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Procedia Manufacturing 54 (2021) 19–24

Procedia MANUFACTURING

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10th CIRP Sponsored Conference on Digital Enterprise Technologies (DET 2021) – Digital Technologies as Enablers of Industrial Competitiveness and Sustainability

Lean industry 4.0: a digital value stream approach to process improvement

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Abstract

As a concept, Industry 4.0 encompasses the total transformation of the 'traditional' production environment with the real-time networking of products, processes and infrastructure via the Internet. What is not clear however, is the functional relationship between pre-existing operational practices such as Lean Manufacturing and Industry 4.0, and thus the associated organisational qualities of 'Lean-ness' and 'Smart-ness' respectively. This work then presents a formulaic approach to the ubiquitous Lean Manufacturing Value Stream Map process, in order to incorporate Digital elements into traditional product value streams. The result is the creation of a Digital Value Stream Map, which may be utilised to rationalise and deploy Industry 4.0 improvement projects.

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Peer-review under responsibility of the scientific committee of the 10th CIRP Sponsored Conference on Digital Enterprise Technologies (DET 2020) – Digital Technologies as Enablers of Industrial Competitiveness and Sustainability.

Keywords: Industry 4.0; Lean Manufacturing; Continous Improvement

1. Introduction

Lean Manufacturing (LM) as an industrial philosophy evolved from the conceptualisation of the Toyota Production System first pioneered in the mid-20th century, over a number of initiatives performed at the Toyota Motor Company of Japan [1]. Here LM may be described as a production approach that is directed towards the identification of customer value, with the intent to create a streamlined flow of processes which contain little non-value adding activities known as 'wastes' [2]. As such, LM has achieved worldwide recognition as the foremost methodology for the improvement of internal production processes [3], popularised by the acclaimed book 'The Machine that Changed the World' that brought the methods of Toyota to the rest of the world more than 28 years ago [4].

Despite the apparent success and popularity of LM throughout industry, literature indicates that less than 10 percent of UK manufacturing organisations have yet accomplished a successful 'Lean Transformation' [5,6,7,8]. This poses an interesting predicament in the current environment, whereby the new paradigm of Industry 4.0 has taken centre stage as the next industrial zeitgeist.

As a concept, Industry 4.0 denotes the transformation of 'traditional' industrial processes with the real-time networking of products, processes and infrastructure whereby the supply, manufacturing, maintenance, delivery and customer service aspects of an organisation are all connected via the Internet, thus transforming rigid value streams into highly flexible value networks [9]. Here, the instrument in which to reach this increased level of organisational automation is the development of CPS's (cyber-physical systems), whereby assets may be equipped with microcontrollers, actuators, sensors or other communication interfaces, thus allowing interaction amongst the production environment. As a result, a factory and its assets may have said to become 'smart' [10,11].

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10.1016/j.promfg.2021.07.004

What is not clear thus far however, is the functional relationship between LM and Industry 4.0, and thus the associated organisational qualities of 'Lean-ness' and 'Smart-ness' respectively. According to a recent global survey conducted by The Boston Consulting Group [12], in a survey of more than 750 production managers, 97% of respondents felt that LM would continue to be highly relevant into 2030, compared with 70% who felt that it is important today. Amongst those respondents, 70% reported that industrial digitalisation under Industry 4.0 would become highly relevant in 2030, compared with 13% who felt that it is important today. From these findings, we may surmise that both approaches are likely to possess a contiguous relationship well into the near future, with clear intent for simultaneous application.

Here however, literature provides a conflicting message surrounding the modes of interaction of the two approaches, whereby LM and Industry 4.0 may be presented as; antecedent and precedent [13], the former as an enabler of the latter [1,14], the latter as an enabler of the former [15], and potentially incongruous [16,17]. Furthermore, in a literature review concerning the topic of LM and Industry 4.0 conducted by Leyh et al. [18], from a total of 31 papers reviewed, only 3 were found to directly refer to the practical application of LM and Industry 4.0 principles in a granular manner, with the remaining addressing the pairing of both approaches from an analytical or taxonomical perspective. Here, the distinct lack of coherence between LM and Industry 4.0 approaches may potentially be attributed with the current commitment dilemma and reluctance of many manufacturers, who remain sceptical of Industry 4.0 and its seemingly unperceivable benefits [1].

