Chapter 12
Design for Changeover (DFC): Enabling Flexible and Highly Responsive Manufacturing

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Abstract A highly flexible manufacturing capability is central to the paradigm of mass customisation. In turn the role of rapid, high quality changeovers is crucial to this capability, whereby production can be switched with minimal penalty across a full (and expanding) range of product offerings. Many companies will seek better changeovers principally by refining the way that personnel complete assigned tasks. Further improvement opportunity can be sought by amending the design of process equipment. By means of focused design improvement an inherently more flexible manufacturing system can become available, on which simpler, more repeatable and faster changeovers can routinely take place.

Abbreviations

CE	Change elements
DFC	Design for changeover
DFMA	Design for manufacture and assembly
DF-X	Design for X
MAS	Manufacturing Advisory Service
MAS-SW	Manufacturing Advisory service South West
OEM	Original equipment manufacturer
SMED	Single minute change of die
UK	United Kingdom

12.1 Introduction

Whether to serve *mass customisation* or the requirements of alternative paradigms of modern manufacturing practice, an enhanced changeover capability has long been acknowledged to have a key enabling role, permitting rapidly achieved production of alternative products from a company's full product range (Sethi and Sethi 1990). This chapter will briefly assess facets of mass customisation alongside those of alternative manufacturing paradigms, emphasising the significant role that a leading changeover capability has. It will then discuss that although various changeover improvement methodologies are in use by industry, these methodologies predominantly concentrate upon organisational refinement, most notably through seeking to externalise as many changeover tasks as possible. The use of design to assist changeover capability is argued to be undervalued. Although some authors have earlier discussed employing design to enable better changeovers

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(Smith 2004, Van Goubergen and Van Landeghem 2002), no comprehensive design for changeover (DFC) methodology is known to have been previously developed, beyond prior work published by University of Bath researchers (Reik *et al.* 2006a–c). The utility of other well known DF-X tools such as DFMA (design for manufacture and assembly) indicates this to be a potentially important omission.

In the years since initial publication (Reik *et al.* 2006a) the University of Bath team has significantly revised the basis of the DFC methodology, seeking to make it more repeatable in use and offering clearer guidance towards the most situation-relevant improvement opportunities. It remains a metric-driven methodology, but is now, as shall be detailed, more coherently structured to assist designers to realise key generic design improvement opportunities. The primary objective of the chapter is to summarise the revised DFC methodology. The chapter will describe the motivation for this work and provide an outline of the theory which underpins it. A summary case study is also presented to illustrate how the methodology has been applied in industry. Space restrictions, however, limit what can be presented and realistically exclude adoption of the methodology based only on what is written in the current chapter. For example, limited space prevents a comprehensive explanation of the mathematical analyses which generate the DFC indices, where the DFC indices in turn guide where iterative design improvement is most advantageously sought. Other important details have similarly had to be omitted but are available upon request to the authors.

12.1.1 Change Drivers: Forces to Change Manufacturing Systems

As well as seeking improvement to the cost, quality and delivery of their products, companies are also increasingly seeking a heightened ability to react to the many uncertainties they will inevitably encounter (Wiendahl and Heger 2003). That companies seek such an enhanced capability is reflected in the literature, with terms such as flexibility, responsiveness, agility, changeability and reconfigurability becoming watchwords of modern manufacturing (Slack 1990, Womack *et al.* 1990, Schuh *et al.* 2004, Kidd 1995). The better that a company (notably including its manufacturing processes) can respond to a changing environment, the greater the long-term commercial success it can expect to enjoy.

12.1.2 The Nature of Uncertainty

Research has been completed to understand the nature of the many uncertainties a business might face. For example, uncertainty has been investigated in mass customisation texts (Pine 1992, Tseng and Jiao 2001, Kaplan and Haenlein 2006), where manufacturing operations are encouraged that enable high levels of responsiveness to changes in customer demands. This in itself though is not sufficient, and the same business must also continue to react to changes arising from environmental, regulatory, economic and other influences (De Toni and Tonchia 1998). These many influences might all dictate necessary changes to a manufacturing system and can together be referred to as change drivers (Neuhausen 2001, Schuh *et al.* 2004).

Wiendahl and Heger (2003) differentiate between direct and indirect change drivers, proposing that many problems manufacturers face are indirectly forced upon them by erratic short cycle changes in one or more of the environment, society, politics and the world economy. They similarly cite that the research and technology resource that is available to the company can also be influential. With parallels to Wiendahl and Heger's work, Neuhausen (2001) distinguishes between external and internal change drivers, each of which have an influence on the design of overall manufacturing systems. Internal change drivers are revisions to company targets, the product programme or the product itself. External change drivers, on which the company has no direct influence, can likewise dictate necessary adaptation of manufacturing processes. Manufacturing systems can range from a single workstation through to global manufacturing networks combining several manufacturing sites, or even several co-ordinated manufacturing companies.

12.1.3 Changeover Assisting Business Response to Uncertainty

A company's overall product manufacturing programme for a forthcoming period defines the necessary capacity requirements for its production system. The design of individual products is similarly fundamental to the design of the production system, where each product must be capable of efficient manufacture. With a wide product offering it is almost inevitable that a company will undertake the manufacture of product families using common manufacturing facilities. These facilities require to be changed over as swiftly as possible and to the highest possible quality (Mileham *et al.* 1999), thereby ensuring minimal disruption as production in ever smaller batch sizes is pursued.

Any specific uncertainty, for example unforeseen patterns of customer preference or changing raw material cost, can impinge upon what product is offered and how that product is delivered, importantly including the manner and speed of its delivery. Whether, for example, a customer-centric manufacturer who is responding to fluctuating high street fashion (Christopher *et al.* 2004) or a manufacturer configuring to supply a major automotive company (Salvador *et al.* 2004), there remains a need (amongst other imperatives) for a company to be able to rapidly adapt its production operations. The importance of responsive small batch flexibility can be underestimated. Studies by University of Bath researchers have shown that a financial benefit to a business exceeding £1m *per annum* can be possible, even when comparatively modest changeover improvement targets are achieved (McIntosh *et al.* 2001).

12.2 Modern Manufacturing Paradigms

Whether to enable viable mass customisation or whether undertaken in pursuit of other goals, an improved changeover capability almost universally remains an attractive outcome to multi-product manufacturing businesses. A brief review of mass customisation and other manufacturing paradigms is presented, where a leading reaction to uncertainty is frequently explicitly described in the literature.

Flexible manufacturing (Slack, 1990, Goldhar and Jelinek 1985) aims for a production system wherein there is a ready ability to change the mix, volume and timing of its output. Within this approach, flexibility has two dimensions, namely range and response. The range flexibility is the range of states a manufacturing system can adopt in terms of the number of different products and their output levels. The response flexibility describes the ease with which a system can be adapted from one state to another. Changeover is of particular significance to response flexibility (Mehrabi *et al.* 2000).

