Applying lean principles for high product variety and low volumes: some issues and propositions

Jay Jina
Arindam K. Bhattacharya and Andrew D. Walton

The philosophy of lean manufacturing (LM) has been popularized by the seminal work of Womack, Jones and Roos under the International Motor Vehicle Programme (IMVP) programme[1]. At its core, lean manufacturing is a means by which the overall business processes are organized so as to deliver products with greater variety and superior quality using less resource and in a shorter time than can be achieved by mass production methods. Studies have shown that lean plants tend to have a “two to one” performance advantage over conventionally organized plants[1-4]. More recently, some researchers have reported the limitations of the lean philosophy, most notably Papahristodoulou[5] and Berggren[6] who argue that environmental and social conditions have not been taken fully into consideration in explaining Japan’s competitive advantage.

Lean principles are manifested by crucial measures such as:

• faster throughput times for in-bound, work in progress (WIP) and out-bound material;
• smaller manufacturing batch sizes;
• shorter set-up and change-over times and greater “up time”;
• greater schedule stability;
• lower rework and rectification costs.

Implicit in the most widely publicized examples of successful lean manufacturing is the fact that the complexities of satisfying order-winning criteria such as product variety and speed of delivery have been mitigated by the high production volumes. This observation is corroborated by the rise of “mass customization” as epitomized by Pine[7] who cites numerous examples of the successful application of this concept. Leaving aside the criticisms of mass customization, notably by Kotha[8], it can be said that as a business philosophy it primarily addresses the high volume, high variety segment of manufacturing activity. Significantly, however, mass customization can be considered to espouse the key lean measures listed above.

Recent developments in the area of manufacturing strategy have led to the term “agile manufacturing” being coined to describe the management structures, technologies and

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business processes associated with the shift from mass to lean manufacturing (see Gold- 
man and Nagel[9] and Goldman et al.[10]). The paramount importance of customer orien-
tation and fast response attached to lean manufacturing is thus shared by agility as well as 
mass customization and time-based strategies.

High variety, low volume (HVLV) and lean manufacturing

The popularity of the LM philosophy has got to the point where many manufacturing 
organizations covering a spectrum of size and complexity are asking: “Is lean manufacturing 
relevant to us and, if so, which of its principles can we apply directly and which can we adapt to 
suit our circumstances?” The driver for this stems from the need to reduce the costs associated 
with having the wrong products in the wrong place in the wrong condition at the 
wrong time. One of the most prominent lean manufacturing programmes outside the 
automotive industry is the lean aircraft initiative involving the US Air Force, MIT and 25 
defence contractors[11]. Examples of the application of the underlying principles to the 
development and manufacture of low volume, high variety products such as aircraft are now 
being reported. Companies such as MCDonnel Douglas and Lockheed have applied lean 
principles right from product design through to product manufacture. Lang and 
Hugge[12] discuss the use of multifunctional teamwork and cellular organizations which 
have resulted in a significant reduction in part counts and product complexity and improved 
customer responsiveness. The critical role that leadership plays in successful implementa-
tion is also highlighted by Day[13].

Focusing on the application of time compression as the driver for redesigning business 
processes within manufacturing, our work with various organizations in different indus-
try segments has led us to address the issue of how the above question could be answered for 
high variety, low volume (HVLV) situations that are characterized by:

- A very high product variety to the extent that products can be customized while both 
  individual product type and total volumes remain low.
- A full “make to order” policy with guaranteed delivery dates and lead times.
- The level of vertical integration ranging from very high level to low. Many HVLV 
  organizations compete on the basis of product uniqueness and variety, so they 
  retain a high level of vertical integration in order to keep greater control of both 
  uniqueness and variety. The other extreme are aerospace firms who cannot keep in-
house control of the technological complexity and cannot afford the high investment 
required and therefore heavily outsource. HVLV companies may have products 
in their portfolios which span these extremes of vertical integration.

- Manufacturing facility that has to satisfy the need of disparate customers’ segments, 
such as specialist, low volume users of the finished product, those who purchase 
complete or partly configured kits and parts for spares together with reasonably 
standard products that are sold in slightly higher volumes than the specialist variants.

