The implementation of Industry 4.0 in manufacturing: from lean manufacturing to product design

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Received: 28 October 2021 / Accepted: 6 June 2022 / Published online: 21 June 2022
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Abstract
With the emergence of Industry 4.0, digitalization and intelligent manufacturing are vital to ensure competitiveness, especially for manufacturers reliant on legacy machines. Upgrading legacy machines with cyber physical technology under Industry 4.0 frameworks can enable connection of these machines to existing IoT networks to allow the sharing and exchange of production information. In this paper, a legacy machine used in sheet metal folding operations is upgraded by integrating switch sensors which provide detailed data on the machine status to stakeholders, enabling in-depth analysis of the production activity before and after the implementation of lean manufacturing methods. Furthermore, it is shown that the data collected can be applied to conduct dynamic value stream mapping (DVSM) in near real time to provide deeper level insight into manufacturing processes. More detailed mapping enables identification of wastes involved with labour and design. Therefore, an innovative graphical technique is proposed to improve the flattened pattern to reduce manual handling and ease bottlenecks identified by VSM. From the collected VSM data, a leanness measure was established to provide objective and quantitative evaluation of the process performance.

Keywords Industry 4.0 · Lean manufacturing · Value stream mapping · Legacy machine · Weighted graph representation · Leanness score

1 Introduction
With increasing global competition and fast adaptation to ever-changing market demands, manufacturing industries are currently being transformed from a focus on mass production to one of mass customization [1]. This transition involves considerable challenges for small and medium-sized enterprises (SMEs) to achieve manufacturing efficiency. In mass production, as the production is standardised and modularized, productivity and efficiency can be improved continuously to decrease production shortages [2]. In this context, lean manufacturing practices can be implemented to enhance throughput by eliminating wastes [3]. Although small batch and multi-variety production poses a greater challenge for implementation of lean manufacturing practices, processes may still be improved as some aspects of production will be similar to those of mass production and so are directly transferable [4]. Industry 4.0 is set to revolutionise manufacturing by building on existing technologies or combining them in new ways to cope with diverse production demands more efficiently and cost-effectively [5]. Importantly, it can provide continuous monitoring and performance measuring to reduce waste, as well as provide better process control and more efficient utilisation of manpower [6]. In this regard, much effort is being directed to reconfigure current manufacturing environments to achieve these goals. As an essential element of production, the shop floor typically houses many legacy machines which perform reliably but are not set up to communicate. By connecting them to a network, detailed information from these machines can be merged into the system to facilitate value stream mapping (VSM), including tool movement and indirect assessments of labour skill competency.
The remaining content of this paper is organised as follows. In the next section, the relationship between legacy machinery in production environments, lean manufacturing, performance measurements, and RAMI4.0 will be discussed. The third section deals with the application methodology while the fourth section presents a practical case study of an upgrade and efficiency enhancement based on the methods established in this research. Finally, a summary of the key achievements is provided in last section.

2 Background

2.1 Legacy machines

Due to their reliable mechanical performance and relatively high replacement costs, an abundance of non-networked, legacy machines continues to be employed by SMEs. However, the lack of native external communication capabilities leaves the machines isolated in a networked industrial setting, making the monitoring or control of the entire production process incomplete. Thus, retrofitting legacy machines to communicate is the first step toward integration into a networked production system which enables the collection of valuable data for analysis and exploitation, so that more efficient production can be attained. Cyber physical system (CPS) technology plays a significant role in enabling legacy devices to form a unified information infrastructure by facilitating collaboration among different entities in a common platform [7]. A cloud-based platform can verify production in virtual space without interference of operational equipment in the real environment [8]. In addition, innovative technology to facilitate “smart legacy machines” can enable higher productivity and reduce machine breakdowns [9].

As a key prerequisite to machine communication, digitalization is the process of creating a digital representation of physical objects or attributes. Hence, the transformation of the machine status or operation is critical. To realise this, Deshpande and Pieper [10] analysed the features related to machinery power signals under various operating conditions. In this way, one can monitor the real-time machine status, energy usage, and other specific machining parameters of a legacy machine, including the potential to detect tool changes or provide part counts. Similarly, Maeda et al. [11] developed a method to recognise the operational status of machine tools on the basis of spindle motor current through the use of a current sensor, since the electrical current is proportional to spindle torque. Accelerometers and microphones have also been tentatively explored as an effective means to monitor the operational status of a horizontal band saw [12]. Furthermore, other parameters such as temperature, pressure, vibration, and oil quality can be applied to not only monitor the basic status of a machine, but they can also be employed to analyse machine health for predictive diagnoses. Consequently, it is important to develop an affordable strategy to retrofit legacy equipment so that it can be integrated into Industry 4.0 frameworks [13]. This not only eliminates “isolated islands” within a production line but also increases the transparency of the entire production flow which can be streamlined to be more stable and effective. Based on an IoT platform, the energy consumption of each machine on the shop floor can provide feedback on the operational condition of the whole production system to support decision making [14].

