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Designing Lean Automation Cells for High-Mix, Low Volume Automotive Parts

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Abstract : The operational issues of high-mix and low-volume (HMLV) automotive parts products are also troubled, as the products are in constant flux, low lot, and are changeable. These lean automation cell environments should be structured in a way that is a balanced design of flexibility, cost-efficiency, and low cost. The provided review paper is grounded in the analysis of scholarly materials, case studies, and the implementation of the concept to reflect on the potential of the concept of lean in the dynamism of HMLV production. The paper evaluates the ability of cell structures, modularization of automation, skillfulness, and digital integration strategy, and describes how the conjunction of these qualities can build a more productive and responsive business by adhering to a more synergistic route. Changeover time, lead time, first-time quality, and the overall effectiveness of the equipment are the significant performance indicators to be used in the evaluation of the contribution of the introduction of the lean cells to the increase in manufacturing performance. The results confirm that, in the case of HMLV (high-mix low-volume), the combination of lean philosophy and high-end automation and Industry 4.0 technologies—a hybrid solution—is the most appropriate one. The proposed method can transform traditional manufacturing models into lean, responsive, customer-oriented systems without sacrificing efficiency.

***IndexTerms* -** Lean automation cells, High-mix low-volume manufacturing, Automotive parts production, Flexible manufacturing systems

1. Introduction

It is known that the high customisation trend and the decrease in the life cycle of automotive products are increasing, and it is making production systems responsive and flexible. The models used currently in the production processes are being substituted with production process models that have the ability to sustain high-mix low-volume (HMLV) production. It is not a smooth transition, especially where introducing lean automation cells into the HMLV environment is concerned. Though the lean principles were originally premised on repetitive mass production, they must be applied to the requirements of HMLV to assemble automotive parts.

The automation design of the lean cells in the design setting should be calculated against the lean manufacturing concept, its possible adaptation to low-repetition manufacturing, and how to automate such without being discriminating. The ancient practices of the lean tools and solutions also need to be adjusted or supplemented to ensure their effectiveness, as the HMLV production process is not as predictable and homogeneous as it would be in case the production takes place on a large scale. The present paper considers both theoretical and practical aspects of lean automation cells' growth that would be specifically applicable to the HMLV automotive setting.

2. Challenges in High-Mix, Low-Volume Automotive Parts Production

High-mix, low-volume manufacturing refers to a production environment where a large variety of products are manufactured in small quantities. Automotive parts manufacturers operating under HMLV conditions frequently face several inherent challenges, including longer changeover times, inventory complexity, and variability in production demand. These challenges are likely to cause inefficiency of the resources and reduction in lead time.

The introduction of lean principles in such an environment is not a simple task. Standardization and repeatability of lean principles have never been left out of lean, but they are not so prevalent in the HMLV systems. In addition, the variability of the structure of such systems tends to create flow interruptions, which makes it extremely difficult to identify a takt time or continuous flow, as defined in lean. Nevertheless, with the appropriate adjustments and considerations, lean manufacturing would have the capacity to offer high-performance additions to HMLV activities to lessen the wastage and maximize responsiveness [1].

The lean cell design within an HMLV environment will be based on the following characteristics: modularity, high changeover capability, and multiple attainability capability to support product variability. This lean-cell design is a winning design founded on flexibility. It should be reconfigurable and programmable and have the capability of producing as many types of products as it can simultaneously (not as costly as mass production automation, which is not flexible or implicitly obedient) [2].

3. Lean Principles Adapted for HMLV Automotive Environments

The fundamental concepts of lean—value, value stream, flow, pull, and perfection—will require significant adjustment so that they will work in high-mix low-volume (HMLV) systems. Customers may identify value as customization in the manufacture of automotive parts, making it difficult to associate value back to a value stream as the processes may transform. Despite these obstacles, streamlining the value stream through identification and elimination of non-value-adding steps remains crucial.

Flow in lean HMLV cells can be established through flexible work cells and U-shaped cell layouts, which minimize travel distances and allow operators to handle multiple tasks. Standardized work, a key element of lean, is also more difficult to implement due to high variability, but it can still be achieved at the task level rather than at the product level. Visual management and 5S continue to offer value in HMLV by improving workplace organization and visibility of production status, which is essential in dynamic environments [3].

Kanban systems, widely used in lean manufacturing to signal demand and control inventory, must be scaled appropriately in HMLV environments. Since the demand for any single item is low, Kanban cards need to reflect smaller lot sizes. In many cases, hybrid systems combining make-to-order and make-to-stock strategies provide a practical solution for dealing with demand fluctuations without overburdening the system [4].