These HVLV characteristics make a formidable array within which to consider the applica-
bility of LM principles. This challenge is firmly put into context when we consider the 
contrast between the conventional lean plant and HVLV as illustrated in Table I. We dis-
cuss the problems of applying LM principles in an HVLV organization in the following 
section.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Lean plant</th>
<th>High variety low volume plant</th>
</tr>
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<tbody>
<tr>
<td>Typical annual volume</td>
<td>From 100,000 to 1,000,000+ units per year</td>
<td>From 20-500 and 5,000-20,000 units per year</td>
</tr>
<tr>
<td>Product variety and complexity</td>
<td>Medium, with no bespoke products. Specialist products separated into dedicated plants</td>
<td>Medium and decreasing</td>
</tr>
<tr>
<td>Degree of vertical integration</td>
<td>Stabilized by a degree of make to stock with primarily assemble to order</td>
<td>Can be low, medium or high - the specialist nature of products often inhibits any increase or decrease</td>
</tr>
<tr>
<td>Manufacturing planning systems</td>
<td>Variety</td>
<td>Low volume with make to order</td>
</tr>
<tr>
<td>Order-winning criteria</td>
<td>Delivery speed</td>
<td>Custom bespoke product</td>
</tr>
<tr>
<td></td>
<td>“All in” product features</td>
<td>“Extra” features</td>
</tr>
<tr>
<td></td>
<td>Delivery speed</td>
<td>Delivery speed</td>
</tr>
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</table>
LM principles in the HVLV organization - the problems

We consider the difficulties associated with applying lean principles within HVLV organizations as being threefold. The first difficulty arises from the lack of clarity of understanding of what HVLV actually means. Second, there is the problem associated with what we term “turbulence”. The third principal problem is to do with the management of the manufacturing system.

Definition of high variety, low volume
This problem concerns the lack of a clear definition of what exactly constitutes HVLV. It can be argued, for example, that both aircraft and heavy earth-moving equipment manufacture are HVLV in character. However, a brief analysis will reveal that there are fundamental differences between these sectors. The most obvious are volume and product complexity. Generally, there are marked differences both in aggregate volumes and product complexity for typical manufacturers of these products. Aircraft are generally made in far lower volumes and thought to be more complex than earth-moving equipment. Also significant are the differences in industry structure which determine both customer and supply chain relationships.

As noted in Table I, the degree of vertical integration can vary from low to high within the same sector. This may be either as a result of strategic choice or through the inherent structure of the industry. This is well illustrated by the aircraft industry which has evolved such that there now exist specialist engine manufacturers and avionics providers who supply to airframe makers and final assemblers. Equally, there are earth-moving equipment and tractor manufacturers who have chosen consciously to retain core component manufacturing capabilities since these are seen as levers for competitive advantage. Collectively, therefore, these subtleties of volume, product complexity, industry structure and supply chain relationships make the task of devising generally applicable lean manufacturing strategies for HVLV situations all the more complicated.

Turbulence
The second key problem facing the HVLV organization is that it experiences generally markedly more manufacturing system turbulence than the typical lean manufacturing situation. “Turbulence”, in this regard, is used to describe behaviour which, as a result of variability and uncertainty of inputs, causes the manufacturing system to experience unpredictable and sub-optimal behaviour as it struggles to achieve the desired outputs[14]. Four types of turbulence causal factors can be identified:

1. Schedule. Changes in the schedule for a given period as time gets closer to the delivery due date.
2. Product mix. This occurs in multiproduct, multimodel facilities and is evidenced by marked differences of product mix between one period and the next.
3. Volume. Like product mix but referring to aggregate volume changes between periods.
4. Design. The degree and frequency of product change particularly within the time-frame of customer lead time expectations.

These four types of turbulence have a far greater impact in the HVLV case than in the typical LM organization in the auto industry as investigated by Womack et al.[1]. This is to be expected since, given the low volume of production, any change (be it in volume, mix, schedule, or design) will of itself have a significantly bigger impact. This bigger impact is exacerbated because of the fact that, as a result of the high variety, it is more likely to occur. So one instance of any such change in an HVLV situation accounts for a bigger percentage change than it would in a conventional LM situation. The much higher aggregate volumes implicit in typical LM systems have a beneficial dampening effect unavailable to HVLV systems.

