and timing of its output and essentially describes the ability to process variant products (Matthews *et al.,* 2006). When considering the overall manufacturing capability, flexibility has the two dimensions, *range* and *response.* The *range flexibility* states what a manufacturing system can adopt in terms of number of different products and output levels - termed product flexibility and volume flexibility; the *response flexibility* describes the ease with which a system can be adapted from one state to another - termed delivery and mix in Slack (2005). This response flexibility must be considered in terms of time, cost and organisational disruption. In general flexibility offers the manufacturer some degrees of freedom to take advantage of demand opportunities and simultaneously provide an ability to reduce losses (Bengtsson, 2001).

Whilst attempts to improve particular aspects of, for example, the product design or the manufacturing process can lead to improvements in the areas of either quality, efficiency or flexibility, it is ultimately the sum of all systems, actors and inputs associated with the realisation of the product that determine levels of quality, efficiency and flexibility. Hence, manufacturing capability is dependent up on an organisation’s people, its processes, its products and its practices (cf. Figure 1b). Achieving a high level of manufacturing capability and the attainment of high levels of performance within each of the these areas is frequently associated with the notion of ‘World Class Manufacturing’ Maskell (1991). Whilst at a given point in time an organisation may be performing at a high capability level it is the ability to sustain an optimal or near optimal level that is the characteristic of a truly world class organisation. Hence, the notion of world class manufacturing and ‘world class’ organisations is more about the ability of an organisation; its people, processes, products and practices (cf. Figure 1b), to adapt, improve and evolve within the context of the changing business environment (cf. Figure 1c) (Riek *et al.,* 2006). This ability to respond and adapt is becoming of increasing importance as product complexity increases (Sommer, 2003); customer demand for product variety increases (Jiao and Tang, 1999); product lifecycles shorten (Christopher and Peck, 2003); legislation concerning areas such as materials (European packaging and packaging waste directive 2004/12/EC), emissions (Ambient air quality assessment EC Directive 96/62/EC) and Health and Safety (European Machine Safety 98/37/EC) tighten; supply chains and customers become global (Gelderman and Semeijn, 2006).

