1. Introduction

In 1977, Sugimori et al. published the first paper on the principles of the Toyota Production System that was written in English [1]. They stated that the use of computer systems for organising production logistics would introduce unnecessary cost, over-production and uncertainty. Instead, they focused upon Kanban (card) systems because of their simplicity and robustness. The Kanban was described as an information system in its own right: "It is only the final assembly line... that can accurately know the necessary timing and quantity of parts" (p. 555). As also noted by New [2], this approach made a striking contrast with that of contemporary Western companies, in which information technology and advanced automation was often seen as the way to gain competitive advantage (for example, General Motors invested $70 billion on information technology and automation[2,3]). Interestingly, a common misperception at that time was that information technology and advanced automation were the main success factors of Japanese production practices [4]. It is now realised that the Japanese approach was not rooted in the use of information technology [5–8]. Nevertheless information technology does have a role to play in achieving excellence in production.

The aim of this article is to review that role through a thorough literature review.

Herron and Braiden [9] presented a three stage maturity model that described the application of Lean Production techniques.

The principles of Lean Production have enabled organisations in the manufacturing and service sectors to significantly improve their competitiveness. The application of Lean principles, derived from the Toyota Production System has enabled many organisations to simultaneously improve productivity, quality and customer service. Similar benefits have been achieved through the application of information technology (IT). The application of IT and Lean principles are claimed to be interdependent and complimentary by some; whilst others have seen as the approaches as being mutually exclusive.

This article presents reviews the role of IT in achieving the principles of Lean Production. Three important topics are reviewed: the use of IT in production logistics; computer-aided production management systems; and advanced plant maintenance. It is shown that the roots of different ways of working were similar, but that subsequent developments followed in opposite directions. Later, when the acceptance of Lean Production became more pervasive, the practices typically converged into hybrid production systems, applying elements of several systems in a way that is consistent with the principles with Lean Production.
the late 1970s had seen an explosion of interest in material requirements planning (MRP), which became known as ‘the MRP crusade’ [10]. There was also a strong interest in numerically controlled machine tools and advanced automation. In the west, there was a view that an automated factory was less vulnerable to worker militancy [2]. In contrast the Japanese were focusing upon just-in-time/Lean methods rather than using computerised tools. They also had a preference for low cost automation and relatively simple manufacturing technologies. Sugimori et al. [1] commented that the Kanban (card) system had various advantages over computerised approaches: (i) the cost of processing information was reduced; (ii) it was better at recording and communicating information in a dynamic environment; and (iii) the demand for all items was synchronised. The Japanese considered Kanban systems to be more transparent; workers could understand the status and requirements of production without having to access and navigate complex software. In fact, Sugimori et al. [1] criticised the lack of respect for humans in production organisations controlled by computerised planning systems. Sugimori et al. described how Kanban delegated control decisions to foremen and workers, rather than adopting centralised decision making, which was the approach adopted by MRP.

2.1. Historical background of production planning and control systems

The Kanban system was developed at a time when economic order quantity (EOQ) systems were widely used. The assumption behind the use of EOQ was that cost advantages could be gained through making an optimum trade off between inventory holding costs and re-ordering costs. Both the EOQ model and inventory reordering systems originated from the work of Harris [11,12]. Whereas the Kanban system uses small transfer batches, EOQ systems independently determine ‘optimal’ process batch sizes for parts and products, resulting in a large variety of order quantities. Burbidge had strong objections against the use of EOQ, which he described as “pseudoscientific nonsense” [13, p. 18]. Burbidge argued that real cost advantages would arise from improving the material flow system with a balanced ordering of parts, based upon explosion of end product demand [14]. EOQ is a simplistic model; it does not take into account the variability of cost factors, stock outs or the costs arising from a lack of co-ordination in the system. These extra costs become particularly visible if demand or product designs change, which can result in stock that cannot be sold. The irregular loading of the production system will entail extra co-ordination or capacity costs. The Kanban system was designed to use small lot sizes and hence to prevent these problems from occurring [13,15].

EOQ systems have been widely used by practitioners and researchers since the beginning of the 20th century. Mabert [10] described various attempts to calculate synchronised inventory requirements before and during World War II. Benders and Riezebos [16] showed that the periodic batch control (PBC) systems are effective at synchronising demand. Burbidge [17] was one of the first researchers to propose a modification of the EOQ system that took into account the relationships between products and parts. This Standard Batch Control (SBC) system synchronised the ordering of a small batch of products with the (re)ordering of exactly the correct amount of components.

The Kanban system can be considered to be a special type of SBC system. It assumes that orders for parts for a parent item are divided into several transfer batches of standard size. The time between issuing these transfer batches is slightly longer than the time needed to refill inventory. The small and standard transfer batch size creates an efficient and regular flow of material. The Kanban system therefore balances material flow throughout the manufacturing system [15].