Responsive manufacturing (Matson and McFarlane 1998) describes how a manufacturing system or process reacts to disturbances in its environment. As earlier noted, disturbances can for example be introduced by suppliers, including delivery delays, or by deficiencies in supplied material. Internal disturbances can arise from problems with internal information, control, decision-making, production equipment, labour, and material handling and flow. Further disturbances are possible, from specific customers or the market as a whole. For example, there may be changes to orders, unforeseen variation in demand or forecasting errors.

Lean manufacturing was prominently introduced to the West through the work of Schonberger (1982) and Hall (1983). The term "lean" was coined by Womack *et al.* (1990) to describe the paradigm's main aim, namely the reduction of waste throughout a company's value stream. For some promoters an externalised focus is employed where lean is not just a set of tools for the reduction of waste, but rather represents a set of tools to maximise benefit to the customer (Bicheno 2003). With an internal focus upon factory operations, waste (non-production) associated with changeover activity can readily be identified (Feld 2000).

Reconfigurable manufacturing: shorter product life-cycles and greater product variety place demands upon manufacturers to find new ways to maximise their equipment's cost effectiveness (Urbani *et al.* 2003, Wiendahl and Heger 2003). Modular approaches to system design not only enable flexible processes but also provide manufacturers with the ability to alter processes by rearranging modules of the manufacturing system (Schuh *et al.* 2004). Since reuse of expensive manufacturing equipment is enhanced, the cost effectiveness of manufacturing hardware can be increased substantially. Changeover is fundamentally still taking place to enable new products to be manufactured, but now involves the introduction entirely new pieces of production equipment rather than just adapting parts of existing equipment or an existing process line.

Agile manufacturing: flexibility and responsiveness are important elements of agile manufacturing (Gould 1997). More than just reacting quickly to environmental change, companies instead will seek both to respond to change and exploit change (Booth 1996, Kidd 1995). Enabling tools and methods are identified (Gunasekaran 1998), many of which overlap with those employed under alternative manufacturing paradigms. An objective of reconfigurable manufacturing systems to provide a necessary level of agility has been reported (Gould 1997).

Mass customisation and personalisation: mass customisation seeks to enable businesses to exploit market trends for greater product variety and individualisation (McCarthy 2004). The tools of mass customisation can substantially enable product personalisation (Montreuil and Poulin 2005). Once again, faced with an objective for efficient, flexible, multi-product manufacture, a need for rapid and high quality changeovers becomes paramount (McIntosh *et al.* 2010). Mass customisation and personalisation are a response to the micro-segmentation of markets and require that changed practices for manufacturing and marketing are introduced across the whole of the supply chain (Coronado *et al.* 2004).

Changeability in the Production System

Changeover capability of manufacturing equipment can be positioned as an element within a wider view of production system “changeability”. Although the above paradigms address different aspects of manufacturing, they all aim to increase a company’s ability to adapt to the influence of change drivers. In other words they aim to increase the changeability of a manufacturing enterprise or parts of that enterprise. This changeability can be seen to affect different levels of a company, from the company as whole (perhaps as a network of manufacturing locations) through to a single processing unit or workstation. Overall five distinct levels of a production system have been identified by different authors (Zhao *et al.* 1999, Neuhausen 2001, Wiendahl and Heger 2003, Nyhuis *et al.* 2006). The current authors’ amalgamation and interpretation of these levels is listed below:

1. *production system level 1:* the production network or enterprise level;
2. *production system level 2:* the factory, facility or site level;
3. *production system level 3:* the sub-factory, manufacturing or logistics area level;
4. *production system level 4:* the manufacturing system or group of workstations level; and
5. *production system level 5:* the processing unit or single workstation level.

If a company wants to be able to react to perturbations initiated by the previously described change drivers, then sufficient “changeability” is required across all levels of its operations. For many businesses, a parallel capability will similarly need to be in place in the businesses it engages with, particularly those as part of its supply chain. Wiendahl and Heger (2003) and Nyhuis *et al.* (2006) combine these different levels of a company with a similar classification of different levels of a product:

1. *product level 1:* product portfolio;
2. *product level 2:* individual product;

3. *product level 3:* sub-product;
4. *product level 4:* single component part of a product; and
5. *product level 5:* feature of a part or component.

The combination of these two classifications permits five different types of changeability to be identified, as illustrated in Figure 12.1.

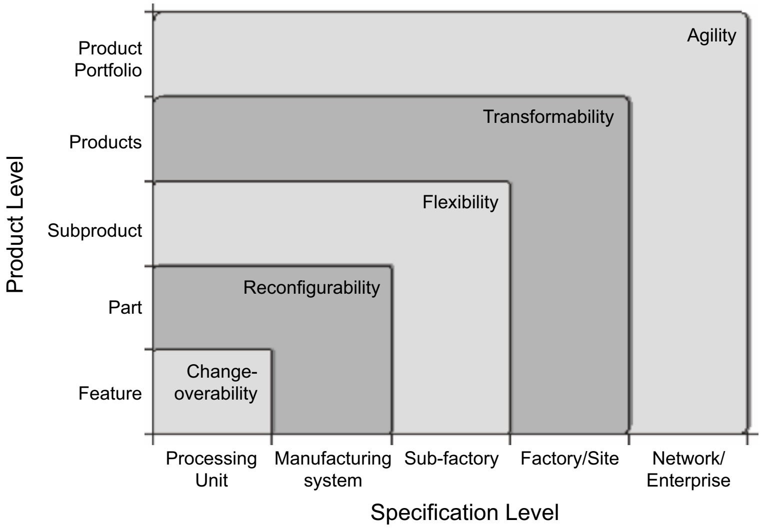


Figure 12.1 Types of changeability (from Nyhuis *et al.* (2006) and Wiendahl and Heger (2003))

Agility stands for the strategic ability of an entire enterprise to open up new markets, to develop the requisite product and service portfolios, and to build up the necessary production capacity. It is desirable that such activity be proactively undertaken.

Transformability describes the tactical ability of an entire factory or site to switch either reactively or proactively to other products.

Flexibility refers to the tactical ability of an entire sub-factory to switch reactively and with reasonably little time and effort to new, but similar, families or sub-products by changing manufacturing processes, material flows and logistics functions.

Reconfigurability describes the practical ability of a manufacturing system to switch reactively and with minimal effort and delay to the manufacture of particular parts through the addition or removal of single functional elements within the system.

Changeoverability describes the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment, again with minimal effort and delay.

The higher levels of changeability build upon the lower levels. In this view agility of an enterprise and its product portfolio is only possible if changeability is sufficient in all the subordinate levels of both the enterprise and the product. The base level changeoverability is the technical capability of manufacturing equipment to flexibly carry out manufacturing processes on features of parts and assemblies. It can be seen as a single core capability which is required for all higher levels or forms of changeability to be successful.