Building on these prior studies, in this paper, we demonstrate that with the installation of sensors onto legacy machinery, not only does it enable direct virtualization of the processing, it also provides indirect feedback on the labour condition. This is critical to addressing bottlenecks involving heavy manual labour caused by inappropriate product design.

2.2 Lean manufacturing

The main priority for lean manufacturing is to eliminate waste through continuous improvement. Identification of processes which lead to waste is the key to implementation of lean manufacturing [15]. With the view that waste is any activity that adds cost but is non-value-adding for the customer, the Toyota production system identifies seven waste classes: overproduction, inventory, motion, defectiveness, transportation, overprocessing, and waiting. Overprocessing is unnecessary or incorrect processing, typically resulting from poor tool or product design [16]. This waste is also related to labour performance since poor design will lead to additional manual work. As one of the prominent methods to combat waste in manufacturing, VSM is a simple, visual process-based tool to identify all underlying wastes to facilitate their elimination [17]. Although VSM is employed increasingly on the shop floor and for supply chains between companies to enable managers to comprehensively understand the diverse material and information flows, its inability to reflect detailed process information at the micro level for each station within a processing system increases difficulties in detecting wastes. This information is necessary in order to implement other lean tools to reduce process wastes. Especially, labour performance in operating machinery and handling materials cannot be readily distinguished from equipment utilisation.

After identifying wastes through initial VSM, other lean tools such as just-in-time (JIT), total productive maintenance (TPM), and Jidoka can be enacted to achieve lean transformation by minimising or eliminating wastes. The equipment availability, performance, and defect rate exhibited in VSM are optimised by the implementation of TPM practices to improve overall productivity [18]. JIT aims to reduce wastes
by coordinating work in progress and inventory management while Jidoka can be implemented to reduce defect rates through the introduction of technologies [19]. Levelling of production, known as Heijunka, can be employed to reduce wastes by sequencing material flows [20].

In addition, lean design approaches based on the principles of lean manufacturing can deliver higher values and less wastes in an indirect manner by increasing production efficiency [21]. The design for manufacture (DFM) philosophy is viewed as one aspect of design thinking to reduce wasteful processes in manufacturing [22]. Through product design optimization, many wastes occurring in manufacturing processes can be removed to maximise product value for customers [23].

Overall, VSM is a critical aspect in transforming a production system through implementation of lean manufacturing principles which can highlight the problematic processes within production flows. Other lean tools or approaches may then be adopted according to the specific issues identified to reduce waste and create lean production flows.

2.3 Reference architecture model for Industry 4.0

RAMI4.0 (Fig. 1) was proposed to aid adoption of Industry 4.0 by integrating available standards into a single new concept [25]. Built on a series of existing and usable approaches, this model provides a more comprehensive version of Industry 4.0 by combining the concepts of vertical integration, horizontal integration, and life cycle evaluation [26]. In the vertical layers, asset and integration layers derived from Smart Grid Architecture (SGAM) represent the separation of the physical from the immaterial information world, while the communication layer is involved with network building. A basic communication protocol is required to provide a general basis for transporting different higher-level protocols over the network [27]. There exist many standardisations which enable devices and applications to exchange information in an interoperable way [28]. On a higher level, the information layer takes charge of bundling data pertinent to assets or processes from the communications. Termined as “Big Data”, these high-volume, high-velocity, and/or high-variety information assets can aid productivity, product, and process implementation and decision-making [29]. Supported by real-time “Big Data”, in higher layers like the functional and business layers, more specific functions like enterprise resource planning (ERP) and business collaboration can analyse, predict, and make appropriate decisions [30]. On the life cycle and value stream axes, there are two distinct parts: the type represents a product in an abstract form while the instance indicates the actual product being manufactured [31]. These two parts are closely related and interactive. In the hierarchy levels, “Product” and “Connected to World” are the new parts to be extended based on the enterprise control system standards (IEC62264). The “Product” indicates the tracking of products through real-time data collection via the network. With the localization of products, production workflow can be controlled or optimised to enhance the process efficiency.

Through this unified model, all resources in the manufacturing domain are closely integrated by the information technology. Advanced technologies implemented under Industry 4.0 frameworks can incorporate traditional lean manufacturing approaches to identify wastes and support decision-making which enhance productivity and efficiency.
toward creating more agile production systems to fulfill consumer demands [32].