However, there are some differences between Kanban and SBC systems. Kanban is a visual mechanism that gives shop floor workers control of the production process, whereas SBC was developed for use by centralised planning departments. In Lean Production the planner is responsible for setting the transfer batch size for Kanbans and for additional procedures, such as level planning that aims to avoid unbalanced loading of different stages of production stages. However, the decision to start the production of a batch, is under the direct control of the shop floor employees [15].

2.1.1. A dynamic world

After World War II the industrialised countries faced a steady increase in demand. Many production facilities had to be rebuilt, as many had been destroyed or reconfigured in order to supply military products. In the post war years the modernisation and rebuilding of industry created a strong increase in the demand. However, resources were scarce, so improving efficiency became a critical issue. In the west, improvements were generally achieved through increasing set up batch sizes, but this made throughput times longer [16]. There was a lot of local optimisation and the effects on inventory and flexibility were often overlooked.

Systems theory and, more specifically, industrial dynamics, did take into account the relationship between the parts of a system and the time varying behaviour. Forrester [18] studied dynamic systems that consisted of time-sequence relationships and amplification behaviour. He observed that the response to a change is generally exaggerated compared to the response that could be reasonably justified by the magnitude of the change. This behaviour has been observed in the ordering behaviour in succeeding stages of the supply chain. The variability in demand increases through the supply chain [19]. This phenomenon is commonly known as the Bullwhip, Whiplash or Forrester effect. The main causes for this erratic or nervous behaviour were found to be due to: (i) a time delay in the information feedback system; (ii) the use of incorrect inventory policies such as increasing safety stock as demand increased; and (iii) the use of statistical forecasting techniques which assumed that the historical demand patterns would prevail in the near future [15]. The effective management of inventory and lead-times therefore requires coordination throughout the supply chain.

The literature on industrial dynamics had an important impact on the design of planning systems. There was more focus on the integrated control of the supply chain, by using the information of end product demand in the control of each manufacturing stage. The important principle of linking product and component demand through a bill of materials explosion, which was known before WWII, was rediscovered. The development of computerised information systems reduced both the required time and the costs of integrated control. Many of the early books on MRP (e.g. [20–22]) paid attention to the detailed options within the systems, such as advanced lot sizing rules. However, the important design parameters, such as lead time offsets, bill of material structure, safety stocks and lot sizes, did not receive particular attention in this early work [10]. This often compromised the quality of the underlying data model within MRP systems, which limited their effectiveness. In consequence, industry became sceptical about the potential of these production planning systems [10]. The result was a tendency to use the systems mainly for administrative purposes such as ordering, maintaining the bills of materials, as well as recording price and lead time information. They were also used for tracking and tracing inventory.

2.2. Production planning systems

The popularity of cyclical planning systems [23–25] and visual control systems including Kanban [1], ConWIP [26,27] and Polca [28,29] has grown rapidly over the last few decades. A major
5. Loading stability

Cost balance

2. Proportionality
Synchronisation

1. of production planning systems [15]. This has had important consequences for the architecture of centralised planning systems. In the area of workload control systems, production planning systems have provided an improved understanding of the consequences of order release on system performance [31].

2.2.1. Centralisation vs. decentralization

One of the reasons for the popularity of ‘pull’ systems is that many production facilities have implemented Group Production/Cellular Manufacturing and team working, which have delegated responsibility and authority to the workforce. This has limited the scope of central planning to: the design of the planning system; the allocation of planning tasks; the determination of the work order release packages; capacity analysis; and the coordination of material flow between autonomous units [15]. These changes have implications in terms of MRP data models. Processing time estimates became less important because process control was delegated to teams within cells. However, the accuracy of transfer and arrival times (particularly at bottlenecks) became more important as centralised planning was responsible for coordinating the flow of materials from suppliers and between cells. Thus, Cellular Manufacturing changed the focus of centralised planning systems. This has had important consequences for the architecture of production planning systems [15].

2.2.2. Planning for Cellular Manufacturing/Group Production

Petrov [32] was one of the first authors to consider the redesign of the planning system to meet the requirements of Group Production/Cellular Manufacturing. He studied 81 firms in St. Petersburg that had adopted Group Production in accordance with the central economic plan of the Russian government for the period 1963–1965. He concluded that “in the vast majority of group flow lines in operation, production is very far from being rhythmic, parallel or proportional, and the problems of materials and technical supplies have not been solved correctly. Basically this arises from the lack of coordination between production engineering aspects of flow line design and its organisational and planning aspects. . . . The real saving to be achieved by adopting group techniques is for most part determined by the success or failure of the system of production organisation and planning.” [32, p. 9, 13]. Petrov [32] proposed five principles that should be followed when designing a planning system for Group Production:

1. Synchronisation: the completion of one stage of production and the initiation of the next should be coordinated and synchronised to generate rhythmic production.

2. Proportionality: the batch sizes or run frequencies for components should be either the same, or a multiple of those used for the products that require them. Proportionality should be maintained for all stages and operations within the process.

3. Limitation: the number of different ordering cycles within the system should be limited as far as economically possible.