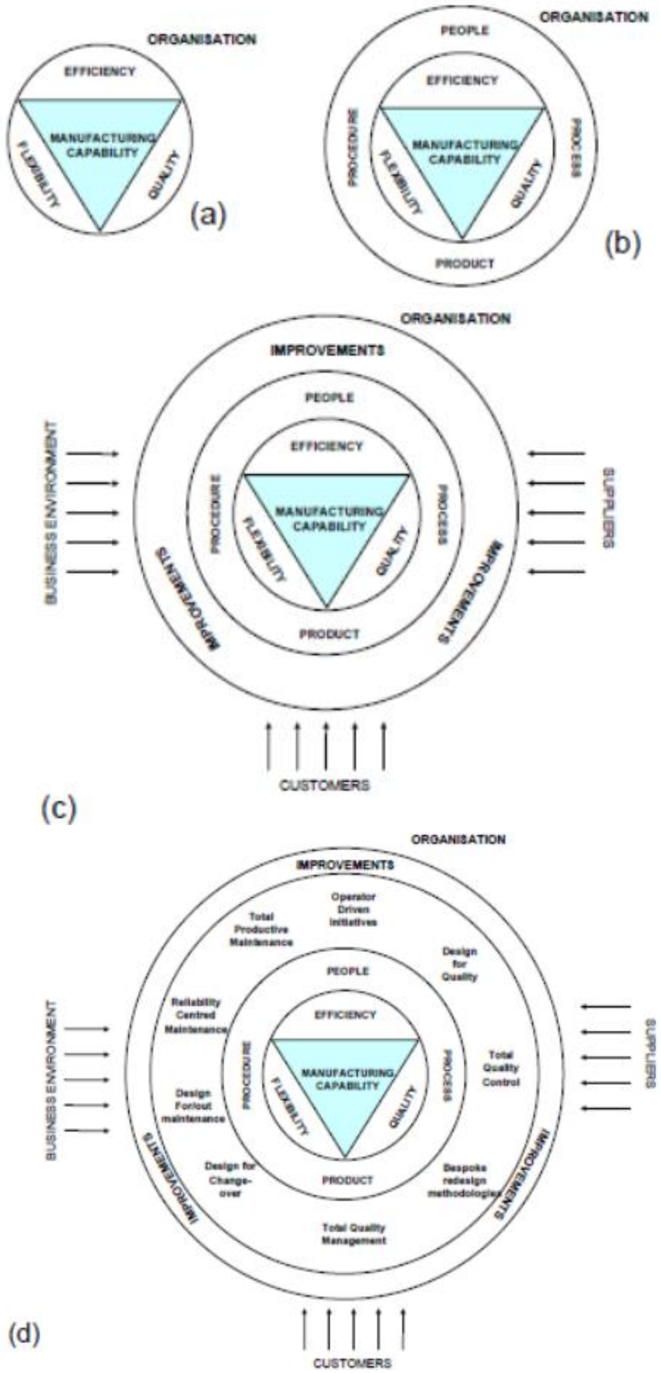

Figure 1 Manufacturing capability, the organisation and the business environment

As a consequence of the influence of people, products, processes and practices on an organisation's manufacturing capability there exists a wide variety of tools, methods and approaches to deliver targeted improvements in a particular area. However, in many cases the improvement projects fail to meet expectations and in extreme cases can fail to deliver any improvement or bring about new less well understood problems (Hicks *et al*., 2002).Furthermore, of those that do deliver improvements many are short-term (Keating *et al.*,1999) and the improvements are lost when there is, for example, a change of staff, variation in materials or process inputs, altered practices, the introduction of new equipment or yet another initiative. From an organisation's perspective these programmes not only require an investment of many tens or hundreds of thousands of pounds (Chapman *et al*., 1997; Keating *et al.*, 1999; Sterman *et al.,* 1997) but in the case of failed initiatives incur an indirect cost which can represent a magnitude of cost and lost opportunity which far exceeds the cost of the original improvement programme. For example, optimising setup and process parameters could make the manufacturing system sensitive to variation in inputs, e.g. materials, and result in significant downtime.

For these reasons and to ensure long-term success, manufacturing organisations need to possess a functional and holistic understanding of the production systems and the variety of tools, methods and approaches for improvement (cf. Figure 1d) in order that they may be successfully applied and reapplied within the context of the changing business environment. Furthermore, as previously stated, it is the ability of an organisation; its people, processes, products and practices to adapt improve and evolve within the context of the changing business that enables it to be 'World Class'. A prerequisite for achieving this is the means or capability to generate the fundamental understanding necessary to respond appropriately. It is the critical dimension of understanding and the creation of methods for generating the necessary understanding that is addressed in this paper. This paper firstly explores the motivations for manufacturing improvement and examines in detail the principles and underlying knowledge requirements of a range of common improvement paradigms. The barriers to realising sustainable improvement are then discussed and the importance of generating and communicating a fundamental understanding is highlighted. The need to support organisations in reinforcing and extending their fundamental understanding is further argued and the deficiencies in existing supportive techniques are described. In order to overcome these deficiencies the concept of machine-material interaction is introduced and its relationship to 'function' and fundamental understanding is discussed. The paper concludes with the development of a set of requirements for a new supportive methodology which enables machine-material interactions to be investigated, and the necessary fundamental understanding to be developed and contextualised with respect to the knowledge requirements of a range of common improvement paradigms.

II. IMPROVEMENT PARADIGMS

There are a wide variety of approaches and philosophies associated with the improvement of manufacturing and production systems. These higher level paradigms generally involve a range of tools and methods to target, plan and implement an improvement programme. For the purpose of considering these various philosophies and their corresponding tools and methods (Brassard and Ritter, 1994), the approaches and the methods can be grouped under the seven areas of: equipment design/redesign, maintenance, operator-led, process-control, product modification and new product introduction, quality, and tooling design and changeover. The various manufacturing paradigms and the corresponding tools and methods that can be associated with each of these seven areas are illustrated in Figure 2 and described in detail in Tables 1 and 2. Of particular interest in this work are the underlying knowledge requirements necessary to successfully apply the various tools and methods. These requirements are developed in Tables 1 and 2 from a discussion of the aims and underlying principles of the various tools and methods, and are now summarised.

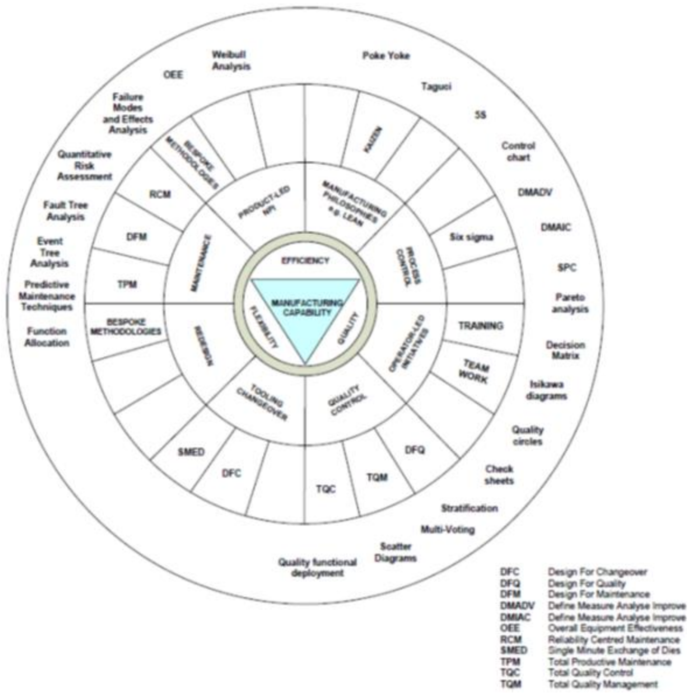

Figure 2 Manufacturing improvements paradigms and their corresponding tools and methods

