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INTEGRATING PRODUCT AND MANUFACTURING SYSTEM DESIGN TO MINIMISE CHANGEOVER LOSSES

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ABSTRACT
In recent decades manufacturing industry has focussed a lot of attention on changeover performance, recognising a need to reduce changeover losses in order to remain competitive. A highly flexible small-lot manufacturing capability arising from better changeover performance permits better responsiveness to customer needs – potentially greatly assisting the supply of exactly the right goods, in the right quantity and at the right time. Important internal operational advantages are also potentially available such that ever more challenging customer demands can be met with minimal penalty to the manufacturing organisation.
By means of a number of case studies this paper investigates the role that design-led changeover improvement can play, separately assessing issues of both product design and manufacturing system design. The paper further investigates the considerable potential benefit of integrating design attention across both the product and manufacturing process together, rather than seeking good design of either in isolation.

Keywords: Changeover classification, Product design for changeover, Process design for changeover

1 INTRODUCTION
From the end of the 1970's and into the 1980's and beyond, western volume manufacturers were confronted with an ever worsening competitive position relative, particularly, to their leading Japanese counterparts [1][2]. In contrast to the outmoded *mass-production* model often then still being followed in the west [3], the best far eastern manufacturers were adopting alternative manufacturing practices which were initially described under the moniker of *just-in-time* [4]. Further alternative manufacturing and improvement practices have subsequently been embraced by the paradigms of *lean* [5] and *mass-customisation* [6]. Awareness has grown that competitive criteria extend considerably beyond those simply of high product quality and low unit cost which traditionally dominated in *mass production* manufacturing environments [3].

1.1 Changes in manufacturing practice
Chronologically the last to enjoy popular adoption, *mass-customisation* in particular drives manufacturing agility and responsiveness. Whereas *lean* might be described in summary as seeking to eliminate all costs which do not add value to a product or process [7], *mass-customisation* represents the adoption of selected work practices within revised business structures for the purpose of creating a highly adaptable, customer-centric, value creating enterprise [6]. The focus of mass-customisation is subtly different, even though the desire to maintain tight control over all waste will still be maintained [8].
The primary driver for mass-customisation is that of an increasingly demanding and segmented marketplace [9]. To prosper in an environment of wide-ranging and volatile customer choice manufacturers have to be able to adapt far better to inevitable market turbulence whilst at the same time avoiding the previously high unit costs traditionally associated with custom made or small volume products. The need is for a matched, integrated selection and implementation of appropriate work practices, where emphasis is on profitably responding to an array of customer demands, most notably in terms of the manufacture of differentiated products [10]. Greatly assisting in achieving this

aim, better changeovers are frequently observed to be sought retrospectively by engaging Shingo's SMED (Single Minute Exchange of Die) methodology [11], as part of a kaizen-based improvement exercise [12]. Exemplary changeover capability is a primary enabling tool [13] and, as shall be assessed, both the design of the product and design of the manufacturing process potentially have a key role to play in achieving such capability. Alongside better organisation of a changeover, they present opportunities to more rapidly and precisely adapt manufacturing operations across a range of products.

1.2 The complexity of changeover and the challenge of improvement

The current authors have previously analysed Shingo's methodology in detail, determining possible shortcomings in its application [14][15][16], in particular that design opportunities are not fully accommodated. Even if design is not vigorously pursued it however remains evident, via the many case studies which have been published [5], that the methodology's adoption can still have a major impact. This paper investigates that substantially more might be achieved were the approach to changeover improvement to be extended to more comprehensively include the application of design.

Notwithstanding the application of SMED or other possible methodologies, the extent of the improvement problem should be appreciated – in many circumstances changeover of equipment to enable the manufacture of a new product represents both highly complex and time consuming activity. Examples presented later in the paper support this assertion, not least by reflecting the number of man-hours which can be devoted to completing the necessary work. Not only are some staff directly employed to conduct the changeover throughout its duration, additional technicians and for example a fork lift truck driver are also sometimes witnessed becoming involved. Some preparatory work is often similarly completed before ceasing production.

Another indicator of complexity might be the often witnessed variability of changeover performance, both when repeating what are nominally identical changeovers [17] and in terms of the substantial difference in changeover times across all the possible different types of changeovers which can occur [18].

1.2.1 A corollary: quicker changeovers achieved by reducing complexity

Implicit in the observation that complex and lengthy changeovers frequently occur is the realisation that reducing complexity – reducing the difficulty of individual tasks and/or their number – should result in a more rapid changeover being completed. As this paper will show, the application of design can significantly assist in achieving these goals.