4. Cost balance: the cost of operating the planning system should be balanced with the cost of operating the production system. Management should strive for rhythmic production. Cycle times and set up times should be minimised, whilst set up batch sizes should be maximised to achieve maximum productivity and low labour costs.

5. Loading stability: the loading of the groups, shops, sections and work places should be stabilised through a correct distribution of the total load over successive time intervals in order to generate a steady output.

The work of Petrov [32] provided insight into the increased sensitivity of Group Production to loading imbalances. These could be tackled by increasing multi-functionality within groups, but a loss of pooling synergy [33] remained a problem that should be taken into account when designing a production planning system for Group Production/Cellular Manufacturing.

2.2.3. Cyclical planning systems and the use of the information technology

Petrov’s [32] work was recognised in the United Kingdom. It supported the development of cyclical planning systems. The contribution of New [34] was particularly important. He considered the changes in planning system design that could be achieved using information technology. The argument that a system had to be as simple as possible because of processing restrictions was no longer considered valid. “The ‘simplicity’ of single phase systems is no longer important, though the advantages that such systems offer in terms of low work-in-process, flexibility and facilitated load planning remain” [34, p. 82]. The use of information technology made it easier to design tailor made planning systems in which specific product types were treated differently. Parts with extremely long or short throughput times, expensive items, general items, items that were produced with uncertain yield etc., could be controlled more easily by the application of appropriate planning principles. This was made possible by the use of information technology [15].

Hall [35] considered that the application of cyclic schedules was important to achieve improvements in manufacturing organisations and achieve close synchronisation. He also considered cyclic scheduling to be a vital concept for continuous improvement. The contributions expected from cyclic planning systems included:

1. Improved supply chain co-ordination;
2. Eliminating the causes of disturbances rather than reacting to them;
3. Improved introduction of engineering changes coordinated with the release of work orders;
4. Increased consciousness of internal client/server relationships between successive cycles.

The renewed interest in cyclical planning systems led to a combination of insights from several branches of research. Attempts were made to integrate methods that had been developed for multi-item lot sizing, capacity constraint scheduling, sequencing, and synchronised flow production. Luss [36] showed that systems were better synchronised when the length of the production interval for the first stage was small. Shhtub [37] developed a heuristic lot sizing procedure for cyclic scheduling that was based on the trade-off between set-up costs and inventory costs. His work was further developed by Jamshidi and Browne [38] and Rachamadugu and Tu [39], who continued research on other lot sizing approaches within a cyclical planning framework.

2.3. ‘Push’ and ‘pull’ systems

The literature makes a distinction between ‘push’ and ‘pull’ material control systems. Hopp and Spearman [40, p. 142] defined a ‘pull’ system as “one that explicitly limits the amount of work in progress that can be in the system”. Therefore, material control systems that are characterised as ‘pull’ need to have an authorisation mechanism to control work-in-progress (WIP) when making decisions to release work to the shop floor. The MRP
system is a typical example of a ‘push’ system, as it does not explicitly limit the amount of work that can be released to the shop floor. Likewise cyclical planning systems are ‘push’ systems. With Kanban and similar card based systems there is a direct relationship between the number of cards and the amount of work in the system [1]. Kanban explicitly limits the amount of WIP in the system and acts as an authorisation mechanism. It is therefore a ‘pull’ system.

2.3.1. Lean or not Lean: the performance comparisons

By the late 1980s, a number of researchers had compared the performance of ‘push’ and ‘pull’ systems. The relationship between performance and the type of manufacturing organisation adopted has been studied extensively (see for example [41,42]). Many researchers have found that Kanban ‘pull’ systems achieve lower inventories and shorter throughput times than MRPIII ‘push’ systems. Cyclical planning systems have been found to achieve similar performance to Kanban if combined with Cellular Manufacturing [43–46].

Rees et al. [43] compared cycle times achieved by Kanban, cyclical planning and an MRPIII system that applied lot-for-lot batching (L4L). Simulation results showed that the MRPIII system generated greater savings than the Kanban system, in spite of the fact that some of the MRPIII offset times were longer than the Kanban throughput time. If MRPIII and Kanban were both implemented with the same number of cycles per day, the results favoured MRPIII because it required fewer set-ups and achieved lower inventory.

2.3.2. Complications

The literature on Kanban and Group Production/Cellular Manufacturing, such as [1,47] generally assumed that: the cell structure is fixed; that cells adopt a line layout; and that the distribution of processing and throughput times are known. The design of the planning systems focuses upon determining the number of Kanbans per product per cell (i.e. determining the total throughput time of a Kanban) as well as achieving a level schedule of end products such that the loading of the various cells fluctuates minimally [15].

The literature on Lean system design describes some desirable characteristics production systems for Kanban system control [35,48,49]. However, it does not offer adequate support for making congruent decisions on the structure of both systems [15].