1. Process Control - As levels of automation increase and in particular, the automation of changeover and machine setup so does the need to possess the understanding necessary to explicitly define setup rules and parameters. Intelligent monitoring and control has been successfully applied in Component manufacture (Uraikul et al., 2000, Murdock and Hayes-Roth, 1991) and Machining processes (Liang et al., 2004 and Hou et al., 2003) but requires in-depth knowledge of the relationship between product variation and process variation - both upstream and downstream. Central to the success of these methods is the need to understand and describe the acceptable variation in product attributes during all stages of production.

2. Operator-led - One of the key elements to the effective operation and improvement of a production system is the successful training of the operating staff (Woodcock, 1972). Training is imperative to ensure changes to working practices and operating procedures are effectively taken-up. For effective training to be delivered the trainer needs to possess an in-depth understanding of the content (Davis and Davis 1998), which in the case of manufacturing improvement concerns both the tools and methods for improvement and the production system(s). Further, the content and learning outcomes of the training have to reflect good-practice or at least improved practices, which must be determined in advance. Central to the success of the training is the need to **develop a common and shared understanding** across all the trainees in order to generate the same intended learning outcome(s). This is necessary to ensure consistent practices and in particular, consistent operation of equipment, control of materials and the adoption of appropriate machine settings to maintain quality and avoid excessive wear (Adebanjo and Kehoe, 2001).

3. Maintenance - The ability to keep a manufacturing process efficient depends heavily upon good work practices and effective maintenance. This is particularly important in today's just-in-time production environment, where as a consequence of reduced stock level minor breakdowns are even more likely to stop or inhibit production (Eti et al., 2006a) and reduce overall equipment effectiveness (efficiency). There are two approaches for achieving this. The first is preventive maintenance which aims to reduce the probability of failure in the time period after maintenance has been applied. The second is corrective maintenance, which strives to reduce the severity of equipment failures once they occur (Loftsen, 2000). As noted by Waeyenbergh and Pintelon (2004) industrial systems evolve rapidly so maintenance initiatives will also have to be reviewed periodically in order to take into account the changing systems and the changing environment. This calls not only for a structured maintenance concept, but also one that is flexible. There are a variety of maintenance improvement methods including Design for Service (DfS) (Dewhurst and Abbatiello, 1996), Total Productive Maintenance (TPM) (Willmott, 1997) and Reliability Centred Maintenance (RCM) (Smith, 2005) which arguably focus on the design, the operator and the engineering function respectively. These various approaches depend on both the management and the operators possessing an understanding of: the function of the process, the influence of machine settings on process performance, the impact of wear on the process, and the effect of operating conditions (production rate and environmental conditions).

4. Quality - In a similar manner to maintenance there are a variety of methods and initiatives that support quality control, improvement and assurance.

These include Quality Function Deployment (QFD) (Govers, 2001), Total Quality Management (TQM) (Oakland, 2003) and aspects of Six Sigma.(Adams et al., 2003) These various approaches require an understanding of function and its relationship to quality, an understanding of the interaction between the process and product, which are essential for directing the measurement, analysis, improvement and control of process and process inputs (materials and staff) (Thomas and Webb (2003) and Antony (2007a; 2007b)).

5. Tooling design and changeover - The ultimate aim of improving tooling design is to improve production performance and in particular flexibility without compromising efficiency. Key to achieving this is to determine the most appropriate design or configuration of tooling and, if appropriate, the most efficient methods for changeover between tooling configurations (i.e. minimising changeovers and/or changeover time). This includes both the physical geometry (size, profile and number of) and control of the tooling (kinematics - motion, velocity and acceleration, timing and clearances) (Hicks et al., 2001).Central to the success of the Single-Minute Exchange of Die (SMED) (Shingo, 1985) or Design for Changeover (DFC)
(McIntosh et al., 2001). activities is the need to be able to **understand and specify in advance the machine settings** (setup point) **and range of variation** (run-up adjustment) necessary for the successful processing of each product variant.