Thus, it may be hypothesised that in order for both LM and Industry 4.0 to be applied successfully in coexistence, concepts from both approaches must be combined within a common medium, that displays clear tangible benefits within a common improvement language. It is proposed then, that the ubiquitous LM method of Value Stream Mapping (VSM) may be augmented to include Industry 4.0 principles collectively in a Digital Value Stream Map (DVSM). In this manner, both approaches may be ratified within a common purpose, whilst minimising incongruities of purpose that may arise from isolated application.

2. Traditional value stream map creation

A value stream, as defined by Rother and Shook [20] encompasses all of the actions essential to the production of a product (both value adding, and non-value adding). Thus a VSM is a pictorial representation of the production flow of a product throughout a facility. Here, the fundamental goal of a VSM is to provide visualisation of process cycle times, inventory buff ers, operator deployment and the information flow within a given area, thus aiming to captures the entire transformation from raw materials to finished goods [21]. As such, a VSM illustrates inter-operation relationships typically omitted from traditional process flow charts. An example of a typical VSM is displayed in Fig. 1.

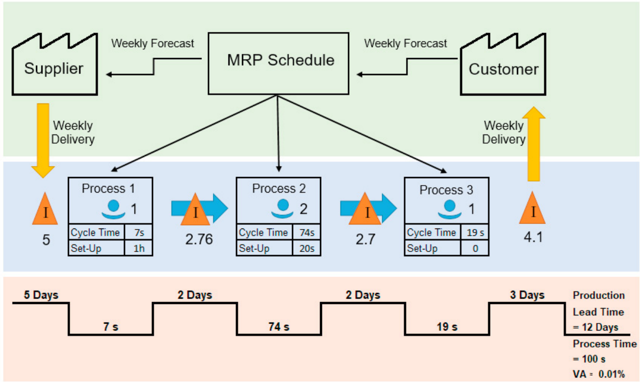

Figure 1. VSM Example – adapted from [22]

Here it may be noted that the focus on traditional VSM creation is the measurable outcomes of overall process visualisation, the calculation of the production lead time of a product, and its relative value-adding process time. However, although displayed as a product of the value stream mapping process, there exists no stage that aims to formally quantify and thus improve the management of data and process information throughout the product value stream.

3. Related work

Within literature, there are several examples of enhancements to the original VSM method, which focus on a variety of different aspects such as product development, logistics, material and data flow, with a small number concerning aspects of Industry 4.0. Here, a comparison of the methods which directly address the integration of Industry 4.0 concepts within a VSM will be presented, hereby identifying existing gaps within the proposed methods and determining necessary extensions for the VSM process.

The concept proposed by Ucklemann [23] considers the value-adding processes concerning the logistics of information within an organisation, and represents a CPS approach to extend the value stream method. This includes interfaces, relative detection levels, as well as inhibitors to information flow. Here, process building blocks are used to determine information logistical waste within the value stream, however the method does not derive a transparent, quantitative method of displaying this information as a tangible factor on shop floor operations from which improvement may clearly be proposed.

Meudt *et al.* [24] suggest a holistic view for information logistics in production, with the creation of a separate data flow VSM. This enables the identification and elimination of information logistical waste and the identification of digital improvement opportunities. Here the use of 'swimlanes' to represent distinct information flows, including the relationships between storage media, informational connections, and the nature of the data transported. Again, this process may be utilised to visually define the transactional flow of data within an organisation, however it is unclear how this information may be utilised to identify 'waste' and thus motivate process improvement.

Finally, Lewin *et al.* [25] propose an approach that aims to combine the previously identified methods, with approaches developed outside the scope of Industry 4.0 applications. Although this approach presents little in the form of novel methodology, the combination of techniques provides a distinctly clarified approach to mapping data transactions within an organisation, which combines positive elements from the aforementioned approaches into a well-rounded visual method that makes use of swimlanes and process blocks to denote process interactions, the nature of their acquisition, and their role within the organisations data network.

