods to extract knowledge from production data that may benefit engineers in NPD to implement DFM. Furthermore, recent quality management is focusing on improving the businesses understanding of project costs and the effects of disruptive events like quality defects and late design changes [13]; but more research is needed that can bridge the gap between understanding the cost of defects and the impact of any subsequent DFM implemented from them.

On the other hand, data mining technologies have been featured in literature to collect manufacturing process data for manufacturing optimization. Artificially intelligent systems that use algorithms have also been reported in a wide range of literature to support decision making for predictive modeling. However these disciplines focus more on the mathematical technicalities and are not seen to consider the knowledge sharing barriers or organizational factors that may result in underutilization of such systems. Similarly organizations are still heavily investing in new quality management systems hoping to get their teams to use them effectively [14]. However, industries have shown that there are yet some challenges in the organizational management of teams such as motivating the right people to use those systems correctly. It is vital now for researchers and industrialists to be able to provide technical considerations as well as an evaluation of existing organizational factors and knowledge sharing barriers to make any introduction of new knowledge management systems more effective.

IV. Industrial Investigation

This research project is carried out at the site of BAE Systems, Electronic Systems, Rochester. They are a large UK based manufacturer of aerospace products.

The investigation is split into two main bodies. The first part of the investigation reports main findings from 13 interviews conducted with the management teams aiming to identify the main organizational factors, and knowledge sharing barriers that need to be addressed for more effective communications of knowledge for DFM implementations.

The second part of the investigation is an observation of product lifecycle management processes that are currently used to communicate DFM knowledge for engineers in NPD. This part of the investigation uses real life observation for a duration of 12 months which identifies the main methods used for communicating DFM knowledge. The observation is supported by 10 focus group discussions to validate and further develop the outcomes. The discussions were based on a mixed type of manufactured products at the collaborating company. The mix includes observations of different maturity levels of each product. Some products have just been developed in the past 2-3 years and others have been ongoing production lines for the past 7 years. The products also vary from mechanical, electromechanical, and optical component assemblies.

[redacted] *Research Approach*

The interviews were carried out to identify the current organizational and knowledge management challenges with members of the technology, innovation and manufacturing management teams. A variety of 13 different managerial positions were selected for the interviews lasting between 30-60 minutes each. The interviews included people from: technical supply chain, procurement, test systems engineering, quality management, mechanical engineering, project management, business improvements, and manufacturing engineering. The interviews consisted of 10 open ended questions related to:

1) *Current KM challenges for each functioning team*
2) *Effects of KM challenges on day-to-day activities*
3) *Overall impact on the organisational KM*
4) *The required KM solutions to overcome challenges*

V. Findings

[redacted] *Industry Challenges*

Although the interviews, observation and focus group discussions were specific to the companies' processes, it is worthwhile highlighting some of the challenges in the industry as a whole. These challenges provide a critical part of understanding some of the organizational factors highlighted in the interviews that may affect knowledge management at the collaborating company:

- In aerospace industry, businesses are primarily based on a systems integrator model. This means that although the company manufactures original novel designs of their own, a large proportion of the assembly cells observed are based on integrating systems designed inhouse but produced or manufactured by other partners including other company approved facilities, suppliers, and manufacturers.

- The supply chain provides a significant proportion of substytems and component designs and in many cases complete assemblies that the company assembling them, also specifies, purchases and integrates its data into the PLM systems used.
- Unlike other industries, a large proportion of parts, systems, and electronic circuitries are of high value, high technology and bespoke (made to order) articles. This makes the process of identifying root causes much more complex than normal mechanical parts.
- Unlike many other industries that manufacture complex systems, the production of aerospace parts/assemblies run only 5-15 projects at a single time. This includes building, testing, and readiness assessments to incorporate into larger avionic products that may not be accessable at the time of design and manufacture.
- The type of volumes this industy works at particularly for smaller sized systems going into larger avionic products can be in the region of 10-20 per month; classifying it as a low volume output manufacturer.

[redacted] *KM Challenges*

The interviews have shown some interesting results. 27 primary challenges were identified. 67% of which were direct knowledge management challenges. 47% of the KM challenges highlighted issues in the way the designs are being manufactured. These were labeled as DFM challenges. The other 53% of the KM challenges highlighted issues in the way that PLM data is handled amongst the organisation (See figure 1 below).