6. Equipment redesign, modification and replacement - Where an increase in manufacturing capability is sought that exceeds the existing equipment or process capability it is necessary to either modify or replace the equipment. In cases where the process and the design principles which underlie the equipment are identified to be close to their limits then a process and equipment redesign may be necessary (Hicks et al., 2002). In either case – modification, replacement or redesign – it is a prerequisite that both capability and functional requirements are determined. Central to determining these requirements is the need to understand the limitations of the existing equipment (Matthews et al., 2007, Ding et al. 2009). The factors that limit the capability can be inverted in order to define the rules which are necessary for successful processing. This understanding is central to realising redesigned or new equipment that overcomes the limitations of existing equipment and ultimately improves performance (quality, efficiency and/or flexibility and capability). The rules also provide a series of objective measures for the evaluation and assessment of new equipment (Matthews et al., 2008).

7. Product modification and new product introduction - In today's dynamic global markets, goods manufacturers are frequently faced with the task of processing new or altered products – such as new sizes, new materials and modified configurations (Matthews et al., 2009). Central to achieving this, is the need to determine an appropriate set of machine settings that enable the product to be successfully processed. No matter whether it is the determination of settings for a new product or the improvement in process capability through product modification, it is necessary to **understand the capability of the production process and its relationship with the properties and characteristics of the product** (Frey et al., 2000).

8. Other manufacturing philosophises - In addition to these seven areas of manufacturing improvement there exist a number of philosophies to support improvements in manufacturing and management. These include lean thinking and Business Process Reengineering. The term 'lean' was coined by Womack et al. (1990) to describe the main aim of the philosophy - the reduction of waste throughout a company's value stream. However, for some lean promoters it is not just a set of
tools for the reduction of waste (Bicheno, 2003), but a way of thinking which puts the customer first. Once this way of thinking is adopted, lean tools are available to reduce waste and improve benefits for the customer. For the successful adoption of a lean approach a functional perspective of the production systems is required in order for value streams to be identified and mapped, and to ensure that value streams flow. In a manufacturing context, function is the only means to add value to the product. Although not all functions may add value. In contrast to lean, business process reengineering or business process redesign (BPR) focuses on improving the efficiency and effectiveness of the overall business processes that exist within and across an organization. This is achieved by

establishing the processes and assigning responsibility for those processes to dedicated teams and, where appropriate, systems
(Hammer & Champy, 1993).In order to maintain and improve processes an understanding of the functions and processes and the value of each function must be elicited. The previous sections have discussed the various manufacturing improvement paradigms and corresponding tools and methods with respect to their underlying principles and the knowledge and understanding that underpin their use. Further examination of the knowledge requirements reveals six fundamental knowledge concepts relating to the improvement of manufacturing systems. These include: 1. An understanding of the relationship between the properties and characteristics of the product, and the machine and process settings. 2. An understanding of the relationship between product variation and process variation, and their influence on quality, efficiency and ultimately capability. 3. An understanding of the influence of operator procedures on quality, efficiency, flexibility and ultimately capability. 4. An understanding of the impact of wear and operating conditions (production rate and environmental conditions) on quality, efficiency and ultimately capability. 5. An understanding of the limitations of the existing equipment (quality, efficiency, flexibility and capability). 6. A functional perspective of the production system that contextualises the process and its operations with respect to the final product. It is arguable that these six knowledge concepts are critical for effective implementation of improvement programmes and that they are hence a prerequisite for realising sustainable improvement. In order to explore this further the barriers and root causes of failed or partially successful organisational improvement programmes are reviewed.

III. BARRIERS TO REALISING MANUFACTURING IMPROVEMENT

While there exists a plethora of publications presenting the successful implementation of different manufacturing improvement strategies (Antony and Banuelas, 2002; Henderson and Evans, 2000; Sohal et al., 1998; Chan et al., 2005; Bamber, 1999; Apte and Goh, 2004; Brown et al., 1994) the experiences of the authors and those of the practitioners we have worked with are that many initiatives fail to meet expectations and can fail to deliver any improvement at all. Furthermore, in extreme cases these initiatives can have a detrimental impact on capability or bring about new less well understood problems. This can result in an indirect cost to an organisation that represents a magnitude of cost and lost opportunity that far exceeds the level of investment in the original improvement programme. The existence of only partially successful and failed initiatives is supported by past and contemporary literature, an example of this being Redman and Grieves (1999), who noted that between 70- 90% of TQM programmes implemented have failed.

In order to provide some insight into the common causes of partially successful and failed initiatives - and what can be thought of as the barriers to successful implementation – literature from the fields of manufacturing, management and information systems are critically reviewed. These fields are selected because of the considerable bodies of work that deal with process improvement, change management, information systems implementation and production systems. An appraisal of the literature reveals six core areas: lack of commitment, reactive organisations, layered initiatives, incomplete implementations, incorrect implementations and resistance to change. These six dimensions are shown in Figure 3 and discussed in the following sections.