4. Approach for process improvement

In order to enhance the traditional Value Stream Mapping method, a stratospheric banding approach is advocated in order to incorporate additional elements without disrupting the intrinsically simple visualisation offered by this tool. Here, two key stratospheres are introduced, namely '*Process KPC Detection'* and *'Digital Information Flow'*.

4.1. Process KPC detection

It may be asserted that a primary motivating factor of the implementation of digitalised Industry 4.0 solutions within a manufacturing value stream is not simply the achievement of inter-process connectivity, but the real-time monitoring, and subsequent reactivity that this approach confers as a result. Therefore, a logical approach to the creation of a DVSM is with the definition of product Key Performance Characteristic (KPC) shop floor relationships, in terms of creation, subsequent verification, and the nature in which this is performed.

Traditionally, many manufacturing organisations create a set of product specific KPC's which are utilised for quality control purposes, in order to ensure the item is within acceptable tolerance, cleanliness, surface finish etc. according to customer defined specifications. Here, deviation from these specifications denote an unacceptable product or 'defect', which may inherently result from a large potential range of factors. Here it may be surmised that the time in which a defective product is identified is of paramount importance to a manufacturing organisation, so that root cause analysis and subsequent countermeasure may be deployed whilst minimising the inherent waste associated with a poorly performing process (e.g. product scrappage, machine downtime, rework) that may be conferred to further products, thereby increasing the likelihood of a 'product escape' (a defective product reaching the customer).

It is here that Industry 4.0 solutions offer a potential means in which to provide instantaneous feedback for the purpose of KPC adherence, so that defective product may be quickly and efficiently identified, or process trends analysed to proactively prevent defect occurrence. Therefore, the functional driving characteristic of this process may be determined as time – specifically, the time in which a KPC is formed within a product (i.e. at the point of 'manufacture'), and the point within the value stream that this KPC is verified (i.e. inspection, test etc.). Here, detection time D_T may be determined utilising equation 1 below;

$$D_T = \frac{\sum_{inventory\ a \ldots a+1}^{a..j^{th}} n}{CT\ a+1} \tag{1}$$

Whereby, the inventory quantity between the point of KPC formation 'a' and the subsequent process 'a+1' is divided by the cycle time (C_T) of the subsequent process (a+1) to yield the time in which the inventory will be processed in seconds. The summation of the inventory processing times between each process up to the 'j^{th}' process – the point in which the KPC is verified, are summed. This results in an overall detection time, which represents the longest possible period in which a KPC relevant defect may be produced and subsequently detected.

The introduction and detection points of a particular KPC may be monitored on the DVSM following the swimlane approach advocated by [24,25]. This may be utilised to define the nature of the data (e.g. digital, analogue) and the means in which the data is presented (e.g. via HMI, database, andon alarm system). This enables the organisation to quantify, and thereby base improvement, on the basis of time reduction as part of improving the responsiveness of production quality control.

4.2. Digital information flow

According to Lee [26], the establishment of CPSs may be identified as one of the main enablers for Industry 4.0. Here CPSs may be defined as systems of collaborating entities which simultaneously provide and utilise data. These are facilitated by a combination of physical and software systems, whose operations are monitored, controlled and coordinated by a central network [27].

Despite the current rising interest in CPS development, it is observed that the combination of physical and computational processing is not a new concept. Such systems, defined as "embedded systems", have been in use for some time in typically self-contained units. Here, the radical transformation that Industry 4.0 envisions, surrounds the networking of such devices so that they may freely interact with one another and their environment to provide superior real-time performance and cumulative collaboration [26]. Here the proposed DVSM concept also advocates the inclusion of a method in which to rationalise and consolidate digital and non-digital information flow.