### 2.3.1 Research structure

A flowchart which shows the implementation of DVSM under an Industry 4.0 framework is presented in Fig. 2. It provides an overview of the guiding steps which were implemented to shorten the cycle time for bending operations for a modern manufacturing enterprise catering to mass customization of its products.

With increasing demand for customization of products, optimised processing requires more transparency across the system which is enabled by real-time collection of detailed information from each workstation or process. This raises the issue of how to efficiently integrate and analyse the multiple types of data collected. A standardised framework brought by Industry 4.0 aims to establish an interoperable network to communicate between different entities across a manufacturing system is required. However, for many SMEs with limited resources and often reliant on legacy non-interfaced equipment, building an interoperable system is a challenging task. Hence, this research aims to address several key issues for SME manufacturers catering to customised production and seeking to implement Industry 4.0.

1. **How to build an economic and effective network suited to a SME manufacturing system under Industry 4.0 frameworks which is interoperable and accessible to outside partners?**

   Lean manufacturing is an important philosophy that is well established in the manufacturing field and many lean tools and lean approaches have been developed to transform legacy production methods into lean manufacturing operations. With the emergence of new technologies, it is necessary to update these traditional lean tools to meet the rapid and variable demands of modern production systems.

2. **How to implement traditional lean tools into networks built according to Industry 4.0 frameworks to detect and reduce wastes within fast-paced and customised production environment?**

   For underlying wastes not addressed by implementation of lean manufacturing tools, lean design is another approach to eliminate manufacturing wastes by improving the product design to minimise processing time and effort. Considering customised production requires an agile approach to design and manufacturing, a design system which can cater to customised production is critical to productivity.

3. **How to enact an innovative design approach based on the product features which can accommodate the demands of customised production while facilitating ease of manufacturing?**

   Finally, a quantifiable measure to evaluate leanness is necessary to provide an objective appraisal of production systems and any improvements made. This is a critical step to verify the methods applied and must be selected according to the real environment including Industry 4.0 technology and corresponding lean tools which are applied.

4. **Which evaluation tool can be employed to objectively evaluate leanness in the context of Industry 4.0 production systems?**

![Flow chart of research](image)
3 Methodology

3.1 Dynamic value stream mapping with micro view

Encompassing the entire production process, value stream mapping is composed of three parts: information flow, material flow, and the time ladder. Information flow takes charge of scheduling each operation, material flow reflects the flow of semi-finished products in the processes, and the time ladder refers to the detailed time consumption in related stations. However, without the dynamic characteristics of production, these results are confined to a specific period. Thus, a static description of the production behaviour makes quick responses impossible. As a result, dynamic value stream mapping (DVSM) is the optimal approach, as the real-time effects can be coupled with e-kanban to deliver timely information to the shop floor. Furthermore, it can help CPS Heijunka to adjust strategies accurately in rapidly changing environments or for line balancing reassignments.

In addition, because it provides an overview of the whole production flow, VSM fails to place emphasis on each detailed activity that must be undertaken such as distinct stations for machining, folding, drilling, etc. Manipulation of the processes works well for standard batch production as the time and activity required for each process can be anticipated well in advance. However, for customised production even if the machine selected is the same, the machining processes may differ markedly, leading to variation in time consumption or higher cost processing that is difficult to predict. Any overprocessing waste caused by incorrect manipulation of the machining operation will not be easily identified. Hence, it is necessary to monitor the detailed processes for each product dynamically. Importantly, the labour performance involved can also be identified by DVSM which provides feedback to managers in near real time.

Aside from wastes identified by DVSM, setup times may be an important indicator for managers, as the consumed time during setup may be greater than the processing time, which is particularly relevant for customised products. In standard batch production, the setup is the same and the time consumption is generally identified as a constant number in the data box. But for individualized products, the different processing flows make the changeover times vary substantially since individual tooling is applied distinctly. Accurate mapping of these time variations is necessary to facilitate optimization to the whole of production.

3.2 Architecture setup

To achieve the dynamic characteristics of DVSM, a system comprised of Arduino micro-controllers and wireless Zigbee transmission modules seeks to provide full connection between the real and virtual objects in order to communicate and exchange information in real time [33]. Based on the RAMI4.0 model, the vertical layer takes charge of transforming factory resources and product life cycles via digitalization. Initially, the integration of these two fields is determinant to the systematic management, including to combine the specific machining parameters with relevant products across the manufacturing phase. Then, the communication layer merges data from multiple sources into the main coordinator [34]. Wireless communication networks such as IEEE 802.11 or IEEE 802.15 are currently employed to facilitate automatic collection and real-time processing of field data in manufacturing processes [35]. Developed under 802.11, Wifi supports a high data transfer speed and long transmission range, but poor energy efficiency limits battery life. In comparison, built upon IEEE802.15.4 with a low data transmission rate, Zigbee has several advantages such as low cost and reduced power consumption. Furthermore, ZigBee has been applied widely in the field, from industrial control, to monitoring and switch signals operations, and other applications requiring low-data-rates and high reliability [36].