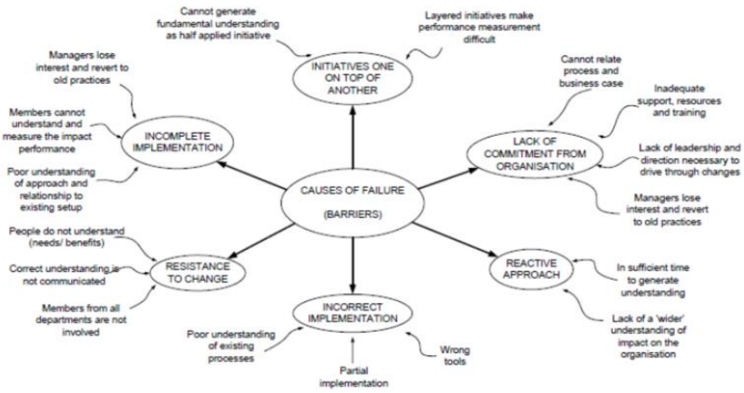

Figure 3 Causes of failure and barriers to realising manufacturing improvement

3.1 Lack of commitment from the organization

One of the most common causes for organisational improvement programmes to fail is the lack of commitment from the organization (Tari and Sabaner, 2004; Sterman et al., 1997; Olivia et al.,

1998; Mellor et al., 2002). This can lead to inadequate support infrastructure or training in improvement techniques, thereby limiting the potential for successful implementation (Keating et al., 1999). Top-down organisational commitment is imperative to successful improvement programmes, although, McIntosh et al. (2001) argue that the focus is often heavily concentrated on organisational-led improvement and that the benefits of product/ process design amendments are often considerably under-exploited. If those responsible for the allocation of resources are not well informed about the pros and cons of the implementation programme, it is highly likely they will underestimate the effort, in terms of time and cost, needed for the successful completion of the project (Wilkinson et al., 1998, Tari and Sabanter, 2004). In the field of business transformation and Enterprise Resource
Planning (ERP) a lack of commitment is also highlighted as a common cause of failure. This includes both lip service from senior staff and a lack of engagement from middle management (Buckhout et al., 1999; Whittaker, 1999).

3.2 Reactive approaches

In the dynamic business environments of today where resources are already stretched it is common for organisations to adopt a reactive approach, always “fire fighting” issues such as quality and efficiency. Research by Olivia et al. (1998) showed that such a reactive approach not only assisted the failure of specific initiates but caused profound effects on other functions in the organisation such as product development, pricing and human resources. Overzealous application of quality tools has led to declining effectiveness and a backlash that damages even the effective programmes in many companies (Keating et al., 1999). Eti et al (2006b) show that chemical plants employing reactive strategies of maintenance are incurring maintenance cost of 5% per annum of the asset-replacement cost, in lost productivity i.e. wastage of $30,000 per $M of asset value, this in comparison to companies employing proactive strategies who are seeing 25% savings on these values. Furthermore, with increased adoption of Total Quality Management approaches and reduced stock level due to just-in-time work practices minor breakdowns are even more likely to stop or inhibit production (Eti et al., 2006a). Because of this, reactive maintenance approaches such as run-to-fail or breakdown are becoming less common, and are only employed in areas that do not result in increased expenditure (Mostafa, 2004). It therefore follows that initiatives, such as those involving quality can rarely be implemented in isolation. Rather, they need to be implemented as part of an overall improvement programme, which in the aforementioned case of quality also includes reliability.

3.3 Layered initiatives one on top of another

The reactive approach discussed in Section 3.2 can also contribute to organisations implementing multiple improvement initiatives concurrently. This makes the lifecycle of the implementation difficult to identify (Irani and Love, 2001) and the tasks of planning, implementation and monitoring difficult. Although research has shown that quality and productivity improvements need to occur together for organizations to maintain or improve their competitive position (Chapman and Hyland, 1997), particular initiatives need to be completed so that their effect can be understood (Bessant et al., 2001) and the concurrent initiatives need to be carefully coordinated. In the field of manufacturing, Wilkinson et al. (1998) identify that a lack of understanding and structure when implementing multiple quality improvements leads to situations that are considered ‘indigestible’ for those on the receiving end of management”. In essence, employees struggle to differentiate between improvement initiatives, so tend to have cursory ‘buy-in’ to the process, or implement initiatives incorrectly.

3.4 Incomplete implementations

A common cause of underperforming improvement initiatives can be attributed to incomplete implementations. This includes partial implementation of an initiative, implementations which have not been fully implemented across the entire organisation and implementations which have not been integrated within the business strategy and processes. The consequences of this are that either little or no measurable performance improvements can be identified and organisations need to maintain their existing systems and processes – effectively maintaining two parallel processes (Hicks et al., 2006). These issues are further frustrated by the fact that there is normally deterioration in performance measures when such programmes are up-andrunning (Carroll et al., 1998). This again causes managers to lose faith in the programme and withdraw to the existing working practices. Haley and Cross, (1993) noted how some managers saw the implementation of quality improvement paradigms as a 'fashion statement'. Redman and Grieves (1999) also reviewed multiple sources of TQM failure through the 1990's and indentified that incomplete implementation was the most common cause.