This is not the only option. A contrasting strategy is also valid in many industrial circumstances, which is to change when tasks occur [16] – 'externalising' them, prior to production being halted [11]. Improvement in this instance is typically sought by organising the changeover better whilst retaining existing hardware essentially unchanged.

2 UNDERSTANDING POTENTIAL IMPROVEMENT OPPORTUNITIES

Understanding that the majority of changeovers are complex and time consuming does relatively little to guide an improvement practitioner, save to embrace a general goal to reduce complexity. Importantly, prior work referenced and discussed in summary above indicates that the SMED methodology is an important potential improvement tool, but does not necessarily guide the practitioner to all available improvement opportunities.

2.1 Organisational and design opportunities: the 4P categorisation

Reik *et al*. [19] have previously classified influences on changeover activity as shown in figure 1. Categorisation occurs as the 4 Ps of People, Practice, Products and Process. 'Practice' refers to the work practices which are undertaken during changeover. 'Process' refers to the manufacturing hardware which is employed.

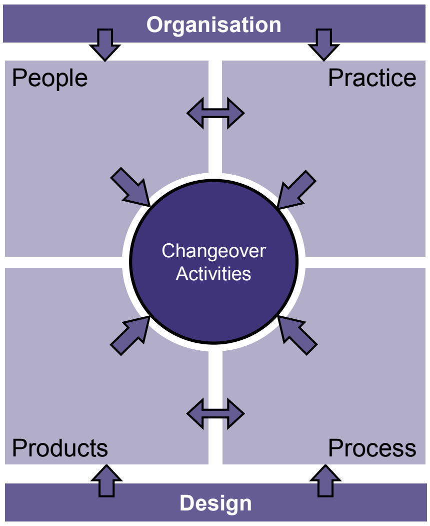

Figure 1. The '4-P' influences on changeover performance [20]

2.1.1 Design-led improvement opportunities

The latter two categories of Products and Process are described by figure 1 as being design-led improvement opportunities. The figure indicates that the products themselves might be revised to enable better changeovers. Equally, physical revision to process hardware is also possible. Both, as examples presented below will show, can be highly significant. The current authors have argued elsewhere that substantive design opportunities are not necessarily embraced within the SMED methodology and can be undervalued in typical *kaizen* improvement programmes [18][16].

2.1.2 Organisation-led improvement opportunities

Design opportunities as noted above can be contrasted with seeking organisational improvement. In this case the motivation of people might be addressed, or better training provided. Or the work practices which are adopted might be revised. Moreover, the potentially powerful option of changing when tasks might be conducted is frequently available. These opportunities represent better changeover activity taking place within the confines of largely unchanged hardware. They are equivalent to doing existing things better – rather than, by exploiting design change and aspiring to a simpler changeover, doing better things.

2.1.3 A design focus to University of Bath research activity: the DFC tool

Research at the University of Bath explicitly does not delve into improvement opportunities categorised under People and Practice, save to try and ensure their integration with design-led opportunities as part of an overall retrospective improvement initiative whenever one is undertaken – it is felt that these aspects have been more than adequately researched already [12]. Instead, the University is developing a generic Design for Changeover (DFC) tool [19][20], along the lines of Design for Manufacture and Assembly (DFMA) [21] and any number of other similar DFX tools.

2.1.4 Further merit in design

The distinction is drawn above between design-led and organisation-led improvement opportunities. Two further important attributes of design may be highlighted when discussing the relative merits of engaging design. First, research has shown that changeover gains are likely to be considerably easier to sustain when they are generated with an emphasis on good design [15], because of simplification to ensuing work practices. Second, organisational refinement might have little impact when targeted at activities occurring during a changeover's run-up phase [16].

3 THE POTENTIAL FOR DESIGN FOR CHANGEOVER – CASE STUDIES

Claims made in the previous section that design can have a significant impact on changeover and in turn on the competitiveness of a business can be explored further by reference to a number of case studies. These case studies are all drawn from research conducted by the Bath team, both in the UK and in mainland Europe. In all the Bath researchers have participated with in excess of 100 industrial partners over a period of nearly 15 years, working within a very wide variety of industries. The examples cited below are deliberately presented only in global terms, simply to give substance to the overall propositions of the paper (reflecting as well the authors' obligations not to breach partner confidentiality).