Impact on the manufacturing system
One of the important characteristics of high volume, low/medium variety organizations is that they are able to dampen the impact of variability of the inputs into the manufacturing system by de-coupling the internal supply chain from the outbound supply chain. The result is levelled schedules within a set of well defined flexibility parameters.

HVLV organizations, by their very nature of make to order, partial bespoke design and low volume business, cannot adopt this de-coupling policy. This is true not only with respect to the boundary between the outbound and internal supply chain, but also...
within the internal supply chain down the bill of material hierarchy. This means that the effect of even small changes in the four factors of turbulence has a proportionately larger impact on the performance of the manufacturing system in an HVLV environment than a high volume environment.

Changes at the saleable product level have a direct impact on part level schedules. These schedule changes tend to hurt the part supplier equally, whether he is external or within the final assembler’s own vertically integrated organization. Additionally, the spares demand at part level for the after-market is often lumpy. These factors are especially symptomatic of HVLV organizations, which militate collectively against a steady “drum beat”-type manufacturing system that is so crucial for effective LM. Design changes also are prone to greater frequency; after all, the ability to adapt existing designs, generate new ones and tailor customer-specific features is one of the strengths of a successful HVLV competitor.

The above factors thus combine to create strong arguments against attempting blindly to apply the principles of LM in HVLV organizations. The procedures and systems appear too complex to surmount the problems. Besides, it is considered that the potential return would be marginal for the effort which would need to be expended. The barriers appear to be both technical and organizational in nature. In the next section we consider how this challenge can be addressed.

Adapting LM principles for HVLV

Despite the difficulties discussed above, we consider that LM principles can be adapted to suit the HVLV situation, provided that careful attention is paid to the fundamentally different circumstances which prevail. The proposed framework is depicted in Figure 1. As with LM, the framework has three interrelated components:

1. Product design geared to logistics and manufacture;
2. Organizing manufacturing along LM principles;
3. Integrative supplier relationships.

These three components are held together by agile, process-oriented organizational capabilities supported by consistent measures which form the centrepiece for the framework. Each is discussed below.

**Figure 1** The components necessary for applying lean manufacturing principles

**Design for logistics and manufacture**

The parts count for HVLV situations, if not managed carefully, will tend to proliferate even faster than a conventional LM situation. This is a consequence of providing high product variety in low volumes. In the interest of speed, new product designs do not always take sufficient account of existing parts. As a result, the part count for raw material parts, finished parts and sub-systems can go up. The lean manufacturing principle of design for logistics and manufacture (DFLM) is therefore even more critical for the HVLV situation. The cost and complexity penalties of not exploiting DFLM are thus much higher. Among the approaches necessary are the following.

**Commonizing raw material parts**

The use of common stock bars or forgings can reduce the complexities associated with material supply as individual raw material part volumes are increased while aggregate purchases are maintained. Such an approach allows the HVLV manufacturer to increase leverage with suppliers as it becomes easier for the supplier to schedule higher volumes for fewer part numbers.

**Common finished parts and use of modular designs**

The more uniqueness there is at part level within products, the more complex the logistics and manufacturing processes become. Use of common parts and modular designs can reduce such complexity while maintaining the product variety. For example, it can be more cost-effective to delete the current version of a part when it is modified for use on a slightly different specification of the product, provided that the new version has been designed with
backward compatibility in mind. Part and sub-systems designs which tolerate an acceptable degree of redundancy and allow modularity can make a significant contribution to HVLV manufacture. Variety reduction techniques such as those described by Suzue and Koh-date[15] may be appropriate in this context.

Staged engineering change control
HVLV manufacture can entail a high degree of product change. Factors such as current stocks and speed of delivery become even more acute than in a typical high volume case. Use of well defined release packages embodying a set of engineering changes either for a major revision or for a totally new product can lead to better control. Note that the engineering change procedure must include the definition and provision of all manufacturing process data, tooling and quality plans.