3.5 Resistance to change

Resistance to change has been widely reported as one of the key barriers to successful implementation of business process transformation and improvement programmes (Rees, 1991; Marchington et al., 1992 and Hill 1991). Whilst senior managers appear to be committed to quality improvement strategies, it was the middle and junior managers that were resistant to such programmes. Middle management see the implementation of such programmes as both labour and resource demanding (Wilkinson et al., 1992), whereas junior management thought it would "reduce their discretion" in the current job roles. From the shop floor viewpoint, almost every book, and academic publication presents the issues of operator 'buy-in'. If the members of the shop floor, who are to be the hands-on users of such processes, do not understand them or the benefits to themselves, the implementation is bound to falter (Schaffer and Thompson, 1992). In addition to this, previous research highlights shop floor suspicion as a barrier when using performance measures as indicators of success of implementation (Ukko et al., 2007). The perception being that the implementation of such programmes only benefits management, and have little impact on the welfare of the shop floor staff.

3.6 Incorrect Implementation

The most commonly reported reason for unsuccessful implementation of is that of incorrect implementation (Taylor, 1997; Nwabueze, 2001; Redman and Grieves, 1999; Regle et al., 1994; Miller and Congemi, 1993). This can include the inappropriate adoption of a particular tool, method or process given the industry sector of the organisation and its existing business processes (Beer et al., 1990), and the incorrect tailoring of the tool, method or process to the business; its processes, people, procedures and products. For example, where ERP systems are considered the alignment of fit to an organisation is critical for success (Holland and Light, 1999; Bingi et al., 1999) this includes both the level of business process reengineering necessary and the amount of customization (tailoring) of the system that is necessary. Where quality programmes are considered, Guptara (1994) highlighted how quality guru's can raise awareness of quality issues; however they rarely provide the tailored mechanisms to integrate improvement programmes within the organisation and this can eventually lead to incorrect implementation.

3.7 The root cause of failed implementations

When considering the causes and consequences of the six areas detailed previously, it is becomes apparent that many arise as either a result of a lack of understanding, an inability to communicate understanding, an inability to generate the necessary understanding. Where this understanding relates to the system, its intrinsic processes, external interactions, the wider environment and the product of the process itself. For example, in the case of resistance to change the primary causes are a lack of understanding, a lack of communication and lack of inclusion – which ultimately leads to lack of shared understanding. In the case of layered initiatives the consequences are an inability to elicit the ore understanding and difficulties in performance measurement – which ultimately influences understanding. Given the aforementioned argumentation it follows that in the context of manufacturing improvement, the underlying root cause of failed and suboptimal initiatives can be largely attributed to the level of understanding of the relationship between the production system, its constituent processes, raw materials and the product. As previously stated, it is this understanding that is necessary for effectively implementing improvement initiatives and determining the optimum mix of tools and methods to generate the maximum benefit. The importance of understanding has been recognised implicitly by researchers; however, addressing this deficiency has been largely overlooked. For example, a weakness of Reliability-Centred Maintenance is that it is not always as analytically rigorous as for all reliability-based analysis and hence is not developed upon a fundamental understanding but rather a simplified or Bayesian approach (Sivia, 1996). Where quality initiatives are considered there is a tendency to hire Total Quality Management (TQM) consultants to visit for a half-day or so to start the process. This puts incredible pressure on managers since they have little ongoing access to the expert help they need to make this work. Also, some activities that are part of TQM are best carried out by "outsiders" who bring a different kind of objectivity to the process and may help in developing the necessary understanding.