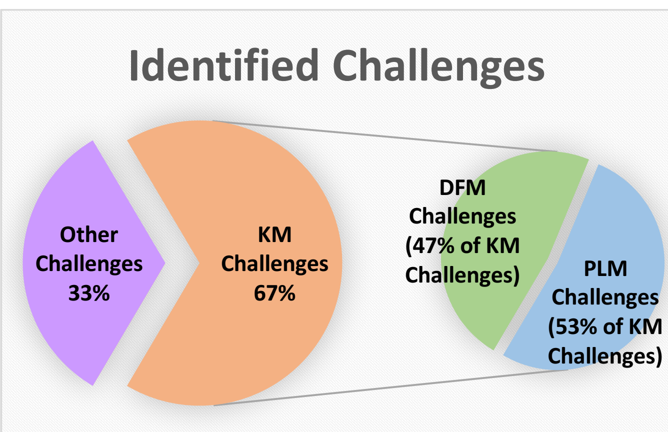

Figure 1. Percentages of DFM and PLM Challenges amongst the overall identified KM Challenges in the interviews.

The common themes across all interviewees suggest a strong link between the knowledge management challenges identified, and some of the organisational factors influencing them. Management members of the Technical Team, Supply Chain, Mechanical Engineering, Commodities, and Project Management have all suggested a need for improvement in the transfer of manufacturing process knowledge into the design function and vice versa. One interview suggested that the change requests for design engineers, raised in production, are difficult to follow up due to production engineer's commitments to production and the design engineer's commitments to engineering. This interview also reported that defects logged often lack descriptions that others can make use due to how data is captured. This drives engineers to access some of the knowledge stored in people's memories as opposed to using the data given.

Another interview reported that manufacturing defect reporting process does not have a driving mechanism that could aim at improving processes due to a shortcoming in route cause identifications. This also is due to the size of the data produced at each production cell. This is also the case with the lessons learnt database that also lacks granularity when reviewed by the various teams at the end of projects, making it very hard to trace back and dig deeper into the details of each part's contribution to a particular lesson learned outcome. Another interview supports this view by acknowledging that there is a lack of understanding of the impact of minor quality defects across the products' lifecycle. This is due to the human's judgement of the defect at a single point in time without having complete visibility of how much that particular defect has had an impact on the business in the past and future in terms of quality, cost and delivery. With persistent customer and time pressure, change control mostly aims at resolving major issues with parts as a constant priority and minor defects may not see the same attention given.

In addition, the project management function is under a large amount of pressure. An interview reported that cross-functional engineering tasks require project managers to communicate the different types of knowledge attained to different types of engineering teams as opposed to accessing knowledge through IT. Expert knowledge of designs and expert knowledge of manufacturing processes is not always stored within the IT systems and this requires project management to know who to communicate with for extracting knowledge of DFM resolutions. A solution is required that can systemically align manufacturing process improvement knowledge with the design engineering activities in order to reduce re-occurring defects in the future without having to rely on human's tacit knowledge stored by individual's experiences.

Furthermore, continuous improvement methods have also been a topic of interesting discussion amongst the interviews. An interview suggests that although incentives are widespread across the organisation to implement certain DFM improvement projects. The process can only support and facilitate - it needs to be developed so that it is driven by engineers in the organisation. The cause for this is due to the lengthy data streams behind the continuous improvement projects and the difficulty required to align DFM improvements (such as design or manufacturing process) with the functional responsible team. Often continuous improvements is treated separately to the defect data although in many cases the defects were the reason for raising a continuous improvement project in the first place. It's difficult to relate both data sets from engineering and manufacturing to a DFM outcome based on both types of knowledge as well as traceability of the data to the right people (such as process or design originators/owners)

[redacted] *DFM Knowledge feedback Cycle*

Interviews with the engineering management as well as the manufacturing engineering teams have reported that some of the occurring defects fixed on the production line in the past may re-occur in another time period in the manufacturing of the same product or other products with similar processes or parts. A classic example was given of a particular gluing process on components that are required to be fitted without fixtures or fasteners. The example discussed here showed that some production engineers have previously resolved this defect by a process improvement approach. Yet sometime later when the product is re-ordered or a similar process is carried out on another product, the same amount of learning and effort may take place again without first-hand knowledge of the resolution implemented previously. In many cases process experts may be called in to support. This suggests that although DFM solutions are being constantly implemented in the production cells, the tactical resolution that could potentially eliminate that particular defect amongst the entire organisation remains a challenge due to difficulties accessing previous knowledge attained and limited communication of it.