It may be noted that the flow of information from the enterprise MRP system is currently captured by the traditional value stream approach as arrows denoting physical or electronic means of communication – Figure 1 (arrows leaving MRP schedule). However, what this approach does not define, is the medium in which this information is transported in the context of digital information flow. A potential result of this non-specification, is the unrestricted proliferation of modes digital communication, which are fundamentally incapable of cross-communication. As a result, we may argue that the enabling of traditional embedded systems to interact beyond their individual system boundaries is necessary in order to create completely new system functionalities, such as the ability to exchange information and autonomously control the performance of operations [28]. As a result, there is the requirement to create a single focal point of data exchange within the organisation, in which information generating and information utilising agents may access as a universal mode of communication. Here, the potential to utilise 'Cloud computing' [29] or 'Blockchain' [30] based communication mediums represent promising methods in which to provide functional levels of universal communication, however are currently beyond the scope of this work.

In application, the DVSM digital information flow may be quantified as a metric, though the categorisation of the modes of communication within the enterprise in which it is to be deployed. Here, an example may be the differentiation between verbal, physical (paper based), electronic, semi-automatic and automatic modes of communication. In turn, these modes of communication may be allocated a score between 1-5, that is representative of the perceived reliability, effectiveness and repeatability of the method from the perspective of the organisation. In application, a score of 1 represents the most favorable means, with 5 representing the least desirable. It must be noted that this enumeration process remains interpretative as an exhaustive categorisation system becomes difficult to formally introduce, due to both the variety and continual development of means of information exchange. Here an example is shown below in Table 1.

Table 1. An example information flow scoring system

Data Transfer Medium	Score Allocation
Employee (Verbal)	5
Manual (Paper)	4
Physical Kanban / FIFO	3
Software (Manual Input)	2
Software (Automatic)	1

Following the establishment of a scoring system, an individual transfer medium score is initially calculated utilising equation 2, which is then followed by an overall Information Transfer score that may be determined for the value stream. This may be calculated utilising equation 3:

$$Transfer\ Media\ Score = Numerical\ Rating\ x\ Number\ of\ Instances \quad (2)$$

$$I.T. Rating = \frac{\Sigma\ Transfer\ Media\ Score}{Number\ of\ Data\ Streams} \quad (3)$$

5. Lean industry 4.0 case study

In order to investigate the use of the DVSM concept, a case study was performed, which aimed to gauge the tools effectiveness in acting as a base in which to formulate capital investment in Industry 4.0 relevant technologies. This case study was performed at Algram Group Limited, a subsidiary of the Olympus group, who manufactures a range of thermoplastic products primarily for the Medical sector from its Plymouth (UK) based facility.

The DVSM has been applied to a value stream dedicated to the manufacture of medical sterilisation cases, that includes injection moulding, printing and assembly processes. Fig. 2 and Fig. 3 show the current and future state results of the DVSM executed according to original Lean VSM method, with the addition of enhancements described within the previous chapter. The defined metrics of KPC detection time and value stream Information Transfer score may then be contrasted and thus utilised to formulate the basis of investment based upon a tangible measure of improvement. The relative metric scores are compared below in Table 2.

Table 2. Comparing DVSM current and future state value streams

	Current State	Future State	Percent Improvement
I.T. Score	3.8	2.65	69.74%
KPC 1 $_{DT\ (Hrs)}$	141.02	0.01	1410200%
KPC 2 $_{DT\ (Hrs)}$	128.36	0.02	641800%
KPC 3 $_{DT\ (Hrs)}$	1.69	0.17	994%
KPC 4 $_{DT\ (Hrs)}$	1.69	0.17	994%

Here it must be recognized, that the intent of the DVSM is to continue to functionally act as a traditional Lean VSM, in the effect of reducing the total internal lead time – in this example from 6.5 days to 1 day. In addition, we may observe through the DVSM future state, that investment in technologies that functionally empower the organisation to verify process KPC's at source, result in a significant improvement to the relative detection time experienced within the current value stream, thus improving the reactivity of the organisation to non-conforming products and processes.