IV. GENERATING A FUNDAMENTAL UNDERSTANDING

In the previous sections it has been shown that the majority of manufacturing improvement approaches and tools require a fundamental understanding of the production system - including its constituent processes, raw materials and the product - and that the barriers to successful implementation can be considered to relate to either a lack of understanding, an inability to generate understanding or an inability to communicate understanding. Furthermore, in today’s dynamic business environments where products, materials, processes and staff continually change, organisations must continually reinforce and extend their understanding. The ability to increase and evolve understanding depends heavily upon tools and methods which support the generation of understanding. For these reasons, it can be argued that a prerequisite for realising sustainable process improvement is fundamental understanding and in particular, an ability to generate understanding. In the context of manufacturing improvement there exist a variety of tools and methods which can be considered to support the development of understanding. These include methods such as Root Cause Analysis (RCA) (Ammerman, 1998) Fault Tree Analysis (FTA) (Vesely *et al.*, 1981), Failure Mode Effect and Critical Analysis FMECA (Stamatis, 1981) and Value Stream Mapping (VSM) (Rother and Shook, 1999). FMECA and FTA are based on the investigation of errors and their causes, and are employed in the product lifecycle’s idea identification, development and manufacturing phases (Pisano, 1997). However, their scope is limited as they are only generally applied to investigate observed failure and its impact, not why it has been observed. Although this is partially addressed by Root Cause Analysis, where there is investigation into why the failure happened, neither method adopts a functional view that contextualises the failure with respect to the intended function and the final product. In contrast to these failure driven approaches, customer focused techniques such as *Value Stream Mapping* do adopt a more functional perspective and attempt to identify what action adds value to the product (Rother and Shook, 1999). However, this is also limited as it does not consider how to assure value levels and whether the levels of value are maintained, only that it flows. From a manufacturing organisation’s perspective it is necessary to have an in-depth understanding of the production system, its constituent processes, raw materials and the product. This perspective must be interdisciplinary (maintenance, operators, quality, materials etc) not just a single perspective such as engineering. Furthermore, the developed understanding needs to be contextualised with respect to the overall production system, product and function. The organisation needs to focus on observed failure (reactive) and possible failure (proactive) this includes the various dimensions of quality and efficiency and their relationship to the production system, its processes, materials and the product.

V. INTERACTION, THE KEY TO FUNDAMENTAL UNDERSTANDING

In the context of manufacturing systems the relationship between the various factors of machine, products, process and materials is defined at the interface during physical interactions between the machine and materials. These machine-material interactions occur where a machine component physically interacts with, or influences, the product and any of its constituent elements. This includes the entire product lifecycle from the processing of raw materials to the assembly of the product, packaging operations and materials, collation and product handling, and eventually disposal and recycling. One specific factor that is evident from the review in Section 3 is that before an organisation can begin to make targeted improvements, implement change or identify the limitations of existing systems, it is first necessary to possess the fundamental understanding of product, process and their combined interaction. This understanding will ultimately provide the structure against which an organisation can reason about a system and thus, implicitly constrains the scope (potential) for realising improvements and for foreseeing and overcoming particular problems and conflicts. More specifically, fundamental understanding is a prerequisite for developing a complete description of the system, its function(s) and performance, the development of common terminology (definitions) and a structured representation (diagram) of the system, its internal relations, inputs and external influences. These elements provide the basis for communication and reasoning about the system and also provide a framework against which tools and methods can be aligned and targeted, and their effects measured. The latter of which is essential for determining the appropriate (optimal) mix of tools and methods which generate the maximum benefit for an organisation. It follows that there is a need to support the investigation of MMIs as not only a means to introduce a specific improvement but to provide support in the generation of the fundamental understanding necessary to best use the various tools and methods to bring about successful improvement (change).

5.1 The requirements for a supportive methodology

The previous section outlines the need to create a structured approach (method) that supports practitioners in auditing and investigating machine-material interaction and contextualizing the understanding generated with respect to the production system, its constituent processes, raw materials and the product. More specifically, the new approach needs to:

- Support the generation of the understanding and knowledge requirements that underpin common improvement paradigms (section 2.0).
- Address the barriers to realising sustainable improvement, and in particular the inability to communicate understanding (section 3.0).
- Overcome the limitations of current techniques for generating understanding and in particular the lack of a proactive approach and the inability to contextualise failure with respect to function (section 4.0). Through consideration of these areas eight core requirements can be elaborated for a new supportive methodology.

1. To provide a scalable and extensible method that provides the generation of a comprehensive and fundamental understanding of the entire production system, its operations, functions and interactions.

2. To support the development of common terminology (definitions) for machinery, operations and functions that is agreed by representatives from production, engineering, quality and operations and shared across an organisation.

3. To enable a formalisation of the understanding and the unification of appropriate interdisciplinary knowledge including materials, machinery and environmental conditions. This would provide an objective view of the process which integrates materials and machinery knowledge providing a means for different departments and groups to undertake objective discussion rather than adopting the cross department blame culture.

4. To provide a more complete description of process efficacy (efficiency and effectiveness) including measures of performance, quality and process failure (including observed and possible modes of failure) across the entire production system.

5. To enable the identification of the factors (including the properties, characteristics and settings of machinery, product and pack) that affect process efficacy and to elicit the important relationships.

6. To provide a structured representation (standardised diagram) of the system, its internal relations, inputs and external influences, which can be used to communicate and ensure all stakeholders have a common, shared understanding.

7. To enable the generation of qualitative and quantitative rules that govern the efficacy of functions (interactions) and define the properties and characteristics of the product, the machine and settings necessary to achieve desired levels of process efficacy. These rules may include for example limiting values, suitable ranges of settings and/or optimal settings for given products and/or materials.