12.3 DFC: Problem Definition and Background

A leading changeover capability is seen to be fundamental to mass customisation, enabling production to switch without undue restriction across all of a company's products, hence assisting highly individualistic satisfaction of customer need. Existing tools to aid achieving a leading changeover capability are known, most particularly Shigeo Shingo's widely adopted SMED (single minute change of die) methodology (Shingo 1985). The authors have previously reported use of the SMED methodology, which in many instances is perceived in industry as inseparable from "changeover improvement" itself, in other words being an applicable tool that addresses all possible improvement opportunities (McIntosh *et al.* 2000). Yet it is a tool that focuses on retrospective improvement and, predominantly, at least in the way that it is typically adopted, is substantially directed towards refining changeover work practice. Most particularly it concentrates upon re-sequencing when individual changeover tasks are conducted, prompting as many as possible to be externalised, hence being completed before production of the current batch ends. Focus is not necessarily on simplifying these tasks, nor reducing the number of tasks which comprise the changeover (McIntosh *et al.* 2000).

Beyond Shingo changeover improvement has been addressed by other authors such as Sekine and Arai (1992), albeit often, in the methodologies they propose, with a significant acknowledgement of Shingo's contribution. Further authors though have presented a stronger design focus on improvement opportunities, for example concerning die changeover in press tools (Smith, 2004). In this case, task simplification and a drive for there to be fewer changeover tasks can become more prevalent. Opportunity is presented for designers to respond at the outset to user needs for responsive, small batch manufacturing by providing changeover-capable machines, rather than necessitating retrospective amendment once machinery has been installed. McIntosh *et al.* (2001) note that such retrospective amendment has often been found to be difficult to financially justify and therefore does not always satisfactorily occur. Other authors still have provided a set of design for changeover rules, presenting these rules as stand-alone guidance without deriving an applicable methodology in which they can be sited (Van Goubergen and Van Landeghem 2002).

As an example of what can be achieved through a design-led approach the authors have researched changeover of large automotive presses. Those being operated by two well known European companies were witnessed enduring changeovers in the range of 10–20 min. Improvement was still being sought, with strictly limited success, by means of in-house SMED teams. By contrast the Japanese press manufacturer Hirotec reports a designed-in changeover capability of 30 s for equipment intended for similar body panel production (Hirotec 2009). The authors have spoken to automotive engineers who have witnessed this claimed capability of Hirotec equipment. A purpose of the DFC methodology is to guide machine designers in all industries towards similar levels of changeover capability.

Motivation: Developing the DFC methodology

Just as certain design for-X tools such as DFMA (design for manufacture and assembly) have proved their value to industry, so too the development of a coherent DFC methodology, outlined in the current paper, is anticipated to be of considerable industrial benefit. No DFC methodology is hitherto known to exist. It is argued elsewhere by the authors (McIntosh *et al.* 2001, 1996) that design-led changeover improvement opportunities are typically undervalued. For original equipment manufacturers (OEMs) the option to supply changeover-proficient equipment new to a user is frequently neglected (McIntosh 1998). The authors note that the work reported in the current chapter is a significant advance on an earlier published version of the University of Bath's DFC methodology (Reik *et al.* 2006b, c).

12.4 An Outline of the University of Bath DFC Methodology

Figure 12.2 presents an outline schematic of the separate steps of the DFC methodology. The methodology is intended to be adopted both by OEMs and practitioners seeking retrospective improvement of existing process hardware. Figure 12.3 provides more detail of the methodology's iterative loops. The methodology is primarily focused on the design of process equipment. Together with a brief ensuing discussion, including later presentation of an overview case study, Figures 12.2 and 12.3 describe the methodology's staged use. The current chapter additionally presents some of the underlying logic of the methodology, which has been successfully trialled in industrial situations where simplicity of use as well as utility is paramount. It extends awareness of changeover improvement opportunities over and above those typically highlighted by traditionally adopted changeover improvement tools, most notably Shingo's SMED methodology. Figures 12.2 and 12.3 show the DFC methodology's use of indices. Summary descriptions of DFC indices ant other major concepts upon which the methodology is founded follow. The figures show the sequential staging of analysis and consequential iterative design refinement to achieve a robust solution to the overall machine design problem.

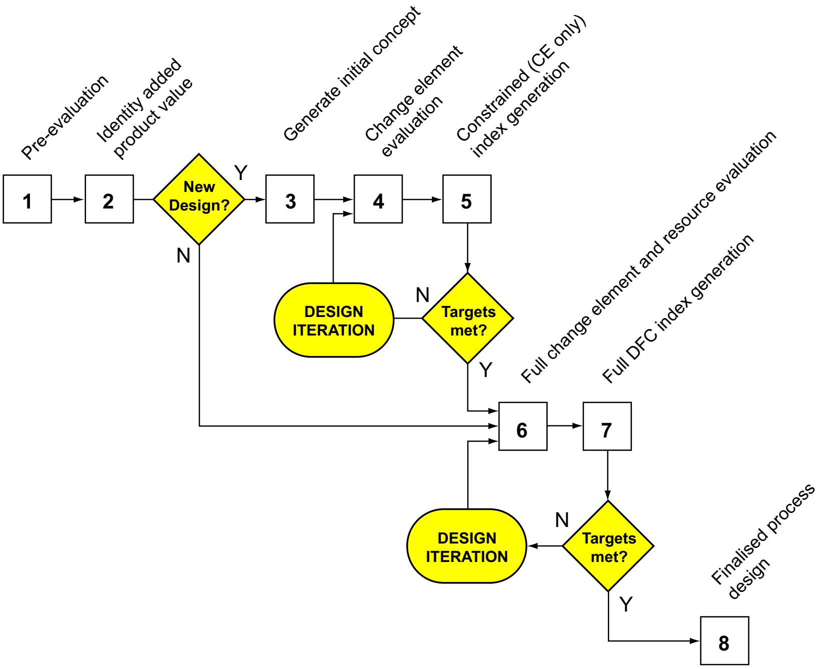


Figure 12.2 A preview of the full DFC methodology (showing two iterative loops)