Multifunctional teamwork
This is one of the underpinning factors within successful lean organizations. The use of integrated teams in automotive design and manufacture leading to improved quality, lower costs and shorter time-scales is well documented (see, for example, Clarke and Fujimoto[16]). Even though the HVLV organization may not have sufficient volume per new product model to dedicate team resources, it can adapt these concepts by creating "product change co-ordinators" whose role would be to take responsibility for all aspects of change control from assessing current parts lists for compatibility, the trade-off between logistics and manufacturing complexity versus adding to the part count, embodying a set of changes into a coherent package, etc.

Organizing manufacturing
The effective organization of the manufacturing system is possibly the most obvious characteristic of LM. The objective for lean manufacturing in HVLV environments is to eliminate or dampen turbulence in the material flow which, if left unchecked, has a damaging effect on performance. In this section we present attributes which are especially pertinent to the HVLV organization.

Organizing for high level (assembly and sub-assembly) demand
The first element of this entails the effective integration of marketing and planning. The manufacturing planning systems for high volume lean manufacturing do not always integrate the customer enquiry stage and the order release stage, which are treated separately. The HVLV manufacturer has two options.

The first is to take orders as they come, on a "first come, first served" basis, and then build them into the master production schedule (MPS). As these orders enter the sequencing horizon, they are sequenced to balance the work content of the assembly line. These sequenced orders are then cascaded down into the sub-assemblies, which are then built to the same sequence. The work content may fluctuate at the sub-assembly level and, as a consequence, this may lead to volume and mix turbulence. The tight coupling between the different levels of the product structure could also cause schedule turbulence after the build sequence has been established because of unforeseen circumstances, such as component non-supply, quality or production problems, and orders being taken out of the line. The weakness of this approach is that it may not provide adequate feedback from the planning process into the customer enquiry process, thereby effectively de-coupling them.

The second option is to integrate the customer enquiry stage and the order release stage[17]. This can be done in two steps. First, the MPS is prepared so that it matches the latest free demand forecast against production capacity. Second, when a customer order is taken, before a due date can be promised, the order is matched to the closest unoccupied order slot in the MPS. If the customer order and the proposed order slot are deemed to be compatible, then the order is accepted into that slot and a delivery due date calculated and promised. Compatibility in this respect may not equate to an exact fit; the manufacturing system would typically allow a predefined degree of latitude. If, on the other hand, the difference is deemed significant, then the customer order is added to the MPS as a totally new order, for which the delivery date is calculated and communicated to the customer. This approach has the benefit of integrating the customer enquiry stage with the planning process, providing a variable customer delivery lead time and minimizing turbulence in the manufacturing system.

The sequencing for each level of assembly is carried out independently and the sequencing policy adopted would relate to the constraints
within that level of assembly alone. A favoured technique could be to assemble runners in lots and intersperse them with repeaters and strangers. De-coupling sub-assembly from final assembly operations with output buffers would further dampen turbulence and allow smoother flow of material. This approach would exploit modular designs with their high degree of common parts which permit buffers without the disadvantage of pushing up inventory to unacceptable levels.

Organizing for lower level (parts) demand
High variety and low volume tend to make the distinction between runners, repeaters and strangers even more stark than is the case in the typical LM example. For our case, we use the “20-80 rule” whereby the 20 per cent of part numbers that make up about 80 per cent of the volume are designated as runners. Typically, around 50 per cent of the parts which make up about 5 per cent of the volume would be categorized as strangers. The manufacture of stranger parts without proper consideration of the associated effect on runner parts, even within a cellular layout, can lead to inefficiencies. Lumpy demand from kits and parts which are required for after-sales can cause further turbulence in the manufacturing system. These problems can be turned to advantage by careful separation of runners from strangers and treating each group differently. To begin with, it is necessary to achieve one of the characteristic features of LM, namely stability. This is achieved by reconciling the three different sources of demand into as smooth a demand pattern as possible. Irrespective of whether a given part is a runner or a stranger, such smoothing will make the task of resource allocation and job sequencing easier and has the effect of de-coupling the part manufacture from the higher level sources of demand. Note, though, that this approach demands a regular assessment and update of the categorization of parts as runners, repeaters and strangers.