2.4. The development of systems for Lean Production

The recent literature on production control in Lean production environments has considered the significance of the characteristics of the production environment. The recognition that make-to-stock or assemble-to-order companies face different problems to make-to-order or engineer-to-order companies has had a large impact on the development of new production control mechanisms for Lean production systems. The ConWIP (constant work in process) system [26,27] is a product-agnostic card system in which all the jobs may be different provided that they follow the same production sequence (routing). Make-to-stock environments may use product-specific cards, such as Kanban. The main difference with Kanban is that ConWIP does not use small intermediate stocks in production or the supply chain. Most ConWIPSTudies have considered the design of systems in a make-to-stock setting [26]. Polca was designed specifically for make-to-order situations [29].

‘Pull’ systems became particularly popular due to the increased application of Lean Production, which aims to minimise waste. Long throughput times and high work in progress are considered to be waste. According to the basic law of Little [50] they are interrelated. Hence, ‘pull’ systems attempt to reduce throughput time by limiting the amount of work-in-progress on the shop floor. If the total WIP is below a critical level, the average throughput time will be very small, but the system will not be able to achieve the required output. Therefore, work-in-progress has an important function in smoothing production output. Some ‘pull’ systems aim to have as little WIP as possible, some aim to keep the WIP as constant as possible, whilst others just use a maximum load limit that may not be exceeded (by restricting the number of cards circulating).

The location of the WIP in the production system is important for the adequate fulfilment of the smoothing function, i.e. it determines whether the required output of the system can be achieved. If the WIP in the production system is located ineffectively (i.e. waiting before machines, whilst other machines are idle) output might be reduced. Therefore, an important further distinction between ‘pull’ systems is the location of the WIP in the production system.

2.4.1. ‘Pull’ systems for to-order-production

This section will discuss and compare some ‘pull’ systems that can be applied in make-to-order or engineer-to-order production. The IT support for these systems will also be considered.

2.5. ConWIP: constant work in process

Hopp and Spearman [51] provided a general introduction to the ConWIP system of material control. Several extensions and variants of ConWIP exist, such as [26]. The important factors are: (i) the authorisation mechanism; (ii) the type and number of items in WIP; and (iii) the location of the WIP. ConWIP is a ‘pull’ system according to the definition of Hopp and Spearman [40]. ConWIP uses a combination of physical and virtual authorisation mechanisms. The physical mechanism, which may use either cards or containers, provides authority to the operators for new order releases. The virtual mechanism is needed to provide guidelines on which order to release. Hopp and Spearman denote this virtual mechanism as a “sequencing and scheduling module” [51, p. 442], which might be a dispatching rule such as earliest due date first, or a more complicated heuristic.

In a ConWIP system the choice of items to produce is determined by the virtual mechanism. The physical system only indicates that a new order may be released, but does not limit the set of orders from which to choose. The sequencing and scheduling module determines which orders will be released in the system. The quality of this element within a ConWIP system may significantly affect the timing and balancing capability of the whole system. Hence, the role of IT support in achieving a good performance of the ConWIP ‘pull’ system should not be underestimated.

2.6. Polca: paired-cell overlapping loops of cards with authorisation

A general introduction to the Polca system of material control can be found in Suri [28] or Riezebos [29]. Polca is a ‘pull’ system in terms of the Hopp and Spearman [40] definition. Polca uses two types of authorisation mechanism. The first is normally a card system that limits the amount of WIP. In order to start production, a cell needs to attach a card to components. It specifies the next cell to visit after the order has been completed. Vandaele et al. [52] developed a Polca system that used virtual cards (their system is a load-based Polca system). In both cases, this triggering mechanism sets an upper limit to the amount of WIP on the shop floor. A release list is the second authorisation mechanism within a Polca system. It is based on the production plan and does not apply a fixed limit to the amount of WIP. It enables the planner to control the progress of orders by having planned release dates for each
Table 1

<table>
<thead>
<tr>
<th>Visual ‘pull’ system</th>
<th>ConWIP</th>
<th>Polca</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Autonomination</strong></td>
<td>Make-to-stock</td>
<td>Make-to-order</td>
</tr>
<tr>
<td><strong>Production environment</strong></td>
<td>Make-to-stock</td>
<td>Make-to-order</td>
</tr>
<tr>
<td><strong>Number of parameters</strong></td>
<td>Has to be set for each product</td>
<td>Has to be set for each routing</td>
</tr>
<tr>
<td><strong>Progress control by planner</strong></td>
<td>No influence</td>
<td>Release sequence for whole order</td>
</tr>
<tr>
<td><strong>Workload balancing capability</strong></td>
<td>Not present</td>
<td>Not present</td>
</tr>
</tbody>
</table>

In the course of time, if new orders are released, the orders do not need to be similar to orders that have been released before. Polca will keep a balanced mix of orders in the routing of the orders within the first two cells. Table 1 compares the Kanban system with the two systems described in this section.

The first row of Table 1 describes the visual signal provided by the systems. All ‘pull’ systems use visual signalling, but Polca uses visual cards that include colour-coding (both cells receive a different colour on the card), which increases the information content of the system.