3.1 Case study 1: Poor process design constraining changeover performance

A glass jar and bottle manufacturer necessarily employed a number of large, expensive-to-run furnaces at the start of its production lines. Originally conceived for mass production, the facility was facing problems as its customers increasingly required greater product variety and smaller batch deliveries (see also section 3.2). A deficient changeover capability represented a very substantial problem on the lines, where approximately 4 hours were lost when manufacture was switched between products. Even though some work had been undertaken to address these losses (previously they had been higher), the then-best 4 hour changeover interval was proving difficult to breach. The authors' assessment was that this difficulty to drive changeover times down further was largely a result of the design of the equipment. As elaborated by other examples in later sections, the authors' suspicion was that local factory improvement teams were nearing the limit of changeover performance achievable by organisational refinement alone. To gain further significant gains the local teams were going to be obliged to seek design-led improvement opportunities [22] – something which they seemed both reluctant and ill-equipped to do.

It was postulated (as similarly occurred in other production instances not reported within the current paper) that the manufacturing paradigm of mass production prevailing at the time of the facility's commissioning had to a large extent removed the need for OEMs to supply key pieces equipment with a high changeover capability. The most problematical piece of equipment on the line in respect of changeover had apparently been designed in the 1960s, and had almost certainly been designed without the need for high flexibility in mind. Moving into an era of mass-customisation, its design was now significantly compromising the competitiveness of the factory.

3.2 Case study 2: An example of the impact of focussed product design

Cigarette manufacture happens across a number of identifiable stages. First the cigarette is made. In turn, as shown by figure 2, cigarettes are wrapped in packs, bundles, cases and pallets, each of which activity occurs in separate identifiable sections of the overall line, each incorporating one or more machines. For most cigarettes (and their subsequent wrapped manifestations) the component parts will be similar – but not necessarily the same. Thus it is possible for example that different tobacco grades may be supplied, or different tipping papers. Changeover is complicated according to the number of these component elements which have to be changed. Additionally the design of the individual component elements in itself may add complexity to the changeover tasks conducted on the process equipment, where for example modular design of interchangeable elements may prove highly advantageous [23]. In addition, some process activities apply to some products but not to others. Affixing a Duty Stamp (or not) represents an example.

Just as manufacturing equipment can be designed for better changeover performance, so too the design of the product can significantly influence changeover capability. The University of Bath is undertaking further research on product design for changeover and the cigarette case study is one of the first to be completed by the Bath changeover team [24].

The study referred to here concluded that opportunity existed to change the design of the product at all the stages represented on figure 2. If these opportunities were all taken it was assessed that their impact would be to reduce changeover times by approximately 37% [24]. If this level of reduction was used solely to enhance productivity it was calculated that manufacture of an additional 0.17 million cigarettes per line per day became possible. Not only this, some redesigns of the product were actually cheaper than those currently under manufacture, irrespective of their influence on changeover.