Runner parts
The high, stable demand for these parts means that it will be possible to implement a “drum beat” manufacturing system. The requirements can be planned using materials requirements planning (MRP) methods and the relatively high volumes would justify the deployment of gross scheduling. The execution of the manufacturing plan would be segregated according to the source of demand: assembly requirements which constitute the bulk of the total production volume can be managed by a JIT kanban system between the parts manufacturing cell and the assembly cell while kit and parts demands from after-sales can be produced and pushed as per the daily buckets in the planned schedule. Use of cellular manufacturing concepts offers significant advantages for the manufacture of runner parts. In particular, the relatively high yet stable demand can be used to develop semi-dedicated or “focused” cells which offer optimal utilization as well as throughput velocity. Each runner part would be launched through a line which would be dedicated for a given duration. Such a dedicated “capacity window” would be temporary and be linked to the kanban trigger for the given part, such that the key to lean parts manufacture would stem from the sequencing of these capacity windows for optimal man-machine combinations. Focusing the cells sufficiently such that parts use most, if not all, machines, even though cycle times may be different, allows high capacity utilization.

Stranger parts
The relatively low volumes for these parts can be used to justify one of three routes: manufacture in larger but less frequent batches within cells, manufacture in flexible job shops which are segregated from conventional cells, or contract out to suppliers. In each of these cases it is considered prudent to adopt net scheduling, with MRP used both for planning and for execution purposes. This would be the case irrespective of the source of demand, be it assembly or after-sales for kits or parts. Where a decision to contract out has been made, it will be imperative that appropriate supplier relationships are developed. In all cases, the DFLM principles of modular design and redundancy can be exploited to leverage the most optimal approach for dealing with stranger parts.

Repeater parts
These parts typically constitute the “difficult” middle of the parts population. As a first step, it serves to consider which of these can be reclassified as either runners or strangers and then treated as per the discussion above. Even in the event that such a reclassification proves impossible, it will be appropriate to employ options such as dedicated job shops or contracting out.
To support the runner-repeater-stranger categorization there have to be slick processes for managing the internal materials flow within the HVLV organization. While localized planning and inventory control systems assist LM, fundamentals such as smaller launch and transfer batches, consistent palletization which offers visibility, stock accuracy and material quality, are also important. These initiatives have to be supported by procedures which clearly define receipt procedures and the ownership of material between workstations.

**Integrative supplier relationships**

Being an HVLV manufacturer puts the organization at an inherent disadvantage with suppliers. The lower volumes make it difficult to develop the most profitable partnerships in terms of delivery quantity, frequency and price. This is where the initiatives of DFLM and better organization of the internal manufacturing operations have most to contribute. As stated previously, the generic raw material designs can be used to boost volumes and leverage the supplier relationship. Part and sub-system redundancy can also be used in this way. Single sourcing for defined commodity groups rather than individual parts then becomes the key to ensuring the level of supplier service needed for lean manufacturing. Backed up by a consistent policy for “make versus buy”, the HVLV organization can get the most out of both its own facilities and its suppliers. With the increasing use of LM techniques, the astute HVLV can benefit also by learning from the larger supplier who may already be a partner in a supply chain with leading high volume LM end assemblers.

**Process orientation and consistent performance measures**

Melding the previous three elements is the vital factor in developing a process orientation and having consistent measures to gauge progress. The turbulent environment in which an HVLV organization operates means that it must be agile: it is essential that the organization develops the ability to “re-invent” the manufacturing system[18] so that it is always geared to suit the prevailing requirements. Use of multifunctional teams on “directed” activities can be managed effectively by exploiting the relatively small size of the HVLV organization. This has to be backed up by the adoption of consistent performance measures. The leading LM organizations offer an important guiding framework here. While conventional finance measures are still important, the HVLV has to take account of “local” ground level measures such as batch sizes, space utilization, cell arrears, set-up times, number and reasons for unplanned engineering changes, supplier delivery frequency, accuracy and timeliness. The measurements need also to include customer satisfaction ratings, delivery promise successes, etc.