‘Autonomination’ is a term used by Ohno [6], which means ‘automation with a human touch’, i.e. involving employees in the process of standardisation and automation of their work practices. Employees have a greater role in the design and adaptation of the Kanban system due to the shorter loops taken by Kanban cards. In the ConWIP and Polca systems the loops are longer as they cover several cells, which makes it more difficult for a single operator to feel completely in control.

Implementations of Kanban are mainly found in make-to-stock environments, as the cards are product specific. It might be possible to implement Kanban in other environments as well, but due to the strict relationship between a card and a specific product the variety of products has to be limited. ConWIP implementations are also mainly found in make-to-stock environments [26]. However, the system can easily cope with make-to-order situations, as the cards are product-anonymous. Polca is somewhat more flexible, as it only requires the current and subsequent cell to be identified when releasing an order. Therefore, Polca can be used in engineer-to-order, make-to-order or make-to-stock situations [15].

There are large differences in the number of parameters that have to be set when using the three systems. The system which requires the minimum number of parameters varies according to the particular production environment. The number of parameters in a Kanban system depends upon the number of different products; in ConWIP on the number of routings; and in Polca on the number of pairs of cells in the routing set.

In a Kanban system, the role of the planner is focused upon generating a level schedule; their contact with shop floor employees may be limited. A planner using a Polca system can influence the choice of orders in a cell by taking authorisation decisions. ConWIP is somewhat in between, as it only allows for release lists per order. It has no separate authorisations per cell or operation. The last row of the table indicates the workload balancing capability of the ‘pull’ system, i.e. the ability to reduce throughput times by: (i) avoiding large WIP buffers before a bottleneck; and (ii) avoiding bottlenecks through the intelligent release of orders. Polca clearly outperforms the other mechanisms in this respect.

This section has discussed the historical background to production planning and control systems. It turns out that the roots of the different systems show similarities, but that later developments and implementations (facilitated by IT) have grown differently. In today’s industrial practice, it is not uncommon to see several types of systems and principles used together in one operational environment. The following section considers the use of systems from the wider viewpoint of a number of integrated functionalities.

3. Computer-aided production management systems

CAPM systems may be considered to be “all computer aids supplied to the production manager” [53]. Information processing activities include: the specification and definition of manufacturing tasks; planning and control; and recording and reporting. CAPM systems are information systems that include: transaction processing, maintaining, updating and making available specifications, instructions and production records; management information used for decision making, particularly relating to the allocation of resources and priorities; and automated decision making [53].

3.1. Integrated functionalities

The following CAPM modules include support for planning:

1. Master production scheduling (MPS) which is “an anticipated build schedule for manufacturing end products (or product options). As such it is a statement of production, not a statement of market demand. That is the MPS is not a forecast” [54]. Coordination between manufacturing and sales personnel is required.

2. MRP is “a set of techniques which uses the bill of materials, inventory data, and the master production schedule to calculate requirements for materials. It makes recommendations to release replenishment orders for material. Furthermore, since it is time phased, it makes recommendations to reschedule open orders when due dates and need dates are not in phase. Originally seen as a better way of ordering inventory, today it is primarily seen as a scheduling technique, i.e. a method for establishing and maintaining valid due dates (priorities on orders)” [55].

3. Capacity requirements planning (CRP) is “The function of establishing, measuring and adjusting limits or levels of capacity. Capacity requirements planning in this context is the process of determining how much labour and machine resources are
required to accomplish the tasks of production. Open shop orders and planned orders in the MRP system are input to the CRP which 'translates' these orders into hours of work by work centre by time period’ [55].

There are also modules which support control:

1. Inventory control, “the activities and techniques of maintaining stock items at desired levels, whether they are raw materials, work in progress or finished products” [55];
2. Shop floor control (sometimes called production activity control) is responsible for transforming planning decisions into control commands for the production process [56];
3. Vendor measurement “the act of measuring the vendor's performance to the contract. Measurements usually cover delivery, quantity and price” [55].

3.1.1. Inconsistent with the principles of Lean

As discussed in Section 2, prior to the 1960s most Western manufacturing companies focused upon inventory control, usually using reorder point systems. Many companies operated in markets where demand exceeded supply. Government policy often sought to reduce domestic competition through the imposition of tariff barriers that encouraged cartelisation and collusion [57]. In the 1960s many companies supplied relatively stable markets and focused on cost minimisation through high volume manufacturing. In this environment it was possible to keep high levels of 'just-in-case' inventory and still stay competitive. Inventory control software provided a mechanism to efficiently manage large volumes of inventory [58]. Computerised reorder point systems based upon economic order quantity and economic reorder point logic met the needs of these firms [59]. The net result was often a combination of high inventory, long cumulative lead times and poor delivery performance. In the academic literature, there was also a strong focus upon dispatching rules (see for example a comprehensive review in [60]), but these are not important when inventory is minimised. It is clear that these early approaches were inconsistent with the principles of Lean.