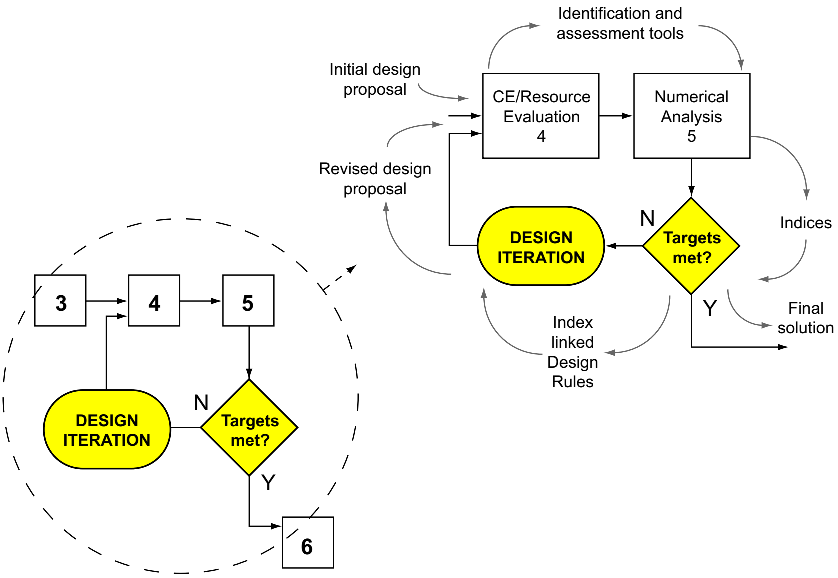


Figure 12.3 Expanded detail of an iterative loop

12.4.1 A Deliberate Avoidance of the Identification of Individual Changeover Tasks

The DFC methodology can be contrasted with many existing DF-X (design for X) methodologies in that it deliberately makes no direct assessment of any individual changeover task which operatives undertake. For example, a task might be to adjust the position of a stop bar, but the DFC methodology will not seek to categorise this or any other task, nor assess its duration. One major problem this approach thereby avoids is defining what constitutes a task. For example, adjusting the stop bar might be a task. Yet at a higher level the full removal of a die set might be conceived as a task. Or, at a much more detailed level, retrieving a hand tool from a tool box might be perceived as a single changeover task, which similarly has to be evaluated and preferably quantified. Ensuing difficulties are also avoided, namely unambiguously assigning a description (moving, placing, aligning, adjusting, lifting, carrying, *etc.*) of the changeover tasks and, further, assigning meaningful and repeatable assessment attributes to those task descriptions.

Instead of a task-led assessment the DFC methodology is based on the simple concept of achieving correct interfaces between all the various machine elements (like the stop bar) that various resources such as personnel or hand tools must act upon. Once all interfaces (typically location) of these machine elements are correctly achieved the machine is ready for production use. By avoiding difficulties inherent in defining what constitute changeover tasks this conceptual approach greatly eases analysis, and in turn eases guiding where design improvement opportunities lie. Elaboration is provided in the following discussion and later *via* the case study.

12.4.2 The Concepts of Resources and Change Elements

The methodology embodies the concepts of *resources* and *change elements* (sometimes abbreviated as CEs). Resources are needed to undertake the changeover. They can include for example personnel, hand tools, cranes and measurement devices. Change elements are the separate hardware entities which are acted upon by resources when conducting the changeover. Change elements, like the previously mentioned stop bar, whether for example being adjusted or substituted, should normally be identifiable from a machine's parts list. With changeover improvement being influenced by the 4Ps of people, practice, process and product (Riek *et al.* 2005), Figure 12.4 shows that design improvement can be sought to both the process (manufacturing hardware) and to the product to raise changeover capability.

12.4.3 The Concept of Interfaces

The methodology identifies that changeover is complete when all change elements have achieved their necessary new interfaces, both with other change elements and with all further machine entities. These further machine entities are not acted upon during changeover and therefore remain in a fixed relationship to one another and hence in an unaltered state. They are collectively referred to as the equipment platform. In a majority of circumstances achieving necessary new interfaces will simply mean that all change elements are amended into their correct location relative to other change elements and relative to the equipment platform.

12.4.4 Further Description of Change Elements

Figure 12.4 indicates that changeover improvement can be sought by organisational refinement or by redesigning the hardware that is worked upon. Thus attention can be concentrated on what resources are allocated and how and when these resources are employed. Or attention can be concentrated on seeking to redesign the change elements that these resources act upon. Each change element is a clearly identifiable physical entity which is acted upon by resources such as a changeover operative. A change element may be a single component or a collection of components that are always (during changeover) retained together in a fixed relationship as a single entity.

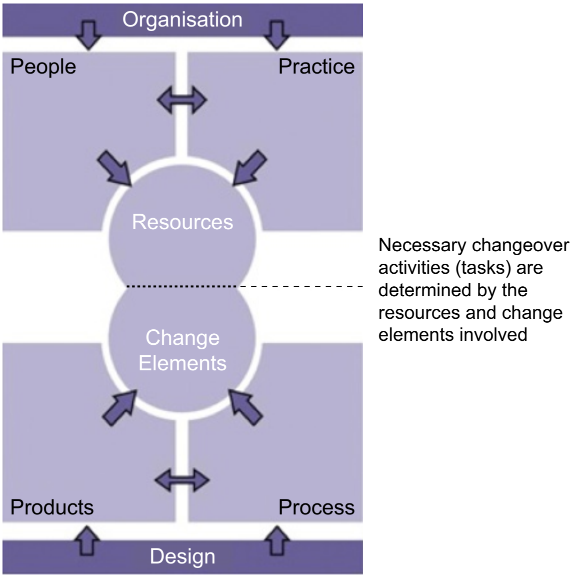


Figure 12.4 Resources acting upon change elements

For example, a screw might be released and then later reset back as it was before. Or a spacing bar might be entirely removed from the machine, to be substituted by an alternative spacing bar. The interfaces of the screw and of both spacing bars, all of which are change elements, are altered. Change elements are the only entities that need to have their interfaces altered to complete a changeover. Therefore operators will only work on change elements when only completing necessary tasks. Resources in total, including the operator(s), act upon the change elements and enable the completion of new change element interfaces. At completion of the changeover all change elements will become either an integral part of the process or will become (if substituted) fully detached and isolated from it.

12.4.5 DFC Indices and DFC Design Rules

The DFC methodology employs a number of *indices* which all assume a value between 0 and 100. By use of indices the designer is informed as to the likely changeover capability of a proposed machine. The methodology's various indices are aligned (as shown later by Figure 12.7) with individual *DFC design rules*. In the event of a weak changeover capability the designer is directed where best to focus attention by the occurrence of low index scores. The DFC indices and the aligned DFC design rules together thus prompt how design improvement can most advantageously be sought.

Index scores will alter after each iterative design revision, rising as the design improves, and only when all index scores are satisfactory should the designer conclude the design exercise. Indices are derived from substantially unambiguous and simply accumulated information relating to the number of change elements of different types present (description of the different types of change element is beyond this current DFC overview) and whether certain conditions are either present or absent with the change elements and in the use of resources. The primary DFC index is the capability index, which indicates the overall changeover capability of the proposed design. The capability index is derived from an assessment of the total number of change elements present. If a low capability index is generated (if the total change element count is unacceptably high) the designer is prompted to seek to reduce the occurrence of change elements in the design, leading in turn to a likely reduction in the overall level of necessary activity to complete the changeover.