In Fig. 3, an architecture for process monitoring of a folding operation is established. The Digi 3.0 device placed on the PC is set as a coordinator to coordinate all information within the network. The information received is analysed for display on the user interface (UI) in near real time and stored in database history records. The foot pedal control switch is connected to a XBee IO port. Owing to the mobility of the pedal control, the XBee module is powered by battery. Hence, with configuration of a sleep mode, the XBee will work as an End Device to save power consumption. Furthermore, configuration of “Transparent” mode ensures any state change of the switch signal is sent instantly by XBee [37]. Similarly, the cylinder limit switch that detects the cylinder travel is monitored and sent by XBee in AT mode (synonymous with “Transparent” mode). Finally, an Arduino system is placed close to the dies and punches in order to detect the changeover condition. Organic liquid crystal displays (OLCD) can show the relevant information including the start and stop of a specific component when it enters into or out of a station. Operating in API (application programming interface) mode, XBee can send a variety of additional information encoded in each packet. This can assist the coordinator to
obtain more information such as the folding component ID number or any specific tooling applied to fold.

### 3.3 Design guidelines

The design for manufacture (DFM) philosophy integrates techniques, practices, and attitudes in the initial design phase to maximise manufactured quality and life cycle support while minimising manufacturing costs [38]. For sheet metal products, the major manufacturing processes are cutting, bending, and assembly. Processing commences with a 2-D layout created in CAD to produce the flat pattern for the shape of the sheet metal part to be formed. Owing to its importance in manufacturing, various approaches have been adopted to design sheet metal products to generate an appropriate flat pattern for near-minimum manufacturing costs [39]. Among them, the method of graph representation is becoming increasingly popular as it provides a computer representation of the topology/connectivity of the faces of the 3-D folded structure and implements an algorithm to operate on this model to unfold and generate the geometry of the planar product layout [40]. Specifically, the face adjacency graph (FAG) can translate topological information by describing the part’s connectivity with nodes and links, which are associated to the product’s faces and edges [41]. Therefore, this information can be evaluated in a generic format by numeric analysis [42]. Researchers have attempted to extract flat patterns by enumerating all possible spanning trees from the FAG [43]. Based on these enumerations, optimisation strategies were developed to determine the most appropriate flat pattern to produce a product [44]. Five different optimization objectives were developed to help designers prioritise flat pattern features in the manufacturing stage [45]. Owing to its objective to facilitate easy manipulation and bending of the product, the compactness criterion is the most popular to optimise the flattened pattern and several approaches have been developed including the geometric compactness and minimum enclosing area methods [46]. Among these, the weighted face adjacency graph (WFAG) method, which removes ambiguity and errors that arise from the use of unweighted graph methods and incorporates the bend lines as a criterion, is an efficient tool to optimise flat pattern designs according to manufacturability and product cost considerations [47, 48].

According to these considerations, it is apparent that developing an innovative design methodology to eliminate production wastes must not only consider the manufacturing efficiency, but also integrate other factors such as material costs and labour skills.

### 3.4 Lean assessment

Lean assessment is a common approach to track the effectiveness of lean initiatives or continuous improvement programs. However, an accurate assessment of leanness is challenging as any assessments in the absence of quantitative measures are inevitably subjective [49]. Although many different measurement tools have been developed, there is
no ideal indicator which can accommodate every system perfectly owing to the complexity of these systems and the many often conflicting objectives [50].

Previous research on leanness assessment can be broadly categorised into either quantitative or qualitative methods according to the nature of the data obtained [51]. Qualitative assessments involve collection of information on the system of production from surveys in the form of questionnaires. A score may be assigned to translate this qualitative evaluation of the system performance to assess the overall leanness according to the degree of adoption of the lean principles. However, this method evaluates the degree of compliance between the system and some predefined determinants according to the surveys and so does not necessarily reflect the real leanness of the system. Hence, a quantitative approach based on collection of data from the system offers a more objective method to assess leanness [52]. Quantification of leanness based on complete and actual data from the production system can provide a more rigorous evaluation. Currently, more than half of the research into lean quantitative assessments adopt benchmarking which facilitates continuous monitoring of leanness through scoring against the benchmark [53]. Using an ideal process as a benchmark, the data envelopment analysis (DEA) can analyse flow performance incorporating multiple input/output variables which take into consideration the consumption of all resources across a manufacturing system (a cell, a production line, or the whole factory) [54]. A DEA assessment based on Charnes-Cooper-Rhodes (CCR) Model was the first mathematical model to assess leanness and successfully capture multiple wastes in manufacturing systems. However, the leanness level estimated by CCR is overestimated due to the influence of slacks (i.e., input excesses and output shortfalls) in the benchmark. Due to slacks frequently existing in a large portion of non-value adding activities, the result of the CCR model is not intuitively understandable without considering those inefficiencies caused by slacks. In this context, the slacks-based measure (SBM) was implemented to address this issue by directly incorporating input excesses or output shortfalls [55]. With capture of the impact of undesirable conditions, the results of SBM-based assessments of leanness are more accurate.