4. Designing Flexible Lean Cells for HMLV

In the design of automation cells for HMLV automotive production, the focus must be on flexibility, modularity, and ease of reconfiguration. The cell design must enable rapid changeovers, minimal downtime, and high operator adaptability. Tools such as Single-Minute Exchange of Dies (SMED) play a pivotal role in achieving quick changeovers. The incorporation of lean principles in cell design ensures that waste is minimized across all types: motion, waiting, transportation, and overproduction.

Table 1 illustrates key design attributes that differentiate lean cells in HMLV environments from those in traditional high-volume production.

Table 1: Key Design Attributes of Lean Cells in HMLV vs. High Volume Environments

Attribute	High Volume Lean Cells	HMLV Lean Cells
Changeover Time	Long, but infrequent	Short, frequent
Workstation Layout	Dedicated, linear	U-shaped, modular
Automation	Fixed, product-specific	Programmable, flexible
Workforce Skill Requirements	Specialized	Multi-skilled
Lot Size	Large	Small
Production Flow	Continuous	Intermittent with buffer zones

Adapted from [5]

Implementing automation in these cells must consider the cost-benefit trade-off. In HMLV, the cost per unit of automation is typically higher due to the complexity and low repetition. Thus, automation must be strategically deployed in processes that are either hazardous, ergonomically challenging, or have minimal variation across products. Programmable logic controllers (PLCs), collaborative robots (cobots), and computer vision systems provide adaptive automation capable of functioning effectively in such dynamic environments [6].

5. The Role of Operator Involvement and Skill

HMLV production is not a stressful task compared to high-volume production, whereby automation of various activities is more accurate at times. The employees of the lean automation cells in HMLV segments of the automotive industry should be multi-skilled and might not work in the improvement process as they engage in other tasks. It is important for operators to be involved not only in the execution of tasks but also in the identification of waste and contributing to kaizen activities.

Furthermore, adjusting the layout to accommodate the cell can be beneficial in performing multiple tasks and reducing unnecessary movements, but careful planning is needed with instruments, components, and directions. Beyond considerations of layout, training programs will have to be introduced to include cross-training and problem-solving skills that allow the operators to improve real-time decision-making that optimizes cell performance [7].

Visual management tools include Andon systems and performance dashboards that are used in the operation to provide real-time feedback, allowing the operators to react to issues quickly and sustain ongoing flow. This participatory culture reinforces lean principles and enables the system to adapt to product mix and changes in volume [8].

6. Quantifying Performance and Measuring Improvements

Matters of variability and responsiveness-based performances should be established to ensure that the lean automation cells are fruitful within the HMLV settings. Ineffective appraisal systems, which revolve around the quantity of output, may not be appropriate. In other cases, they may be applied better regarding other indicators such as Overall Equipment Effectiveness (OEE), changeover time, order lead time, and first-time quality.

Figure 1: Performance Metrics Before and After Lean Cell Implementation in HMLV Automotive Manufacturing

Figure adapted and modified from various open-source metrics models [9]

The chart indicates that critical measures report gains after the lean automation cells have been introduced in one of the automotive parts plants. It should be mentioned that the changeover time and the lead time are decreased by a significant percentage, while the first-time quality and OEE are improved due to reduced rework and downtime.

These are the feedbacks that are required for continuous improvement and to scale the cell design, automation arrangements, and optimized manpower planning. Data analytics and Industrial Internet of Things (IIoT) devices are also added, and they may help to enhance real-time monitoring and predictive maintenance, particularly in working environments with high variability [10].

7. Strategic Integration of Automation in HMLV Lean Cells

The automation of lean cells in high-mix and low-volume facilities is a complex matter. Automation should be utilized in a manner that embraces lean while not being rigid or capital intensive. Automation technologies must be adaptable and easily reconfigured when necessary, for example, when there is a change in the type and specifications of the product, as occurs in HMLV automotive parts manufacturing.

Collaborative robots (cobots), machine vision, and automated guided vehicles (AGVs) are reputable automation solutions that support flexible automation. Cobots that can work alongside humans are an example of overcoming manual or hazardous tasks by transferring the task to a machine that can be easily reprogrammed for other tasks. This flexibility supports lean philosophy, which reduces waste, enhances safety, and improves productivity [11].

Most importantly, the modular automation approach aids in optimizing the HMLV environment. Another example is plug-and-play tooling in modular workstations, which provides the production line with the ability to be reconfigured quickly. The adoption of modularity supports lean principles of flow and continuous improvement, enabling a company to flexibly change layouts and workflows with the product. In addition, gradual automation can be observed, triggered in sectors where time-based automation may eventually lead to full automation [1].