6. Discussion

The DVSM concept described is designed to enhance the original Lean VSM method, through the addition of a tangible means of measuring 'digital improvement' – an element that is felt to be neglected from the original VSM method. The potential here, is to create a rationalised foundation for an organisation to base its move towards Industry 4.0, in conjunction with enhancing its operational efficiency in line with Lean manufacturing principles. Here it is intended, that the DVSM tool is to act as a focal point in which the host organisation must begin to investigate, and thus either recognise or indeed develop engineering solutions which allow its future state to be realised. Naturally, these solutions may take on a plethora of different forms, and will vary greatly from organisation-to-organisation and industry-to-industry. An example taken from the practical example discussed in this work – is the realisation of an enabling technology in which to detect at source the means to verify KPC 1 – in this case a dimensional tolerance of an injection moulded component. Here the host organisation may explore a number of potential technologies in which to achieve this aim, for example: mould monitoring software, machine vision, or sensor driven dimensional measurement systems that may be incorporated into the process as part of the machine cycle which thus enables the verification of the KPC at source. The result is a vast improvement in the organisations ability to recognise and thus react to the process as it begins to produce non-conformances. In this manner, material scrappage may be reduced as the root cause is identified, which then yields the knock-on effect of preventing future re-work operations, as well as reducing the possibility of a defect escaping to the customer.

As a result, the DVSM method remains suitably vague, in the sense that there is no prescribed path in which a solution must take. Indeed, it is the responsibility of the user to formulate an appropriate strategy in which to develop or identify and appropriate solution – the goal of the DVSM here is to simply identify the points of the value stream which may be critically leveraged through technological means. In this manner, an organisation may begin its Industry 4.0 journey through a targeted point, that is justified against a tangible measure of improvement.

7. Conclusion

The presented DVSM concept may be developed and applied for the purpose of integrating Industry 4.0 concepts into the traditional LM VSM method. This may be utilised to formulate a quantitative measure of data acquisition, which may then form the foundation of process improvement effort. Here, the possibilities surrounding the application of emerging digital technologies may be applied in order to strategically reduce the time in which process specific KPC's are monitored,