In quantifying leanness in a cell or station on the manufacturing floor, the slacks-based measure (SBM) provides information to support decision-making, complementing information gathered from value stream mapping [56].

4 Case study

4.1 Product and manufacturing analysis

The case study presented is an Australian manufacturer producing customised alloy ute canopies. As shown in Fig. 4, the whole pull process starts from the order’s product dimension input. As each ute tray is generally different
in size, the key dimensional information including length, angle, height, and top width are known only after the order is submitted. This submission triggers a chain of inputs and actions across the production stream, from the design file to the manufacturing processes. A former investigation [57, 58] has identified the bending process as a bottleneck, with the sideboard part specifically consuming significant time. VSM was instrumental in making this determination. However, to uncover further information during the bending process, hidden from the original VSM, an improved workflow was implemented (Fig. 4, blue frame) starting with the bending machine. The upgraded wireless system installed on the machine transforms the process activity into a digital operation signal and provides feedback on time consumption. Based on the machine logic process diagram, the value adding and non-value adding processes can be easily distinguished to enable a better understanding of waste. When combined with the component folding sketch and change over setting, DVSM provides a detailed manufacturing analysis and reporting in near real time.

4.2 Dynamic value stream map building

To explore the component processing with DVSM including dynamic characteristics such as inconstant tool changeover times caused by customised production, as well as inconsistent processing times due to the multiple elements involved, the plate folding process has been illustrated from the flattened pattern to the folded state shown in Fig. 5a, b. To detail the processing sequence, all 19 bends to the sideboard plate are illustrated in Fig. 5c with the step number. Considering the part-tool interference fit condition required to achieve the folds, an appropriate combination of accurately aligned punch-die pairs is exhibited in Fig. 5e-g), matching the corresponding processes.

Following the folding process, DVSM results are depicted in Fig. 6 where each dark green value-adding bar relates to the time consumed for each fold, and a detailed breakdown is shown in the associated pie chart containing theoretical folding time (green), over folding time (red) and additional labour time consumption (orange). The theoretical folding time indicates the ideal folding time, only accounting for the down and up travel of the punches, and is used as a reference or ideal benchmark. However, the real folding time for a process includes the over folding time in addition to the theoretical folding time. The over folding time can often occur when novice operators struggle to align the bending line, which is critical to quality but can be a challenging and time-consuming task. Non-value adding to the product, the over folding time is classed as overprocessing waste. Additional labour time is displayed as the orange slice in Fig. 6, which includes any other non-value adding manual handling. Labour time is inversely correlated with labour skill since the plate adjustments for aligning the bending line with the punch are impacted by the technical proficiency and experience.

In this operation, we can see that the changeover (dark red) costs considerable time in comparison to the folding time (dark green). In order to display these two aspects suitably in the DVSM, a “×10” scaling was applied to the changeover time for viewing purposes.

![Processing diagram](image-url)
In the real manufacturing environment, the labour time spent to draw the folding lines and setup the initial tooling is recorded as changeover time depicted by the dark red bar F1 in Fig. 6. Based on this setup, the first bending operation is illustrated with the dark green bar F1. After that, the following 11 bends were achieved with the same setup of punch and die and the actual folding operations of this component are depicted from F2 to F12 with only dark green bars since no tooling changes were required. To complete the folding of F13 and F14, the punch and die must be adjusted to be equal to the top width illustrated in Fig. 5d. The following processes are all illustrated in the same manner.

A substantial proportion of the processing time is spent changing tools; therefore, SMED might be an ideal method to reduce overall processing times by allowing the tooling setup to be performed while the machine is running [59]. However, the specific operation of the folding machine mechanism prevents any changeover while it is in a working condition. Instead, type levelling using Heijunka is applied to minimise equipment changeovers [60]. In this case, we can use two different sized side boards, but of the same type, together to enable the same types of fold to be processed in sequence. Although the size difference will still require adjustments to be made, their common characteristics reduces the changeover times as the punches or dies only require minor adjustments. This is verified by the reduced dark red bars shown in Fig. 7, where the second board changeover time is substantially lower than that of the first board, particularly for the F16 changeover whose boards have the same height, negating any need for adjustments.