The discussion went further into detailed conversation about the process of managing the DFM knowledge attained from defects. It was found that the actual data input relating to defects are mostly captured for the purpose of logging, documentation and quality control and do not have a feedback feature designed to implement process control specifications in the design data. Although these defects are internally managed in production, the amount of similar defects may continuously be logged into the master quality data management systems. This makes the list of re-occurring defects extremely long and exhaustive to search through or group classify them for a tactical fix across the entire organisation. This results in putting a big strain on the people in the organisation to prioritise the communications of knowledge through production meetings and product reviews in order of importance, making many of the smaller issues slip to re-occur again later.

[redacted] *Knowledge Sharing Barriers*

The challenges reported in the findings above require the development of a systemic method of gathering manufacturing defect data and classifying them into DFM recommendations. This must then be also systemically fed back to the design engineers working on both existing products and new product development for maximum benefit. From an organizational point of view, for the knowledge management approach to be optimal, effective and operational, some knowledge sharing barriers need to be considered and also addressed in the design of the system that would implement such approach. From the interview data, 8 different types of barriers have been concluded that hinders the sharing of DFM knowledge for implementation. The findings have also been validated by further discussions in the focus groups:

1. Prioritization: when projects are mobilized (bid ended and project starts), a timeframe is allocated, usually placing the project and design engineering teams under pressure to deliver on time. This results in an organization very customer project oriented and may not provide motivation to engage with any available data from the production line to be reviewed for carrying out DFM.
2. Perception: improving design for manufacturing on ongoing projects may not particularly be seen as a primary opportunity in the business but rather a support activity to aid production when needed. In order to overcome this barrier, DFM implementation needs to be widely recognized as a means to reduce cost, positively impact the business, and as a standard expectation from the teams involved.
3. Distraction: process improvements for DFM based on lessons learned or knowledge transfer may be seen as a diversion from achieving the main targets of the engineering activity; limiting resource allocation for it particularly when projects are urgent. This is supported with the gap found of not having enough understanding of the impact of re-occurring defect and its subsequent impact post DFM implementation.
4. Measurement: DFM resolutions, process improvements, and defect fixes at the production cell may not be seen reflected as a performance indicator that reflects engineering implementation.
5. Data Structures: day to day difficulties often caused by the complex nature of the types of systems manufactured in the aerospace industry results in a large amount of data input at different stages of the lifecycle and by different people. This may drive a culture reliant on human communications by responding to certain problems at one time. Data needs to be structured for quick, easy, and effective implementation of DFM methods at any given stage of the lifecycle.
6. Missing Knowledge: Route cause investigation are more often carried out on major defects and can be carried out as production lines become more mature on minor defects. When a production line is committed to a delivery deadline, historic route cause investigations are no longer prioritized. Additionally defect data often reports the visible symptoms but may not be allocated a resource to discover its route cause if a strategic resolution is implemented as opposed to a technical one. This can often be the case by changing a batch of defective components to another, or a supplier to another without allocating defects to any particular technical process causes. Additionally, resolutions implemented at other production lines may not be communicated across the organization without a need to; making it very difficult to build knowledge blocks that can be used for future DFM implementations or reviews.

VI. Conclusions and Recommendations

This paper analyses some of the organizational factors in the aerospace industry in order to improve DFM implementation in a knowledge intensive collaborative environment. The main findings show that although there are many approaches in literature and in industry that improve Knowledge Management for Collaborative Environment – the communication of knowledge particularly in engineering projects has still got some major limitations. The main challenge is being able to capture, process and make use of quality defect data on the production line in order to provide engineers a knowledge repository that can be accessed to improve DFM implementations. In order to achieve that a system design must consider the challenges of the industry as a whole. This includes considering that many of the parts designed in house are manufactured by third parties. This must be accommodated by allowing the defect data to have access to some of the data held at the third party suppliers in order to identify the root causes. In addition, the interviews at the collaborating company have shown that looking at defect data to identify improvements is limited due to the amount of data being captured across the business and the exhaustive effort needed order to extract useful knowledge. Other knowledge found in individuals whom have been involved with resolving defects using DFM methods does not have the facility to elicit either.

Additionally the process of capturing data is not currently purposed for extracting knowledge for engineers. In order to do that, the defect data process needs to allow classifications of defects based on critical design or manufacturing factors that the engineers can begin reviewing for carrying out DFM. From an organizational point of view it was found that there six challenges that need to be addressed in order to design a new knowledge feedback system. The system must have the same priority as the typical design activities or must sit in the engineering lifecycle as a standard procedure for new product design. The extraction of knowledge was found to be a challenge for most departments. A new mechanism for extracting knowledge must allow potential users to use the system with ease as well as seeing the impact it has on the engineering or manufacturing activities. The way that quality defects are captured need to have an ontology that can link them to the engineering lifecycle for further investigation of DFM resolutions.

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