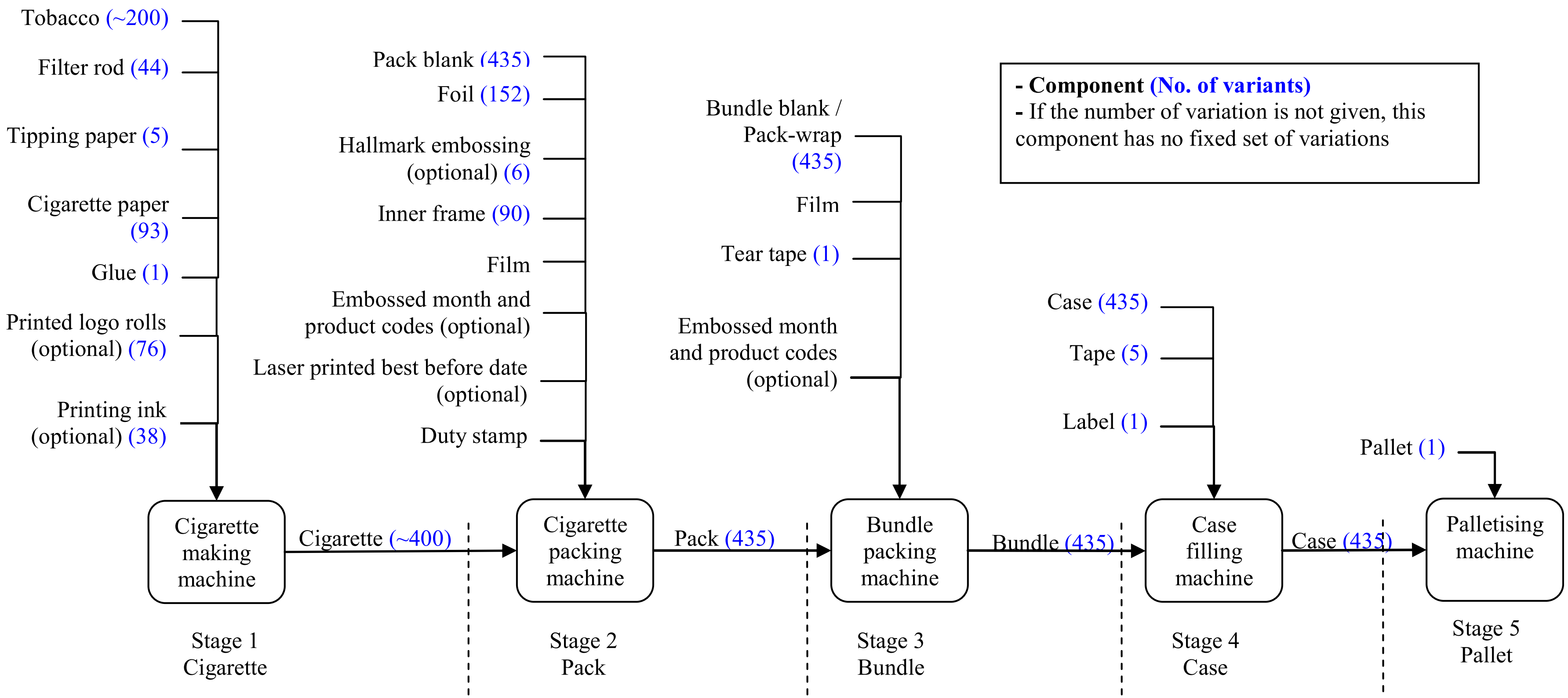

Figure 2. Stages in the cigarette manufacturing process [25]

The cigarette study emphasises one further point extremely well, which is the changing nature of customer demands. Over a period of approximately 5 years the company's product range (the number of stock keeping units, or SKUs, leaving the factory) has seen a 50-fold increase. Over the same period the total number of cigarettes that it has been possible to manufacture annually – because of a lack of flexibility arising from comparatively poor changeover performance – has fallen by more than 50%.

3.3 Case study 3: The extent of design-led improvement which can be possible

Shingo's work [11] was in large measure directed to the press tool industry and significant changeover improvement endeavour has followed in this industry since.

Likewise, the Bath team has been involved with press tools. The initial press which came under scrutiny was a double acting machine at the start of a drinks can manufacturing line. Its changeover time at the start of the authors' research was approximately 24 hours (having come down from a previous maximum of 48 hours). Through a programme of improvement the time was anticipated to come down in further stages, first to below 4 hours, and then to below 2 hours. For the latter stage in particular, redesign was being undertaken to the press and its associated tools.

More recently the Bath researchers have studied changeover in the automotive industry. The presses were essentially very similar – although significantly larger. For each of two separate European auto manufacturers the changeover time was found to be in the range 10-20 minutes (exact times cannot be disclosed). The two companies recorded different levels of performance and each was – by applying the SMED methodology – seeking to drive times down further. These further gains were proving very difficult to achieve.

Relative to the final press now discussed in this sequence, a sub-20 minute changeover was still poor. Hirotec [25] manufacture automotive presses which are deliberately designed to have outstanding changeover performance, from their date of first commissioning into a factory. For a similar press to those witnessed in Europe, changeover times of just 30 seconds are claimed by the company [25]. These claims have been verified in conversation between the authors and a production engineer who had visited Japan to see these machines.

3.4 Case study 4: 'Beyond-SMED' design improvement

As in some of the previous studies, SMED was witnessed being engaged in the search for improvement to a silk screen printing line. Savings were indeed made but, like other instances reported in this paper, a changeover time limit was apparently reached. This time was approximately 39 minutes – being the time taken to exchange a series of change parts. As described more fully by McIntosh *et al*. [18], this time had been achieved with the aid of some minor design amendments, most of which are discussed by Shingo [11], and as such can be assumed to be embraced by the SMED methodology.

A 39 minute changeover was still regarded as being too long. It was deliberately decided to forego SMED and determine what improvement targeted design might be able to contribute. Design options being considered were deliberately more aggressively targeted than those apparently countenanced by the SMED methodology – or indeed by SMED programmes, which can in practice be different [18]. Their result was to reduce the changeover time to approximately 6 minutes. At the same time the cost of the change parts was substantially reduced and their manufacturing lead time (when new parts needed to be made for new products) massively reduced. By design, changeover tasks had become highly amended, becoming both much simpler to complete and fewer in number.