4.3 Product design improvement

Considering the advantages of minimal material usage and ease of assembly, the flat pattern for the sideboard was developed based on the compactness criterion. To construct the WFAG of the sideboard, the No.1 plate was first selected as the base plate as it has the largest area [61], and all connected edges were assigned corresponding lengths as shown in Fig. 8a. After searching based on the edge length, a graph was constructed by joining every pair of vertices (or nodes) to represent the optimal compactness illustrated in Fig. 8b.

Although material cost is saved, this design inadvertently creates a self-blocking area shown in Fig. 8d which complicates the bending process. Accordingly, the bending process for the sideboard becomes an unexpected bottleneck in the production which would severely affect the productivity. Hence, the process improvements focus on the generation of the flat pattern as it impacts on the fabrication. Here, we propose an innovative graphical representation to assign more geometric information to the edges.

The edge data includes the line orientation relative to the x, y, and z axes in the first line; e.g., 70/20/90 indicates that the angle of the line to the x, y, and z axes is 70, 20, and 90, respectively. Additionally, the bend angle is incorporated with the length in the second data label line, i.e., as angle (green)/length (red). The new WFAG representing the sideboard component assembly is shown in Fig. 9.

To alleviate bottlenecks in the bending operation, the number of bending steps must be reduced to the least possible. Hence, shared faces (4, 6, 10, 14, 18) are selected as priority bends. Additionally, a consistent part orientation
is preferable across a series of bends so that they can be performed without further adjustments. Using the same angle settings to complete all folding processes can save the operator from updating the control panel frequently. As the final criteria, short seaming is prioritised in the operations as this can make following joining process easier.

Fig. 7 Lean method to fold two different sized side boards of the same type: (a) the first board results, which includes tooling change for the new type (bottom width 1760 mm, downside height 465 mm, upside height 445 mm, top width 1400 mm); (b) the second board results, which includes tooling changes for the different size (bottom width 1790 mm, downside height 445 mm, upside height 445 mm, top width 1425 mm)

Fig. 8 Original design (a) weighted face adjacency graph construction, (b) spanning tree based on compactness, (c) flat pattern, and (d) formed side board with blocking area
Following the prioritisation, the connections are generated to form a spanning tree diagram where every pair of vertices (or nodes) are joined by a path as shown in Fig. 10a. However, this flat pattern, shown in Fig. 10b, increases the production difficulty as it is too large for plate materials available in the market. A suitable decomposition must be applied using a minimum joint criterion as shown in Fig. 10c. The decomposed spanning tree in Fig. 10d shows the prioritised folding operations for the three components which are generated accordingly.

For productivity in assembly, some design modifications are required to facilitate the joining process for the decomposed parts [39]. Parallel to two shared faces, an assembly tab is incorporated as the time spent on this joint through the use of an adhesive in negligible in comparison to welding [39]. The final product is shown in Fig. 11.

4.4 Measuring leanness

Value stream map (VSM) allows lean practitioners to visualise the performance intuitively by graphically mapping the manufacturing processes. In Fig. 12, the DVSM reflects the improved bending performance after design improvements. The setup time is reduced as the tooling is simplified and the labour is reduced as handling is minimised leading to less time consumption in the bending operations. Although these value-added and non-value-added activities are easily differentiated, an objective and quantitative indication of the value stream improvements is not available. Hence, implementation of a combined VSM and DEA leanness assessment offers the potential to establish overall leanness of the current production state in comparison to an ideal state. A relative score can be calculated based on VA time collected and cost analysed.
In this study, decision-making units (DMU) are identified as the observation of a work piece flowing through the bending machine. An actual DMU (ADMU) is an observation of the actual production with actual time and costs as the input variables while the created value is output variable. In contrast, an ideal lean DMU (IDMU) only includes the value-added (VA) costs and VA time spans. To build these two types of DMU, several data entries from the VSM are collected in Table 1.