3.2. Enterprise Requirements Planning (ERP)

In 1975 Orlicky commented that the number of pages written on independent demand systems outnumbered those written on dependent demand by 100 to 1 [21,59]. MRP originated in the early 1960s as computerised method for the time-phased ordering of materials with either independent or dependent demand. The timing and quantity of demand specified in the MPS was combined with information in the bill of materials to calculate the gross requirements for components and assemblies within each time period. This was compared with the inventory status and scheduled receipts to calculate net requirements for each item [56]. Material requirements planning assumes infinite capacity, fixed leads lead-times and a predetermined product structure. In its basic form there was no attempt to model the current shop loading or capacity constraints [61]. MRP works best in stable environments in which the demand for products is very predictable. When there is uncertainty MRP needs to frequently reschedule. To cope with changes in demand additional subsystems such as purchasing and feedback loops were incorporated [62].

The combination of master production scheduling, material requirements planning and capacity planning together with the potential to provide feedback from the shop floor and vendor management systems was termed 'closed loop' MRP. This integration was necessary to achieve control over lead-times [63]. Various financial modules were added to provide software that offered an integrated approach to the management of resources [56]. Wight [64] coined the term 'Manufacturing Resources Planning' MRPII; the old term MRP is sometimes referred to as 'MRPI', 'mrp' or 'little MRP' [54]. By the 1990s MRPII had been developed to provide support for a wide range of functions including product design, warehousing, human resources, project management and communications. The term enterprise resource planning (ERP) was coined because the systems supported the whole enterprise [58]. The Eleventh Edition of the APICS dictionary defined enterprise resources planning as “a framework for organising, defining and standardising the business processes necessary to effectively plan and control and organisation so that the organisation can use its internal knowledge to seek competitive advantage” [55, p. 38].

MRP systems contain many parameters that determine how the system operates. Some of the parameters, such as the planning horizon and the frequency of regeneration influence the volume of data and the amount of processing required [61]. Typical packages also include control parameters relating to each item of inventory such as: the minimum days between orders, maximum number of days supply, order cut off date, shrinkage factors, lead times, annual stock costs, order quantity categories, fixed order quantities, minimum/maximum order quantities, safety stocks, safety lead times and fixed order costs [53]. The use of these parameters aims to tackle the effects of uncertainty (through increasing inventory) rather than addressing the underlying cause. This is contrary to the principles of Lean thinking which are based upon process improvement and minimising inventory.

3.3. Transformation to hybrids: ERP, 'pull' systems and just-in-time

Companies are increasingly using off-the-shelf ERP solutions [65]. Gefen and Ragowsky [66] estimated that the cost of implementing ERP systems ranged from $200,000 for small companies with a turnover $10m, $600,000–$800,000 for companies with a turnover in the range $50m–$80m and up to several million dollars for larger companies. ERP systems can dramatically reduce the amount of time required to obtain information relating to products and processes. They can help increase the speed and quality of management decisions, whilst simultaneously reducing costs. It is also possible to improve communication with suppliers and customers. The use of ERP can stimulate the adoption of standardised business processes throughout the organisation [65]. Indeed Al-Mashari [67] comments that one of the major drivers for implementing ERP systems is the fact their design is based upon best practices and they provide a mechanism for the standardisation of business processes. These motivations and benefits are clearly well aligned to the principles of Lean Production. Furthermore, many Lean companies now use ERP based approaches for communicating demand through the supply chain to facilitate just-in-time delivery. For example, Nissan Motors (UK) communicates its requirement for products to the correct specification and sequence and delivers them directly to the production line within 20 min. Not surprisingly, Kanban is used throughout the plant to fulfill local materials supply. Such hybrid situations (MRP/ERP, Kanban) have become quite common in modern industry.

In the 1960s, computer-aided production management systems and just-in-time were divergent technologies. The situation is now transformed—computer-aided production management and Lean are now complementary technologies.

4. Advanced maintenance processes

Over the last three decades there has been an increasing demand to improve product quality whilst simultaneously
Reducing costs. Lean Production is particularly sensitive to quality problems and strives to minimise waste. For production facilities in high cost countries, quality and efficiency have become prerequisites for survival. It has become important to maximise the technical performance of production equipment whilst minimising production disturbances. This is the aim of the maintenance function.

Current maintenance practice is usually heavily supported by information technology (IT). However, as with other elements of Lean Production, the value that IT can add in practice varies according to the specific characteristics of the application, the quality of the data and the robustness of the inherent models. The objective of this review is to describe the aspects of the maintenance function known to benefit from IT. It will also identify the risks and limitations. For this purpose it is necessary to start with a brief review of different maintenance principles and techniques.

4.1. The development of the maintenance function

Waeyenbergh and Pintelon [72] provided an overview of the development of the maintenance function and different strategies, as did others [68–71]. The chronology of the development of the maintenance function [72] is shown in Table 2, which shows four stages. During the first stage maintenance was purely corrective and seen as a cost, a necessary evil. The risks and limitations. For this purpose it is necessary to start with a brief review of different maintenance principles and techniques.