The automation of HMLV production can be cost-effective when applied to less variable processes or processes that consume high amounts of human labour. It may be considered for automating parts checking, packing, and excessively repetitive assembly processes. However, it must be borne in mind that manual activity must be retained for highly tailored or low-rate tasks. This kind of hybrid ensures that automation is not a retrogressive undertaking but rather a positive one, in alignment with lean objectives.

8. Case Studies in Lean Cell Implementation

The effectiveness of different design methods is also valuable data, as shown in the practical examples of lean cells in HMLV automotive production. According to Ljunggren (2013), a case study of a facility involved in the manufacturing of automotive parts in Scandinavia demonstrated this. The similarities between the company and typical HMLV systems included long setup times and colossal changes in the production schedule. By implementing flexible lean cells, multi-functional operators, and SMED, the facility reduced changeover time by 45 percent and increased total productivity by 25 percent [1].

It is important to mention research at MIT that utilized lean systems design in low-volume applications, which recognized the importance of parallel value stream mapping and facility layout design. One of these projects was reported to have reduced lead time in production by half through visual controls and Kanban systems in the lean cells [2]. All these examples demonstrate that while lean cell implementation within HMLV is more complex than in a high-volume environment, the leverage on investment can be very significant when implemented correctly.

A second example illustrates that for a U.S.-based manufacturer, flow was preserved in a difficult, unpredictable environment through the quick implementation of operator-controlled lean cells. The operators also had autonomy in scheduling, inventory, and maintenance operations, which fostered a sense of ownership and reduced downtime. This type of decentralized control mechanism suits the HMLV setting particularly well, where top-down designs of control mechanisms may not respond promptly to changes [3].

9. Literature Synthesis and Theoretical Foundations

There is a significant body of academic information related to the strategic implementation of lean in HMLV production. Wenzel (2021) explores the relevance of lean techniques to an engineer-to-order environment, which corresponds with HMLV. The findings suggest that visual management, pull systems, and value-stream mapping tools apply perfectly in this context, particularly with an engaged workforce and ongoing training [4].

Tomashevics et al. (2021) complete a systematic literature review on effective lean in HMLV enterprises and point to some common themes related to modular design, digital integration, and operator autonomy. Another point noted in their review is that cultural change is necessary, again indicating that lean is more than simply another set of tools—it defines a philosophy that must be embraced in the future and updated as required.

Joing (2004) contrasts lean manufacturing and Quick Response Manufacturing (QRM) in an HMLV-styled manufacturing process, concluding that lean and QRM are ways of thinking to be deployed systematically, alongside cellular manufacturing and Total Productive Maintenance (TPM). This theoretical foundation offers strong potential for framing the design of lean cells that are robust, adaptable, and efficient.

10. Digital Transformation and Industry 4.0 Synergies

The opportunities presented by Industry 4.0 and digitalization technologies are opening the possibilities of converting lean automation cells into a high-mix, low-volume (HMLV) setting. The reason is that after implementing smart sensors, cloud computing, and AI-based analytics, it will be possible to predict maintenance, monitor the real-time situation, and dynamically schedule the production variables. These technologies are relevant in automotive product production, owing to the rate at which requirements and design specifications are evolving.

In this regard, Irani (2020) translates the concept of Job Shop Lean as the introduction of digital work instructions, electronic Kanban systems, and IIoT devices to synchronize decision-making and make operations more agile at HMLV job shops. The digital technology, coupled with lean concepts, results in high visibility across the total value stream, thus improving responsiveness to variability.

The digital lean strategies are also cited because the studies provided by Gan et al. (2023) looked at case studies of HMLV manufacturing in Southeast Asia. It has enhanced the throughput and customer satisfaction of businesses that utilized emotion machine learning algorithms and cloud-based ERP software to predict unknown demands [8]. This indicates that although the cost might be high at the point of start-up, the cost of the transition to digital infrastructure can be met, as it is a worthwhile venture in the long term because it offers a more flexible and efficient experience.

11. Strategic Framework for Lean Cell Design in HMLV

A structured framework is required to steer the design and execution of lean automation cells in HMLV automotive environments. Based on literature and case studies, the following phased approach should be useful:

1. **Assessment of Product Mix and Volume Variability**: Look at the product mix, how often it changes from, to and how variable the demand is to establish how flexible the cell must be.
2. **Process Segmentation**: Identify processes that can be standardized or automated and those that require manual intervention.
3. **Layout and Flow Design**: Develop U-shaped or modular cell layouts that minimize movement and support multi-skilled operators.
4. **Technology Integration**: Deploy adaptable automation tools such as cobots, smart fixtures, and vision systems.
5. **Training and Cultural Alignment**: Invest in workforce training to promote lean thinking, problem-solving, and autonomy.
6. **Feedback and Continuous Improvement**: Use KPIs and digital dashboards to monitor performance and support kaizen initiatives.