Five merit indices additionally qualify where improvement opportunities predominate for the current design iteration. Their purpose is to draw attention to deficiencies (opportunities) present in the design based on an analysis of change element features and resource use when acting upon those change elements. This activity is assisted by completion of the methodology's design infringement matrix, as detailed below.

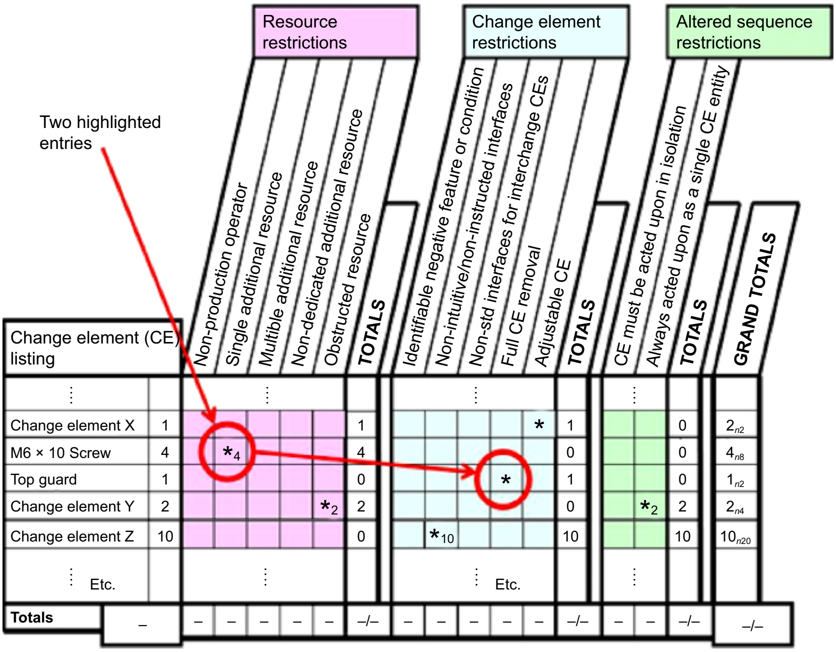
For every index a score of 100 determines that the design is optimal. For all indices the greater the respective opportunity (the greater the determined deficiency relative to prescribed optimum design practice) the lower the index score will be.

All merit indices should attain a score of 100 before the capability index becomes fully representative. The mathematics employed to generate the capability index are relatively complex, but serve the simple purpose of describing a generic curve, an example of which is later presented as Figure 12.6. The capability index curves adopted by the DFC methodology are empirical.

Spreadsheets are available such that index derivations which involve relatively complex mathematical formulae can be invisible the methodology user. In this case, only simply determined criteria of the current design iteration need be entered into the spreadsheet in numerical format. In particular, the capability index, merit index 1 and merit index 2 can be generated in this way.

12.4.6 The Design Infringement Matrix

For merit index 3, merit index 4 and merit index 5 the identification and assessment device signified by Figure 12.2 is the design infringement matrix. Its completion in conjunction with the spreadsheet tool again permits these summary index data again to be automatically generated. Figure 12.5 shows a part-completed design infringement matrix. For example 4 × M6 screws require the use of an appropriate Allen key, which represents use of an additional resource (the Allen key) over and above the engagement of the machine operator in completing the



		Resource restrictions						Change element restrictions						Altered sequence restrictions			
Change element (CE) listing		Non-production operator	Single additional resource	Multible additional resource	Non-dedicated additional resource	Obstructed resource	**TOTALS**	Identifiable negative feature or condition	Non-intuitive/non-instructed interfaces	Non-std interfaces for interchange CEs	Full CE removal	Adjustable CE	**TOTALS**	CE must be acted upon in isolation	Always acted upon as a single CE entity	**TOTALS**	**GRAND TOTALS**
⋮				⋮						⋮				⋮			
Change element X	1						1					*	1			0	2_{n2}
M6 × 10 Screw	4		$*_4$				4						0			0	4_{n8}
Top guard	1						0				*		1			0	1_{n2}
Change element Y	2					$*_2$	2						0		$*_2$	2	2_{n4}
Change element Z	10						0		$*_{10}$				10			10	10_{n20}
⋮ Etc.				⋮						⋮ Etc.				⋮			
Totals	–	–	–	–	–	–	–/–	–	–	–	–	–	–/–	–	–	–/–	–/–

Figure 12.5 Example use of the design infringement matrix (partial analysis shown, with the majority of summary totaled data being omitted)

screws' location. The DFC methodology deems this to be a sub-optimal design feature. Figure 12.5 further shows that a top guard change element has to be fully removed during changeover. Once again infringement of optimal design practice is noted and is penalised once the appropriate merit index is generated.

12.4.7 The Concept of a Complexity Quotient

At stage 2 of the methodology, as shown by Figure 12.2, the complexity of the machine needs to be determined. Knowing how many value adding stages there are (the number of distinct and separate ways that the product is altered within the confines of the machine), the user should read the appropriate complexity quotient "*n*" from Table 12.1.

The mechanism of a complexity quotient normalises capability index scores for machines of differing complexity (Boyles 1991). Hence similar capability index scores for significantly different machines suggest similar relative overall improvement potential. An example capability index function for a machine with a complexity quotient of "*n*" = 2 is schematically illustrated as Figure 12.6.

Table 12.1 Determining the value of "*n*" for value adding machines

Value adding stages within the machine under analysis	Complexity quotient "*n*"
1	1
2 to 3	2
4 to 7	3
8 and more	4

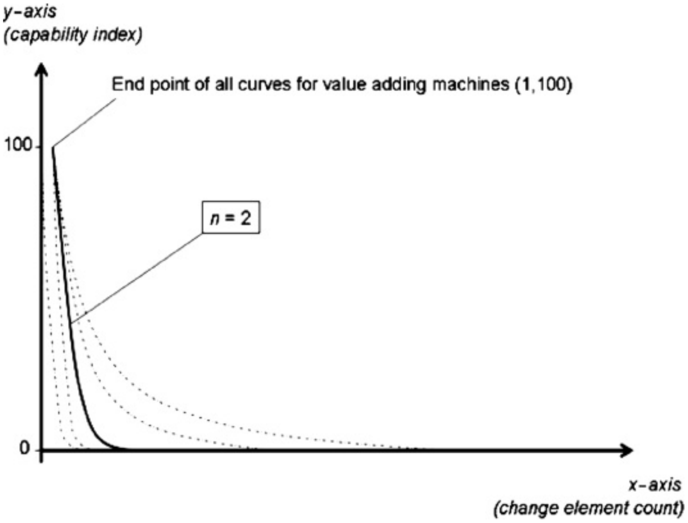


Figure 12.6 Capability index function, value adding machine, complexity quotient "*n*" = 2

12.4.8 Change Drivers

In developing a flexible machine solution a designer needs to be aware how the market for the company's products may change, both imminently and into the future. Hence in assessing change drivers it is being assessed how the company's product ranges, response capabilities and production volumes are likely to alter. This information is critical to being able to decide the changeover specification that the overall manufacturing process has to meet – and hence the changeover capability that constituent machine elements must have. Applicable change drivers and target capability needs to be determined at the outset, during stage 1 of the methodology, as schematically outlined by Figure 12.2. In doing so the index targets at the methodology's decision gates, after stages 5 and 7, are set.