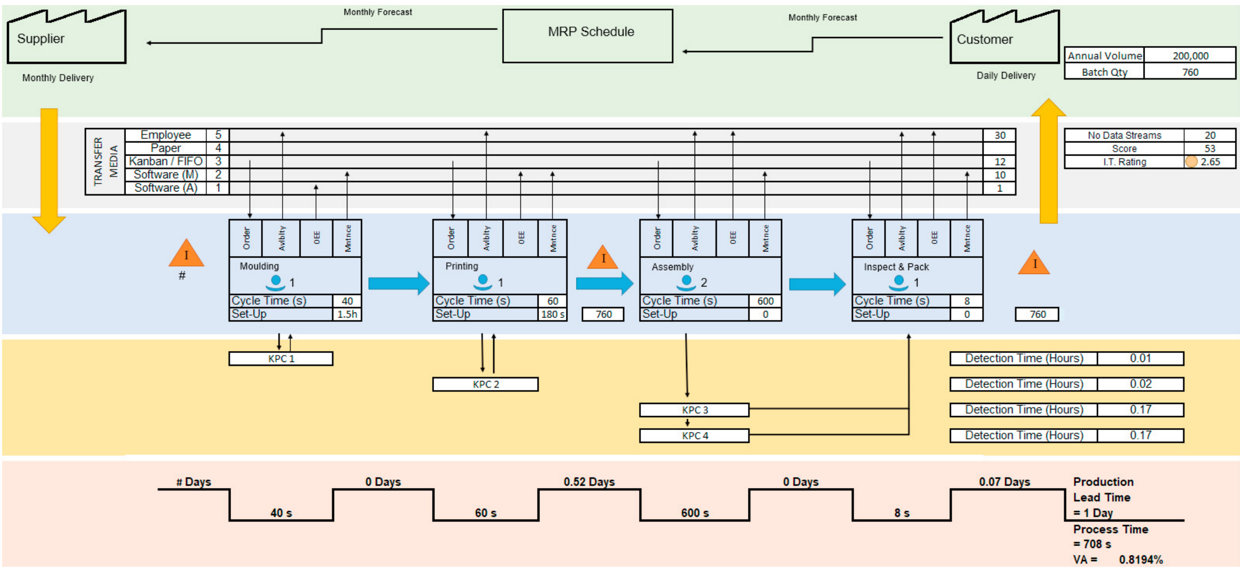

Figure 2. Current State DVSM - a practical example

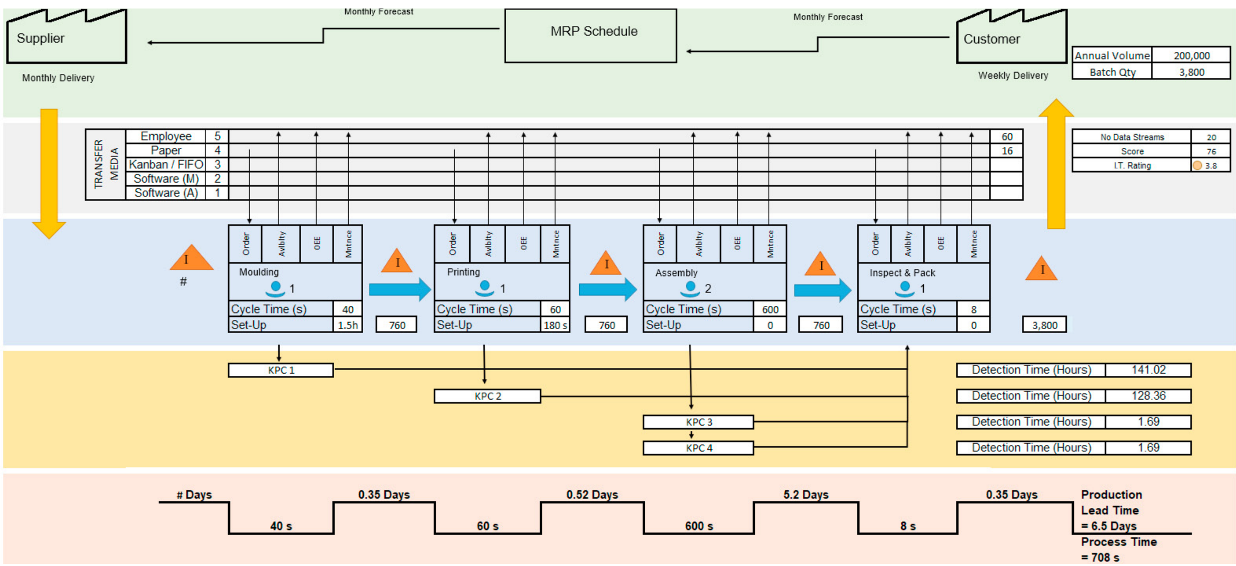

Figure 3. Future State DVSM - a practical example

thus enabling organisation to make informed investment decisions to increase the robustness of manufacturing processes. Furthermore, the formulation of a centralised information processing point, provides a necessary foundation in which to establish enterprise level CPSs regardless of the chosen medium of communication, and thus enhance the robustness of a value streams ability to transfer and store information.

Here the practical example of DVSM deployment shows how waste in process verification may be eliminated so that an organisation may vastly reduce the lead time in which identified KPCs are formed and identified. In addition, the traditional benefit of a LM VSM is displayed, through the reduction of internal lead time of a product from 6.5 days to 1 day. As a result, the organisation may become inherently more efficient through the acceleration of flow throughout the value stream, and prevent the proliferation of non-confirming product.

In future research, the DVSM method should be employed further to develop and verify its usability across a wide range of industries. Following this, a detailed method of the technological identification may present an opportunity to enhance the DVSM method further, through aiding organisations to recognise and select a means in which to realise the opportunities identified as part of this tool.

8. Acknowledgements

This work was undertaken as part of the Interreg funded CoRoT project, investigating the use of collaborative and autonomous systems in improving the flexibility and responsiveness of manufacturing systems (www.corot-project.org). The authors would like to thank all the personnel of Olympus Algram Ltd (Plymouth, UK) involved in the investigation for their support and collaboration. Also, thanks to the supervision and administrative teams at the University of Greenwich for facilitating our research.

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