4.1.1. The organisation of maintenance

Table 2 shows that maintenance is increasingly recognised as an integrated function in terms of: (i) integration with the other life cycle phases of the asset [89] and (ii) integration with the other primary processes within the organisation [73]. There are four approaches to organising the maintenance function [69,72].

4.1.1.1. Total productive maintenance. TPM is a holistic approach, in which a combination of techniques and improvement campaigns aim to improve the Overall Equipment Effectiveness (OEE) [84]. The maximisation of OEE requires excellence in several operational aspects including the design/selection and purchase of the equipment, maintenance, appropriate usage and continuous improvement. There are other important factors relating to organisation and culture (particularly a focus on excellence and

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Table 2
Maintenance in a time perspective (adapted from [72]).

<table>
<thead>
<tr>
<th>Year</th>
<th>Maintenance Philosophy</th>
<th>Integration Efforts</th>
<th>Maintenance Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1950</td>
<td>‘Fix it when broken’</td>
<td>‘Production task’</td>
<td>CM (simple)</td>
</tr>
<tr>
<td>1950–1975</td>
<td>‘I operate—you fix’</td>
<td>‘Technical matter’</td>
<td>Maintenance is ‘task of the maintenance department’</td>
</tr>
<tr>
<td>&gt;1975</td>
<td>‘Necessary evil’</td>
<td>‘Profit contributor’</td>
<td>Maintenance is ‘isolated function’</td>
</tr>
<tr>
<td>2000–now</td>
<td>‘Partnership’</td>
<td>‘Internal and external partnerships’</td>
<td>Maintenance meets production department</td>
</tr>
</tbody>
</table>


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continuous improvement). TPM is therefore complimentary to Lean Production.

4.1.1.2. Condition-based maintenance. CBM aims to detect incipient failures long before their occurrence. CBM uses condition monitoring techniques to determine whether a problem exists, how serious the problem is, how long the asset can run before failure and to detect and identify specific components [90]. As explained by Tsang et al. [90], CBM is appropriate when: (i) time-directed preventive maintenance is not feasible (because failures happen randomly and/or an in-service failure not acceptable); (ii) a measurable parameter which correlates with the onset of failure can be identified; and (iii) it is possible to determine a threshold value for the parameter when action is to be taken [90].

De Boer and Klingenberg [91,92] described several methods for condition monitoring, which were characterised by: (i) the method for establishing the threshold value of the parameter; and (ii) the type of knowledge inherent in the model. CBM has received increasing attention in recent years [75]. It has been proved that CBM concepts can be applied practically [93–95]. CBM has included the monitoring of vibrations [98], the modelling of sheet metal blanking [96–98] and there are many other interesting examples [99,100]. Various methods have been used to ascertain some threshold value or trend with which the measured parameter can be compared to in order to predict the need for maintenance action. These include artificial neural networks [101], expert systems or analytical schemes [98] and hybrid systems containing elements of both [91]. These examples show that maintenance practice has developed in line with the Lean principles, which aim to prevention disturbances and waste. These approaches have been facilitated by IT.

4.1.1.3. Reliability centred maintenance. RCM was developed by the US aircraft industry [78]. Later, the concept was developed and made applicable for use in other industries by Moubray [77]. RCM can be described as a framework within which a maintenance regime can be designed. The first activity is to gather information through comprehensive failure modes, effects and criticality analyses (FMECA). Based on these analyses, appropriate maintenance routines can be determined for each element of an asset. These routines are prepared for by translating them into detailed work packages. The effectiveness of the RCM activities is monitored and adjusted when necessary. Some authors such as Waeyenbergh and Pintelon [72] have criticised the RCM approach because it appears complex and time consuming. It is claimed that the thoroughness of the approach can only be warranted in environments where reliability is critical (such as in the aircraft industry). However, one could argue that reliable equipment is increasingly seen as a prerequisite for Lean production systems.

4.1.1.4. Risk-based maintenance. Preventive maintenance activities may be considered to be ‘waste’ as they add cost but do not necessarily add value. They would only be applied if the alternative meant even greater waste (such as stoppage or loss of quality). Often, such assumptions are based on rules of thumb or general specifications from suppliers. In risk-based maintenance, the company is trying to express the risk accurately and to compare it to an acceptable benchmark figure [76]. In some cases, such risk calculations can help minimise waste. Researchers have proposed many models [102,103]. Other researchers, such as Garg and Deshmukh [69] have found that these risk models can become complex. The problem with using these models in practice is that the quality of the available data is often problematic and the models may be sensitive to inaccuracies in the data. Garg and Deshmukh [69, p. 214] argued that “(t)hese models have flourished only as a mathematical discipline within operations research (OR). The applications of the same have been very limited so far as virtually no case studies have been published”. Practical limitations in feeding and using the models appear to have prevented their use. These issues are similar to those Sugimori et al. [1] attributed to the use of complex planning tools.