12.4.9 Design Improvement Opportunities

As well as being founded on the concepts described in outline above, the DFC methodology is structured to align with previously determined global opportunities where design can be applied to achieve faster, repeatable, higher quality changeovers (Owen *et al.* 2007):

1. Reduce the number of changeover tasks which need to be completed.
2. Ease completion of the changeover tasks.
3. Enable the changeover task sequence to be altered.

These global expressions of opportunity are task-based and must be translated into a DFC compatible format if a designer is to be able to usefully focus improvement attention. The DFC methodology models changeover as resources acting upon change elements to establish the required new interfaces for each of those change elements. With this perspective of a changeover these global design improvement opportunities can more accessibly be written as:

1. *Global opportunity 1:* reduce the change element count.
2. *Global opportunity 2:* ease restrictions to interface completion.
3. *Global opportunity 3:* ease restrictions that limit when interfaces can be completed.

12.4.9.1 Global Design Opportunity 1

With fewer change elements to act upon less overall work is likely to be necessary.

12.4.9.2 Global Design Opportunity 2

All change element interfaces should ideally be as easy as possible to complete. Poor design can impose restrictions on optimum practice. By simply and consistently analysing restricted resource use and restrictive features of the change elements themselves, the methodology enables the designer to identify specific opportunities to ease interface completion.

12.4.9.3 Global Design Opportunity 3

Shingo's SMED work concentrated strongly on changing the sequence in which tasks are completed (Shingo 1985). In particular he emphasised externalising tasks, although there are also likely to be opportunities to conduct work more in parallel and to diminish occurrences (if more than one person is involved) of staff waiting to be able to commence new tasks (McIntosh *et al.* 2001).

12.4.10 Mapping the DFC Indices and the DFC Design Rules

The DFC methodology's description of global design opportunity is typically not focussed at a level of sufficient detail to provide meaningful assistance to the designer. The methodology addresses this issue by means of the DFC indices and the DFC design rules. Figure 12.7 illustrates how the DFC design rules, the DFC

Global opportunity	DFC Index	DFC design rule (if showing an unacceptable index value)
1	**Capability Index**	Minimise the change element count
	Merit Index 1	Prioritise secondary change element elimination
	Merit Index 2	Sub-prioritise non-value adding change element elimination
2	**Merit Index 3**	Seek operator-executed changeovers (CE interfaces)
		Seek for the to be additional resources +
		If essential, limit additional resources to jus one enbity +
		Dedicate essential additional resources (full availability) +
		Seek unobstructed resource use
	Merit Index 4	By CE design, seek to assist effective resource use
		Seek clear instruction/intuitive interface outcomes
		Seek standard interfaces for sustitutable CEs
		Seek to avoid full change element removal
		Seek elimination of any scope to adus ("right first time")
3	**Merit Index 5**	Seek full independence of interface achievement
		Seek multiple change element entries

+ Note: Any resource (person or tool etc.) other than process operator is an additional resource
[DFC = Design for Changeover, CE = change element]

Figure 12.7 Design opportunity, DFC indices and DFC design rules in full, showing alignment indices and the three identified global opportunities for design-led improvement are aligned. With post-analysis index knowledge, the designer can prioritise where his or her attention is most beneficially directed. Deficient (low) indices are raised, along with a commensurate rise in the machine's changeover capability.

12.4.11 Presenting Summary Information to the Designer

Figure 12.8 shows how summary data has previously been presented to a designer. The numbers will alter as successive design improvement iterations are undertaken. The focus as the design is refined is to raise all DFC indices as far as possible. This is an inevitable outcome as numbers relating to change elements, resources and restriction entries (the latter being taken from the design infringement matrix) are reduced as far as possible.

ANALYSIS ON: Cropping machine – original design
CHANGEOVER TIME: 23 minutes

Value adding stages:	5	Complexity quotient:	3
Change elements:	44	VA $CE_{primary}$:	10
		NVA $CE_{primary}$:	0
		$CE_{secondary}$:	34
Additional resources:	9	Personnel:	1
		Hand tools:	7
		Other:	1
Capability index:	21.7	Merit index 1:	5
		Merit index 2:	100
		Merit index 3:	38
		Merit index 4:	77
		Merit index 5:	68
$\sum$ Restriction entries:	1016	Highest restriction entry:	240

RECOMMENDATION: Radical redesign
MAIN OPPORTUNITIES: $CE_{secondary}$ elimination, adjustment elimination

Figure 12.8 Presentation of summary analysis data

With reference to Figures 12.7 and 12.8, use of the DFC indices in conjunction with the DFC design rules directs the iterative improvement effort. Thus for example merit index 1 might be targeted at the outset to be 75, at which point the design is deemed to be satisfactory. Concentration during the current design iteration could therefore be to "prioritise secondary change element elimination". The summary data of Figure 12.8 can be generated automatically via use of the methodology's previously discussed spreadsheet tool.

12.5 Industrial Validation: A Case of Study

UK Government-supported *lean* consultants, the Manufacturing Advisory Service South West (MAS-SW) are frequently called upon by industry to address changeover losses. Interventions by the MAS are typically of 5 days' duration and frequently employ a specialist changeover training game developed by Lean Games (www.leangames.co.uk). This training game highlights both what can be achieved through better organisation in preparation for the forthcoming changeover (which the authors argue is the primary focus of Shingo's SMED methodology (McIntosh *et al.* 2001) and what can be achieved by better process design. Photographic details of the game are provided on the Lean Games website.

The DFC methodology has been applied to assist designers and other personnel to investigate where design improvement opportunities lie. In its initial embodiment, changeover of the game hardware takes approximately 30 min to complete, with variation being apparent dependent on the skill of the personnel who conduct it. After design improvement opportunities have been identified and pursued (there are fixed opportunities built into the game) the changeover time typically falls below 2 min. The DFC methodology has been employed to assist identification of these opportunities, highlighting where particular problems are apparent in the game, with indices changing as hardware changes are successively undertaken. Access is available to simple spreadsheet programs that allow the respective DFC indices to be calculated automatically upon:

1. input of the complexity quotient;
2. input of the number of change elements of different types present in the proposed design; and
3. completion of the design infringement matrix.