The SBM fractional program is defined as follows:

\[
\rho_{\text{lean}} = \frac{1 - (\frac{1}{m}) \sum_{i=1}^{m} \frac{\phi_{i}}{x_{i0}}}{1 + (\frac{1}{s}) \sum_{r=1}^{s} \frac{\psi_{r}}{y_{0r}}}
\]  \hspace{1cm} (1)

Subject to

\[
x_{0} = X \lambda + s^{-}
\]  \hspace{1cm} (2)

\[
y_{0} = Y \lambda - s^{+}
\]  \hspace{1cm} (3)

where \( \lambda, s^{-}, s^{+} \geq 0 \)

Fig. 10 Design modification: (a) spanning tree for improved flat pattern, (b) improved flat pattern, (c) decomposed flat pattern, (d) spanning tree for decomposed flat pattern

Fig. 11 New flatten pattern: (a) left part with tab, (b) right part with tab, (c) side board, (e) flat pattern of three components, (f) three folded components assembled
Notation:

\(\rho_{\text{lean}}\) : leanness score

\(s^-\) and \(s^+\) : slacks associated with inputs/outputs

\(x_0\) : inputs of \(\text{DMU}_0\)

\(y_0\) : outputs of \(\text{DMU}_0\)

\(m\) and \(s\) : numbers of input/output variables

\(\lambda\) : weights for \(\text{DMUs}\)

To evaluate the single machine operational performance, one pair of \(\text{DMU}\) and \(\text{IDMU}\) is applied based on the data collected from the bending operation. Equations (1) to (3) are reduced to calculate the leanness with two inputs and one output:

\[
\text{Leanness Score} = 1 - \frac{1}{2} \left( \sum_{r=1}^{s^-} \frac{x_r}{x_0} + \sum_{r=1}^{s^+} \frac{y_r}{y_0} \right)
\]

\[
\text{Leanness Score} = 1 - \frac{1}{2} \left( \frac{x_{TA}}{x_{CA}} + \frac{y_{VA}}{y_{VI}} \right)
\]

\[
\text{Based on the prepared data in Table 1, the results of the SBM model are calculated below:}
\]

\[
\text{ADMU} \left( x_{TA}, x_{CA}, y_{VA} \right) = (676, 8.15, 190)
\]

\[
\text{IDMU} \left( x_{TI}, x_{CI}, y_{VI} \right) = (76, 1.54, 190)
\]

\[
\text{Leanness Score} = \frac{1 - \frac{1}{2} \left( \frac{x_{TA}-x_{TI}}{x_{TA}} + \frac{x_{CA}-x_{CI}}{x_{CA}} \right)}{1 + \frac{1}{2} \left( \frac{y_{VA}-y_{VI}}{y_{VA}} \right)}
\]

\[
= \frac{1 - \frac{1}{2} \left( \frac{676-76}{676} + \frac{8.15-1.54}{8.15} \right)}{1 + \frac{1}{2} \left( \frac{190-190}{190} \right)} = 0.151
\]

Through the design improvement in the flattened pattern, the bending process has been adjusted for ease of handling by the labour force. Table 2 depicts the value from the system after design improved.

Based on the data in Table 2, the SBM model is calculated as below:

\[
\text{ADMU} \left( x_{TA}, x_{CA}, y_{VA} \right) = (219, 2.458, 190)
\]

Table 1 Data entries before design improvements

| Variable         | Procedure                                                   | Example                                      |
|------------------|-------------------------------------------------------------|----------------------------------------------|
| Time             | Side board folding lead time                                | Setup & process time = 676 s                 |
| ADMU Cost        | Labour and machine cost spent on side board folding         | (676 × 30 + 210.69 × 43)/3600 = $ 8.15      |
| Value            | Retail price × customer satisfaction                         | $ 200 × 95% = 190                           |
| Value adding time| Ideal side board folding lead time                          | Ideal setup & process time = 76 s           |
| IDMU Value adding cost | Ideal labour and machine cost spent on side board folding | (76 × 30 + 76 × 43)/3600 = $1.54             |
| Value            | Retail price × customer satisfaction                         | $ 200 × 95% = 190                           |
Owing to its quantitative and objective assessment of the leanness, the performance can be compared between the two production states. It is clear that the redesign has doubled the efficiency proving the effectiveness of the design improvements in reducing wastes in processing and setup times. A cost analysis reveals estimated savings of $5.692 for each unit which represents a large economic benefit to the company due to the substantial production volumes for this component.

### Conclusion

With the emergence of Industry 4.0, implementation of digitalized technology can enable SMEs to enhance their production efficiency. The process transparency and interconnectivity afforded by these technologies can detect wastes on the shop floor which are otherwise difficult to identify. In this study, a bottleneck was identified in a mass customised production line and dynamic value stream mapping (DVSM) analysis was able to reveal that the cause was inefficient manual handling during bending operations. Lean tools and design improvements were implemented to enhance the labour efficiency in order to relieve the bottleneck. This research set out to address four key research questions (RQ). The solutions implemented and key achievements arising from the research are outlined below:

### RQ 1: How to build an economic and effective network suited to a SME manufacturing system under Industry 4.0 frameworks which is interoperable and accessible to outside partners?

**Solution:** All activities within a manufacturing operation should reference the industry 4.0 framework and provide understanding of the processes and transformations from the bottom to the top level. Any resources on the shop floor or other areas are digitalized for communication and integrated to reflect into the higher level cyber space. This unified, interoperable digitalized information from resource models can be shared with internal or external stakeholders.