The diagram below visualizes this framework:

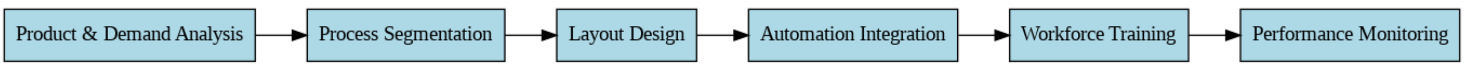

Figure 2: Lean Automation Cell Design Framework for HMLV Automotive Environments

Diagram Source: Adapted from [7], [8], [9] *12. Future Directions and Research Opportunities*

The evolving manufacturing technology provides additional research opportunities for using lean cells in the context of HMLV. The potential areas of interest include the means of human-robot cooperation, the mimicking of digital twins, or scheduling, which are founded on AI. In addition, the scalability of lean cells across different product lines and the sustainability measure in lean performance measurement, which may be introduced, should be explored further.

Rodriguez (2021) rationalizes the application of simulation as a solution to evaluate the lean cell structures before the actual implementation. It helps in minimizing risks of reconfiguring, and also the design alternatives can be run quickly [9]. In this regard, Hantila (2022) also reflects on the advantages of digital twins to model the sub-assembly production under dynamical conditions and plan the allocation of resources and design layouts in the most efficient way in real-time [10].

With the shift toward hyper-customization and circularity in the manufacturing industry, the lean cells will be required to go beyond efficiency and versatility, and be environmentally conscious. A green lean cell study, which is reducing the amount of waste it produces and the impacts it has on the environment, is a potential research area with untainted potential.

13. Conclusion

The lean automation cell design in high-mix low-volume manufacturing of automobile parts will not be made effective in any case without being a success should one of the variations of the hybrid approach be undertaken in which the old principles of lean will be incorporated into the new automation systems and digital tools. The major pillars which will help in the implementation of lean in such dynamic environments are: flexibility, modularity, and empowering of the operators. Even when the variability of the set-up, intensive customization, and demand changes make the implementation of lean difficult, the strategic planning and the automation of choice can be productive.

The synthesis of scholarly work, the existing case studies discussed in an empirical manner, and the technological trends outlined in the current paper highlight the flexibility of the lean approach in case it is applied to the operations of the HMLV. Human-machine cooperation in the future will also comprise additional additions to lean cells by AI and IoT applications and open the opportunities to a more robust, responsive, and sustainable mechanism in automotive manufacturing.

14. References

[1] Ljunggren, B. (2013). Lean cell implementation in high mix, low volume manufacturing.

[2] Gates, M. D. (2004). *Lean manufacturing system design and value stream management in a high-mix, low-volume environment* (Doctoral dissertation, Massachusetts Institute of Technology).

[3] Martin, J. (2024). A Review of Techniques for Improving Productivity in High-Mix Production Systems. *American Journal Of Industrial And Production Engineering*, *5*(2), 9-13.

[4] Wenzel, Y. (2021). *An Evaluation of the applicability of lean methods in an engineer-to-order, high-mix-low-volume manufacturing environment-a case study in the heavy industry* (Doctoral dissertation, Technische Universität Wien).

[5] Tomašević, I., Stojanović, D., Slović, D., Simeunović, B., & Jovanović, I. (2021). Lean in High-Mix/Low-Volume industry: a systematic literature review. *Production Planning & Control*, *32*(12), 1004-1019.

[6] Joing, M. J. (2004). *Applicability of lean manufacturing and quick response manufacturing in a high-mix low-volume environment* (Doctoral dissertation, Massachusetts Institute of Technology).

[7] Irani, S. A. (2020). *Job shop lean: an industrial engineering approach to implementing lean in high-mix low-volume production systems*. Productivity Press.

[8] Gan, Z. L., Musa, S. N., & Yap, H. J. (2023). A review of the high-mix, low-volume manufacturing industry. *Applied Sciences*, *13*(3), 1687.

[9] Rodriguez, A. (2021). *Applying Lean Manufacturing Concepts to a High-Mix Low-Volume Make to Order Environment* (Doctoral dissertation, Massachusetts Institute of Technology).

[10] Hantila, N. (2022). Optimizing the production of the sub-assemblies in a high-mix-low-volume environment.

[11] Aljubiri, A. (2019). *An implementation strategy for lean manufacturing in high mix and low volume (HMLV) environment* (Doctoral dissertation, University of Akron).