3.5 Case study 5: The potential of some simple, single product design modifications

An internal combustion engine manufacturer post-machined engine blocks from the foundry. In batches, four different blocks were machined. Undue penalties were experienced during changeover because the product had not been designed with this requirement in mind. Staff pointed out one particular opportunity, which was simply to machine dipstick holes at a consistent angle. Doing so would instantly eliminate more that fifteen minutes from changeover losses, whereby associated machinery elements no longer had to be reset.

4 INTEGRATING PRODUCT AND PROCESS DESIGN

The 4-P model of figure 1 succinctly describes improvement opportunity. Attention to each categorised influence on changeover activity – each of the 4Ps – can separately impact upon changeover performance, and balanced improvement activity will ensure that attention is accorded as appropriate to each in turn. It is now investigated that integrating Product and Process design with the objective of faster and higher quality changeovers can give better results than focusing design on either Products or Processes separately (as in the previously cited case studies).

To show that this result might ensue, the situation of integrating both People and Procedure organisation opportunities is first very briefly evaluated.

4.1 Integrating organisational improvement to both People and Practice

It can sensibly be argued that higher levels of improvement will be achieved by simultaneously concentrating on the dual organisational areas of People and Practice, rather than concentrating on either in isolation. Thus, as one simple example, superior results are likely if both the people who conduct the changeover are adequately skilled and best practice procedures are followed. Having available skilled personnel to conduct the changeover in the absence of a clearly defined optimum procedure would be less satisfactory. Conversely, having defined procedures but untrained staff would equally be detrimental to attained levels of performance.

4.2 Integrating design improvement to both Products and Processes

Work at Bath is currently being undertaken on the unified design of products and their associated manufacturing processes. One example of a glass jar closure and its manufacturing system is presented by Reik [26].

A further study concerns the manufacture of supermarket shopping trolleys. The product's customers (the major supermarket chains) were seeking much wider product diversity, principally reflected in a greater range of trolley sizes. Price remained a key issue, where the price paid per unit was determined via Internet auctions. The existing range was limited to just three main products (although obsolete ranges could also be unprofitably accommodated), and manufacturing was heavily dependent on manual operations within successive work cells. Manufacturing flexibility was poor also in terms of changeover performance, which typically exceeded three hours.

Ambitious decisions were taken to seek greatly superior manufacturing performance in terms of:

- To at least double the volume capability
- To reduce changeover times to below 5 minutes
- To reduce the product cost
- To expand the range to a family of at least 30 products

Tactics which were adopted to successfully achieve all these objectives included:

- Using robotics where possible, to significantly reduce the manual task content
- To modularise the product, including seeking commonality of product features and construction method
- To switch to a production line operation
- The elimination of product-specific jigs

These objectives were not possible unless redesign of the product occurred simultaneously with re-appraisal of the manufacturing system: both needed to be addressed in unison if these challenges were to be met.

Some specific details are:

- The new trolley basket comprised the assembly of flat pack components, rather than folded single-piece assemblies
- By virtue of the above method, the product (as a finished welded assembly) was stronger
- The product cost more in terms of its material content, but still cost less overall to make
- Changeover very substantially occurred via reprogramming (from a database) the production line robots. Tooling did not need to be changed.
- Further feature standardisation was adopted where possible throughout, to enable common handling and common welding tool access (hence again eliminating the need for amendment during changeover)

With availability of suitable pre-used robots, the necessary investment was of the order of £1m.

5 CONCLUSIONS

Flexibility and responsiveness are watchwords of modern manufacturing, driven by a desire to reduce non-value-added activity and better respond to customer demands. Rapid changeover between products is paramount if genuine manufacturing flexibility and efficiency are to be achieved, where a leading changeover capability is strongly identified with the modern manufacturing paradigms of *lean* and *mass customisation.*

To date the quest for better changeover performance has been substantially focussed on retrospective organisation-led improvement. However there has always been an absence of a comprehensive and coherent methodology to assist designers to create engineering systems which have a 'designed in' ease-of-changeover capability. Poor design imposes sub-optimal changeover practice, which subsequent organisational refinement will be unable to fully redress. Work at the University of Bath has identified that significant design-led improvement opportunities can frequently exist and ideally require to be addressed alongside those of organisational refinement. Provisional work at Bath indicates that simultaneous design attention to both manufacturing systems and to the product under manufacture can optimise changeover capability, sometimes simplifying changeover procedures to the extent that any chance for further meaningful organisational refinement is eliminated.

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