**Achievement:** A legacy machine was upgraded with cost-effective sensors and wireless modules under an Industry 4.0 framework, which enabled interconnection with existing networks to share and exchange information. It facilitated detailed data collection on the bending processes in real time including the labour condition, setup, and tooling to facilitate informed decision-making by management.

### RQ 2: How to implement traditional lean tools into networks built according to Industry 4.0 frameworks to detect and reduce wastes within fast-paced and customised production environment?

**Solution:** The transparency of the manufacturing environment afforded by Industry 4.0 upgrades enables lean tools to be efficiently implemented to make flexible process adjustments without needing to physically walk around and detect issues on the shop floor. Lean strategies can be enacted to address bottlenecks and assess the impacts of any changes.

**Achievement:** Near real-time data collection enabled DVSM to visualise performance at the individual process level. This provides complementary feedback to traditional VSM which is focused on an overview of the entire process.

### 5 Conclusion

Table 2  Data entries after design improvements

| Variable            | Procedure                                                                 | Example                                                                 |
|---------------------|---------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Time                | Side board folding lead time                                              | Setup & process time = 219 s                                            |
| ADMU Cost           | Labour and machine cost spent on side board folding                       | (219×30 + 52.95×43)/3600 = $2.458                                      |
| Value               | Retail price × customer satisfaction                                       | $200×95% = 190                                                          |
| Value adding time   | Ideal side board folding lead time                                        | Ideal setup & process time = 44 s                                      |
| IDMU Value adding cost| Ideal labour and machine cost spent on side board folding                | (44×30 + 44×43)/3600 = $0.89                                            |
| Value               | Retail price × customer satisfaction                                       | $200×95% = 190                                                          |

**IDMU** ($x_{TA}, x_{CT}, y_{VI}) = (44, 0.89, 190)

**leaness**

\[
Leanness = \frac{1 - \frac{1}{2} \left( \frac{x_{TA} - x_{VT}}{x_{TA}} + \frac{x_{CA} - x_{CT}}{x_{CA}} \right)}{1 + \frac{1}{2} \left( \frac{x_{TA} - x_{VT}}{y_{VT}} + \frac{x_{CA} - x_{CT}}{y_{CA}} \right)}
\]

\[
= \frac{1 - \frac{1}{2} \left( \frac{219 - 44}{219} + \frac{2.458 - 0.89}{2.458} \right)}{1 + \frac{1}{2} \left( \frac{190 - 190}{190} \right)}
\]

\[
= \frac{1 - \frac{1}{2} (0.799 + 0.638)}{1} = 0.2815
\]

Owing to its quantitative and objective assessment of the leanness, the performance can be compared between the two production states. It is clear that the redesign has doubled the efficiency proving the effectiveness of the design improvements in reducing wastes in processing and setup times. A cost analysis reveals estimated savings of $5.692 for each unit which represents a large economic benefit to the company due to the substantial production volumes for this component.
production but is unable to identify wastes at individual workstations. A lean tool Heijunka was implemented and DVSM successfully captured the process improvements.

RQ 3: How to enact an innovative design approach based on the product features which can accommodate the demands of customised production while facilitating ease of manufacturing?

Solution: Lean thinking, which is traditionally applied to manufacturing processes, can be directed toward product design to support agile manufacturing operations. With the shift toward service-oriented manufacturing, product design can be optimised to enable flexible manufacturing which caters to mass customisation production. Achievement: An innovative graphical representation of a component design and its processing was developed which provides enhanced geometric information to optimise the processing operations compared to conventional weighted face adjacency graphical approaches. The method provides more in-depth data on the process operations to enable the selection of processing sequences which reduce manual handling and minimise impacts on downstream processes.

RQ 4: Which evaluation tools can be employed to objectively evaluate leanness in the context of Industry 4.0 production systems?

Solution: Quantitative evaluations of processing performance provide superior insight into manufacturing operations configured under Industry 4.0 frameworks. The enhanced digitalisation of process information enables unbiased evaluations of leanness and provides more accurate assessments to decision-makers on the performance and improvements implemented. Achievement: A slack-based model which provides an objective, quantitative, and integrated assessment of leanness of the value stream map was established. Based on detailed data from production activities, it enables real-time analysis of the performance. Furthermore, the model incorporates all sources of inefficiency into a single leanness score between 0 and 1 to enable direct comparison of different processing strategies.

In summary, with interconnection through Industry 4.0, upgraded legacy machinery can provide more in-depth and detailed process information which, as well as enabling process improvements, can inform the product design to achieve higher production efficiency.
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