**Application of the approaches**

Many of these principles have been applied by the authors in HVLV organizations. We conclude by examining some of the developments in two very different types of HVLV organization – one a very low volume manufacturer in the aerospace sector, and the other a manufacturer of low to average volumes (in the low thousands) of specialist machinery. Both have a “high variety, make to order” business strategy. The approaches of these two companies, their similarities and the differences have been summarized in Table II. It is evident that the emphasis of the LM elements employed depends on the specific circumstances of the HVLV organization.

**Conclusions**

The dramatic performance improvements available by following lean, low waste principles are well established in high volume, relatively low variety situations. Many companies aspire to achieve equal, or better, levels of performance and are therefore keen to adopt lean practices. However, the lean formula is applicable directly only to a small proportion of manufacturers: most companies must carefully judge which lean practices they can use immediately and which need to be adapted to meet their special circumstances. This paper has outlined the barriers which many HVLV organizations see as impediments to applying LM principles in their operations. We have shown how these principles can be adapted to suit the requirements and the challenges such companies face. We have also identified the specific advantages inherent within HVLVs which can be exploited and have illustrated how they are being applied within companies.
The understanding of the application of the principles of lean production is still evolving. The authors consider that the framework presented in this paper provides a structure for explaining both the process and content aspects of the subject but that further research with other cases and comparative studies will provide refinements to the present model.

Table II: Comparison of lean manufacturing in two HVLV organizations

<table>
<thead>
<tr>
<th>Characteristics of LM in HVLV</th>
<th>Company A: aerospace manufacturer</th>
<th>Company B: specialist machinery</th>
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</thead>
<tbody>
<tr>
<td><strong>Design logistics and manufacture</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commonizing raw material</td>
<td>Divide parts into standard and bespoke parts. Rationalize finished part designs to increase share of standard parts in total part count. Bespoke parts to be used as late as possible in the product configuration</td>
<td>Increased use of common stock bars and standardized forgings</td>
</tr>
<tr>
<td>Commonizing finished parts and use of modular design</td>
<td></td>
<td>Upgrade some of the parts from lower to higher specifications, even if it means carrying some redundancy, in order to reduce part variety without losing variety for the customer</td>
</tr>
<tr>
<td><strong>Staged engineering change</strong></td>
<td>Revised engineering change request (ECR) process to weed out the trivial many; fast track product change control to deal with customization needs</td>
<td>Bundle individual engineering changes into packages to be introduced as part of well defined “gateway” process, which evaluates the impact of the engineering change on the logistics process among other criteria</td>
</tr>
<tr>
<td><strong>Multifunctional teamwork</strong></td>
<td>Customer specification, engineering and manufacturing are part of integrated product ECR team</td>
<td>Closer tie-up between engineering, manufacturing and logistics functions means speedy problem resolution</td>
</tr>
<tr>
<td><strong>Organizing manufacture</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organizing for high level demand</td>
<td>Closer tie-up between marketing and end customer reinforced by internal multifunctional teams leading to speedy customer specification</td>
<td>“Fast MRP” with ability to monitor schedule changes and their impact on lower level demand. Order sequencing with lead time and work content smoothing objectives. Delivery dates of specialized products or those with bespoke designs calculated from the pipeline and communicated to the customer</td>
</tr>
<tr>
<td>Organizing for low level demand</td>
<td>Low level parts outsourced</td>
<td>Flow runner parts through temporarily dedicated processes. Use kanban for those parts with reasonably stable demand. Use batches for the stranger parts</td>
</tr>
<tr>
<td><strong>Integrative supplier relationships</strong></td>
<td>Supplier development strategy including “risk-sharing partnerships” for outsourced product sub-systems</td>
<td>Identify key suppliers and rationalize the number of suppliers in order to single source for groups of products like same type of castings</td>
</tr>
<tr>
<td><strong>Process orientation and consistent performance measures</strong></td>
<td>Team-based engineering of the customer specification coupled with number of product changes, scale of importance and speed of resolution</td>
<td>Time compression goals for all runner parts, stock turn trends, use of internal kanbans</td>
</tr>
</tbody>
</table>
References