Target index outcomes need to have been defined at the outset of the exercise, which determine when further iterative design (Figures 12.1 and 12.2) is no longer required. As an existing machine is under scrutiny only the second iterative loop, commencing with DFC methodology stage 6 (Figure 12.1), is employed.

12.5.1 A Brief Description of the Game

The game is intended to represent a factory machine. The machine (the game) draws a full curve onto a sheet of paper. The curve's profile is determined by the machine's linkages. The linkages are reset during changeover if an alternative curve profile is required. Turning a handle drives the mechanism, whereby a pen is pulled across the surface of a piece of paper, representing adding value to the product. Another changeover option is to change the colour of the curve, which is achieved by substituting an alternative pen. The position of the curve on the paper is deemed to be critical and requires that the paper is carefully aligned and secured before the handle is turned.

12.5.2 Value Adding Stages

The machine adds value by a pen describing a coloured curve over the paper's surface. One or both the pen or the curve profile can be changed. The machine thus comprises two value adding stages. A full changeover is sought during the exercise, both of the pen and of the curve's profile. The machine has a complexity quotient of 2 (Table 12.1).

12.5.3 Target Indices to Achieve

The exercise facilitator knows the options built into the machine, which enable a sub 2 min changeover to be achieved. Modest index targets are set to enable this performance, post design improvement, to be realised. Most notably a relatively modest capability index score of 40 is targeted. The capability index initially, before design modification is undertaken, is much lower than this (see below) and is raised by reducing the number of change elements in the design (Figure 12.7). The capability index formulae are not here reproduced, but for a value adding machine with a complexity quotient of 2 this target score equates to a reduction in the total number of change elements to 15 or less.

Comparatively modest targets are also set for the merit indices. For example, the DFC methodology penalises the use of resources (including the use of tools) over and above the machine's operator alone completing the changeover. Entries made under the classification of "resource restrictions" (Figure 12.5) reflect infringements of optimum design practice which will lower merit index 3. Knowing what specific restrictions are present, through completion of the design infringement matrix, the designers are able to focus applicable improvement activity. For illustrative purposes improvements which raise merit index 3 are later briefly described. The merit index 3 target is set at 70/100.

12.5.4 Raising the Capability Index

With fewer change elements for resources to act upon there are likely to be fewer tasks comprising the changeover. In its original configuration the game has 53 change elements. These comprise all machine elements which must be acted upon and include substitutable elements where applicable. Notably there are many screws, nuts and washers, each of which must separately be counted. A total of 53 change elements for a value adding machine with a complexity quotient of 2 generate a very low capability index of 4.1/100.

After improvement there are 14 change elements:

1. 2 × pen location catches;
2. on/off switch;
3. 2 × screws;
4. pen holder assembly – existing;
5. substitutable pen holder assembly – replacement, with alternative colour pen;
6. link arm – existing;
7. link arm – replacement;
8. 2 × link arm attachment pins;
9. air pipe;
10. air pipe attachment;
11. USB link – switch.

Although exceeding the target outcome, a resultant capability index of 44.6 tells the designers that there are still appreciably more change elements than would be present in an ideal design. More improvement is thus certainly still possible, driving the capability index yet closer towards 100.

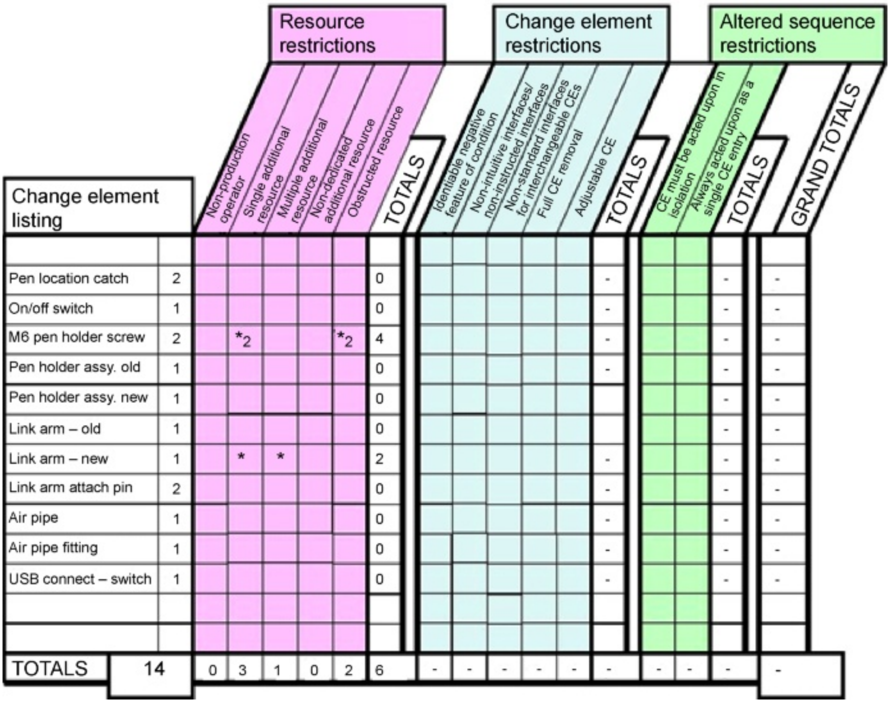
12.5.5 Resource Restrictions – Raising Merit Index 3

Just as there is a focus to reduce the number of change elements, so too the DFC methodology drives a reduction in the resources that are employed beyond engaging just the machine's operator. The methodology seeks for as many changeover activities as possible to be de-skilled, including conducting those activities without a need for separate tools.

Some design improvements for this exercise feature:

1. elimination of the need to use any spanners;
2. elimination of the need to use two hand tools simultaneously;
3. making change elements fully accessible to be acted upon.

Figure 12.9 shows data input to a section of the design infringement matrix with these and other amendments having been made. The predetermined merit index 3 target of 70/100 is comfortably exceeded at 91.4, being derived upon completion of this relevant section of the matrix (91.4 = 100 – (100 × 6/70)). Figure 12.9 further shows how completion of the matrix draws the designer's attention to the explicit flaws that are still present at any stage of the design's evolution. It is seen that in this particular example there is very little further improvement to be found. In the case, however, of further activity to raise the capability index (further design improvement to reduce the total number of change elements in the design) the change element listing would alter and the design infringement matrix, now for these new change elements, would have to be completed afresh.