4.2. Further specific applications of IT in maintenance

This section will outline some additional use of IT in support of the maintenance function.

4.2.1. MMIS

Experience of industrial practice gained by the authors suggests that by far the most widespread IT application used to support the maintenance function is the MMIS. Maximo and SAP plant maintenance are common examples [69]. However, this does not appear to be reflected in the academic literature on the maintenance function, although several authors have written on elements of the MMIS [69,72,87,88]. The basic functionality of MMIS is to process maintenance work-orders efficiently. This includes materials management, spare parts management, vendor management together with the reporting and monitoring of maintenance activities. This functionality may be integrated within ERP, however these materials are not stored/procured for use in production, but for use in maintenance of production assets. The planning and decision support functions appear to be the most conceptually challenging area; most of the academic literature appears to be directed towards these issues.

4.2.2. Decision support systems

Minimising and optimally timing inspection and maintenance is an area in which cost can be minimised and value can be found. This is potentially very complex, since it depends upon the behaviour of production equipment. It has proved possible to develop maintenance planning and decision making for a variety of situations, using different optimisation approaches. Examples include decision support for maintenance using the analytic hierarchy process [104], fuzzy analytic multiple criteria decision making [105] and expert systems [106]. Garg and Deshmukh [69] argued that there is a gap between theory and practice and that application of the DSS models proposed in the literature are very limited in industry.

4.2.3. Performance monitoring and evaluation

Significant performance monitoring and data management efforts have been reported in the literature and witnessed in industrial practice by the authors. The aim may be to gather all possible time stamped data from a piece of equipment in order to recognise trends and signs which could identify or predict equipment wear or other types of malfunction. Effective performance monitoring and evaluation could prevent interruptions and suboptimal behaviour. Other examples of performance monitoring are described in Bandi et al. [107] and Rochdi et al. [108].

4.3. Summary, discussion and observations

This section has described the development of the maintenance function, partially aided by the developments in IT. Four important approaches were considered; TPM, RCM, RBM and CBM. The literature describes applications of these approaches in industry. TPM and CBM support the principles of Lean Production because they prevent disturbances and support the reliable operation of production equipment. The most common maintenance-based IT application found in industry is the maintenance management information system, which is comparable to ERP.

The academic literature documents the initial developments and quantitative models that have been developed to support the
more complex areas of the Maintenance function. However, many of these proposals do not appear to have been applied in practice. In fact, Garg and Deshmukh [69, p. 214] concluded that: “(p)resently, many researchers are pursuing the development of various mathematical maintenance models to estimate the reliability measures and determine the optimum maintenance policy. However, these models may be useful to maintenance engineers if they are capable of incorporating information about the repair and maintenance strategy, … the methods of failure detection, failure mechanisms etc. that justify the production management. Companies that stuck to the limited successful developments in both automation and computer-aided production control approaches [3]. However, there have since been many other approaches, in particular CBM, show the ability to support Lean principles, since it allows prevention of disturbances and support reliable operations of production equipment. The most common IT application found in industry is the MMIS which is comparable to ERP (but specifically aimed at supporting Maintenance).

5.1.2. Advanced maintenance processes

Section 4 described the development of the maintenance function, partially aided by the developments in IT. Four important approaches were discussed: TPM, RCM, RBM and CBM. The literature describes applications of these approaches in industry. It appears that TPM overlaps with the principles of Lean Production. Other approaches, in particular CBM, show the ability to support Lean principles, since it allows prevention of disturbances and support reliable operations of production equipment. The most common IT application found in industry is the MMIS which is comparable to ERP (but specifically aimed at supporting Maintenance).

RCM and RBM are focussed approaches of which evidence of (varying degree of) adoption by industry is available. However, a gap was identified between significant efforts in advanced maintenance modelling papers and limited application in practice. Identifying causes for the apparently limited use of a wealth of quantitative models and tools in practice, and possibly finding solutions for these causes, may be an important suggestion for further work.

5.1.3. Suggested research directions

Based on the observations made in this review, the authors would suggest the following topics for further research:

- The recent development of hybrid production environments, as described in Section 3, appears to have received limited attention in the academic literature so far. Typically, researchers tend to select one particular topic for in-depth study. The hybrids are broad in their scope. Their development and use appears to be an important development in practice and requires attention.
- Opportunities were identified for the further development of specific ‘pull’ applications such as Polca that can be facilitated by IT.
- The combination of Lean Production with computerised methods provides an effective way to manage the supply chain. Research in Lean Production and its relationship with information technology should adopt a supply chain perspective.
- There appears to be significant opportunities for the use of CBM in various situations. The literature has shown that the CBM principles can be used in practical situations, but its usage does not appear to be commonplace as yet. This means that for many specific situations/requirements, the development of specific CBM solutions needs further work.
- In the literature on maintenance (e.g. RBM), a gap was identified between significant modelling efforts and limited application in practice. Effort is required in translating the theoretical progress into actual practical use.

References


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