8. To provide direction for the targeting of tools and methods for manufacturing improvement in order to deliver targets and sustainable improvements and maximise benefits. It is has been argued that these

requirements and a supportive methodology which meet these requirements would generate the understanding and knowledge necessary to effectively implement targeted improvements in the areas of process control, training, maintenance, quality, tooling design and changeover, redesign and replacement of machinery and new product introduction. To illustrate the importance and potential of a new supportive method the relationships between various common improvement approaches and the requirements (1- 7) are shown in Figure 4. In particular, Figure 4 highlights the importance of holistic understanding, adopting a functional perspective, determining a complete description of process efficacy and identifying the factors which affect it. It also highlights the importance
of 'rules' for maintenance and design-led methods and their benefit to quality based methods.

While the approach presented in this paper concerns

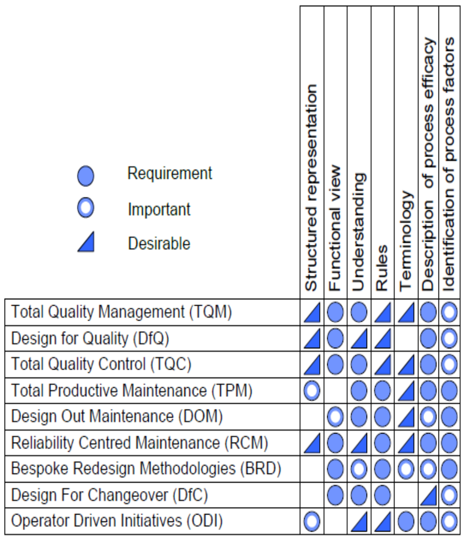

Figure 4 The knowledge requirements of common manufacturing improvement approaches

manufacturing systems the requirements and argumentation have been developed from a variety of fields including manufacturing, management and information systems, leading to a more generalised set of issues. Similarly, the proposed requirements of a supportive methodology are arguably of wider applicability than manufacturing systems alone. In particular, the interaction-centred approach could be applied to any systems that can be decomposed into operations and functions that interact or manipulate the product. This could include, for example, manual tasks, data processing and work flows. In fact, interaction diagrams have been developed within the UML framework to describe interactions among the different elements of a model. This interactive behaviour is represented in UML by two diagrams known as Sequence diagram and Collaboration diagram (Abdurazik and Offutt, 2000; Bauer et al.,2001). Sequence diagram emphasizes on time sequence of messages and collaboration diagram emphasizes on the structural organization of the objects that send and receive messages. While this form of diagram has been applied predominantly to software systems there may be opportunities for its application to production systems.

VI. CONCLUSIONS

This paper deals with the area of manufacturing (production) systems improvement and considers the issues surrounding the realisation of sustainable process improvement within the context of today's dynamic business environments. In particular, the motivations for manufacturing improvement have been discussed and the important relationship between quality, efficiency, flexibility and capability are described within the context of equipment design/redesign, improved maintenance, operator-led improvement, process-control, product modification and new product introduction, quality improvement, and tooling design and changeover improvement. Within these seven areas of manufacturing improvement the principles and underlying knowledge requirements of a range of common improvement paradigms are examined and six fundamental knowledge concepts are elaborated that can be considered to represent the understanding necessary to implement the various tools and methods. In addition to examining the knowledge requirements of improvement paradigms the barriers to realising sustainable improvement are also examined through consideration and review of the literature from the fields of manufacturing, management and information systems. These fields are selected because of the considerable bodies of work that deal with process improvement, change management, information systems implementation and production systems. This review reveals the importance of understanding and highlights the issues of a lack of understanding, an inability to generate understanding and an inability to communicate understanding as the root causes of failed and partially successful implementations. The issue concerning understanding and generating understanding are further examined through consideration of existing techniques that support the generation of understanding with the context of manufacturing. The limitations of these approaches and in particular, the lack of a *'proactiveness'* and the inability to contextualise failure with respect to function are highlighted. In order to overcome these deficiencies, within the context of manufacturing systems, the concept of machine-material interaction is introduced and its relationship to 'function' and fundamental understanding is discussed. Using the six fundamental knowledge requirements of manufacturing improvement tools, the barriers to successful implementation and the limitations of existing techniques for generating an understanding of manufacturing systems, a set of eight requirements for a new supportive methodology are developed. These requirements include the need for a functional perspective, an interdisciplinary understanding, common terminology, a complete understanding of process efficacy, identification of key relationships, a structured representation and the generation of qualitative and quantitative rules, and the need to provide direction for targeting improvements. To illustrate the importance and potential of a new supportive method that meets these requirements the relationship between the various improvement paradigms and the individual requirements are described.

VII. REFERENCES

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