Change element listing		Resource restrictions						Change element restrictions						Altered sequence restrictions			
		Non-production operator	Single additional resource	Multiple additional resource	Non-dedicated additional resource	Obstructed resource	TOTALS	Identifiable negative feature of condition	Non-intuitive interfaces/ non-instructed interfaces	Non-standard interfaces for interchangeable CEs	Full CE removal	Adjustable CE	TOTALS	CE must be acted upon in isolation	Always acted upon as a single CE entry	TOTALS	GRAND TOTALS
Pen location catch	2						0						-			-	-
On/off switch	1						0						-			-	-
M6 pen holder screw	2		*2			*2	4						-			-	-
Pen holder assy. old	1						0						-			-	-
Pen holder assy. new	1						0									-	-
Link arm – old	1						0									-	-
Link arm – new	1		*	*			2						-			-	-
Link arm attach pin	2						0						-			-	-
Air pipe	1						0						-			-	-
Air pipe fitting	1						0						-			-	-
USB connect – switch	1						0						-			-	-
TOTALS	14	0	3	1	0	2	6	-	-	-	-	-	-	-	-	-	-

Figure 12.9 Completion of the design infringement matrix in relation to the derivation of merit index 3

Post-improvement resources include the continued use of a reference sheet that illustrates how the link arms are to be assembled. A need for this resource could be eliminated in the future by fool-proofing the link arms' orientation, for example, by using different location hole sizes for the respective links. Similarly the use of a transparent check sheet resource is currently retained, whereby the pen-marked sheet of paper (the product) is inspected for image alignment quality. With attention elsewhere given to achieving "right first time" location of all change elements the designers may have the confidence in future to eliminate its use.

12.5.6 Change Element Restrictions – Raising Merit Index 4

Merit index 4 is driven by elimination of sub-optimal design features of the change elements themselves. Improvements undertaken include:

1. elimination of the need for any 'trial and error' adjustment;
2. elimination of a need to fully remove remaining screws (by use of keyhole slots);
3. elimination of previously present torque setting problems.

12.5.7 Altered Sequence Restrictions – Raising Merit Index 5

Merit index 5 is raised by increasing the facility to complete change element interfaces (conduct tasks) at an alternative time. Hence opportunities are being sought to alter the interface completion sequence, to complete interfaces in parallel or to eliminate possible occurrences (for more complicated changeovers) of operator waiting when two or more operators are employed together to complete the changeover.

Implemented improvements include:

1. replicating the pen holder assembly; and
2. acting upon the pen holder assembly during internal time as a single component.

These modifications enable parallel working concerning the pen assembly, or enable the assembly to be built with an alternative colour pen in external time. A penalty is, however, generated in that replicated parts increase the overall change element count, hence lowering the capability index. It is thereby communicated that, notwithstanding when it is undertaken, the total amount of work necessary to complete the changeover rises.

12.5.8 Further Industrial Validation

Application of the methodology has similarly been undertaken *via* a University research associate working on site with an industrial partner. Attention was concentrated on machines used in the manufacture of industrial filters and has resulted in changeover reduction in one instance from over 25 min to under 5 min through design improvement alone. Implementation cost was low, with projected payback occurring in approximately 7 months. The results of further industrial studies are pending, where early results are similarly encouraging.

12.6 Discussion

A leading changeover capability is frequently sought by retrospectively emphasising organisational refinement, seeking to complete tasks both as efficiently as possible and in external time. This though does not represent the only changeover improvement opportunity, where design can alternatively be employed to reduce the number of tasks necessary to conclude the changeover and to make those individual tasks simpler to complete. Ultimately (although not necessarily a sensible goal) changeovers have the potential to be fully automated, being completed, by means of equipment redesign, by an operator throwing a switch. Just one single, simple task remains. For a mass customisation enterprise a leading changeover capability permits highly responsive manufacture between successive product batches with minimum penalty, both in terms of production downtime and deficient product quality. With a mass customisation enterprise typically seeking to present a wide ranging product selection to its customers, this capability can be highly prized.

The current chapter describes how earlier DFC research at the University of Bath has been extended. The use of metrics to guide the designer through iterative improvement is retained, but greater alignment with previously determined high-level design improvement opportunities, such as reducing the number of changeover tasks that need to be conducted, has been sought. The DFC indices and the DFC design rules are both revised and applied accordingly. The DFC methodology is further sought to be unambiguous and repeatable in its use, and this goal has been addressed through the novel modelling of a changeover as the achievement of change element interfaces by the resources that act upon those change elements. Any attempt to break down the changeover into a series of tasks is deliberately avoided, as is the challenge of allocating measurable attributes to those tasks. The measureable attributes of the change elements and resources, as required when applying the DFC methodology, have alternatively demonstrated themselves to be easily determined.

In extending earlier DFC research at the University of Bath the authors argue that greater coherence has been provided to practitioners seeking design-led improvement. Perhaps because of its prominence, Shingo's SMED methodology is sometimes portrayed as a universally applicable tool, more than adequately embracing design as well as organisational refinement opportunity (Cakmakci 2009). The current authors do not share this view, instead recognizing that application of the SMED methodology certainly has its place but arguing that it fails adequately to detail, direct or prioritise what can be achieved through design. The DFC methodology is available to be used alongside the SMED methodology or, for OEM designers, is applicable in place of the SMED methodology.

The authors continue to validate the DFC methodology's use through industrial use trials. In time there may be found to be scope to change the profile of the generic capability index curves, or to weight the penalty applicable when assessing the separate categories of "resource restrictions", "change element restrictions" and "altered sequence restrictions" (Figure 12.8). Again at a later date there is the possibility for other potential users of the methodology, as a community, to access and interactively update such criteria *via* a common database.

12.7 Conclusions

This chapter has given an overview of the field of changeable manufacturing systems and has assessed "changeoverability" from this perspective, which Nyhuis *et al.* (2006) describe as "the technical ability of a processing unit to perform particular operations on a feature of a part or assembly at any desired moment with minimal effort and delay". Equally, Wiendahl and Heger (2003) propose "changeability has become a decisive factor in the competitiveness of manufacturing companies in addition to the classical target factors of cost, time and quality". Uncertainties influence today's manufacturing environment more than ever, for example due to increasing customer demand for product variety, and modern manufacturing paradigms share a fundamental aim to enhance the ability of manufacturing systems to react quickly to such uncertainty. Collectively a need for high levels of inherent system "changeoverability" through changeover-focused design of equipment is identified. Change drivers have been outlined, and their role when specifying the changeover capability of new equipment has been briefly described. The authors have outlined the University of Bath's metric-driven DFC methodology. It addresses three identified global opportunities where improved machine design can impact upon changeover capability. Further, it has been founded on the premise that changeover tasks need not be explicitly evaluated and that index-generating data should be both simply and unambiguously determined. The methodology has initially been validated through protracted research collaboration with an industrial partner and, additionally, in conjunction with the changeover offering of a vendor of lean industrial games.

Space restrictions necessarily limit what can here be described, including derivation of the DFC indices, which reflect the competence of various aspects of the overall design. Only a summary of work completed to date is presented, where omissions that are necessarily dictated by lack of space may perhaps hinder understanding of what is involved. Contact with the authors is invited to gain further details, for example, of the theory upon which the DFC methodology is built, as well as greater in-depth understanding of its application across varied case study situations.

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