World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(REVIEW ARTICLE)

Check for updates

# Design for manufacturing of class IIb medical devices with risk-based approach

Yashwanth Teja Donga *

*Northern Illinois University. IL, USA.*

World Journal of Advanced Engineering Technology and Sciences, 2026, 19(01), 094-103

Publication history: Received on 16 February 2026; revised on 02 April 2026; accepted on 04 April 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.19.1.0191

## Abstract

Design for Manufacturing (DfM) for Class IIb medical devices requires structured regulatory compliance, lifecycle risk management, process capability engineering, and digital traceability. Class IIb devices require a high degree of confidence in safety and performance during development, scale-up, and commercial production because of prolonged patient contact or life-sustaining functions. Current regulatory developments, especially the European Union Medical Device Regulation (EU MDR), have greatly increased the expectations regarding clinical evidence, post-market surveillance, and risk management integration. At the same time, digital manufacturing transformation, such as smart manufacturing and Industry 4.0 architectures, have added new opportunities and complexities to ensuring validated risk-controlled production systems. The existing literature points to ongoing disconnection between design intent and manufacturing implementation, in particular, design transfer, software-controlled device control, and lifecycle data integration. Recent studies indicate that proactive risk reduction in a regulated setting can be aided with the help of predictive analytics, model-based systems engineering (MBSE), and AI-based quality monitoring. Nevertheless, unified models that match DfM, risk management standards, and digital lifecycle infrastructure have not been developed yet. This review brings together regulatory precepts, risk-based engineering approaches, manufacturability schemes, and ideas of digital integration that are peculiar to Class IIb products. It suggests organized life cycle integration models which relate design controls, risk control allocation, process validation, and post-market intelligence. The analysis shows that risk-informed DfM that is incorporated early in the development process can significantly improve process capability, minimize nonconformities, and decrease recall exposure.

**Keywords:** Design for Manufacturing (DfM); Class IIb medical devices; Risk-based approach; ISO 14971; EU MDR; Process validation; Quality Management System; Digital thread

## 1. Introduction

The category of Class IIb medical devices is a vital part of regulated healthcare technology that may include products such as long-term surgically invasive devices, infusion pumps, ventilators, orthopaedic implants, and some other active therapeutic systems. According to regulatory frameworks like the European Union Medical Device Regulation (2017/745) and other similar international classifications, Class IIb devices are classified as high-risk because of the length of contact with patients, the large amount of physiological interaction with the patient, or because they might have life-sustaining functions [1], [2]. These devices must demonstrate safety, performance, and quality assurance across the entire lifecycle, from design and development to mass production and post-market surveillance.

Design for Manufacturing (DfM) has become an area of main engineering intent to guarantee that medical equipment is not only operationally efficient but can be produced at industrial scale with consistency in quality, cost-efficiency, and regulatory assurance [3]. In highly controlled areas like medical technology, DfM goes beyond the established manufacturability optimization, and it has to incorporate quality system requirements (e.g., ISO 13485), risk management processes (e.g., ISO 14971), process validation, and traceability requirements [4], [5]. With increasing

* Corresponding author: Yashwanth Teja Donga.

global supply-chain complexity and the growing importance of advanced production technologies like additive manufacturing and automation, the integration of DfM and regulatory risk control has never been more essential [6].

Regulatory guidance documents and quality management standards underscore the significance of a risk-based approach in the manufacturing of medical devices, by requiring the identification, assessment, and mitigation of risks in a systematic product lifecycle manner [5], [7]. The malfunction of design transfer, process validation, and manufacturing controls may lead to recalls of the device, injuries to patients, and serious financial losses [8]. The rising rate of worldwide medical device recalls due to production and quality failures seems to illustrate the ongoing distinction between design intent and manufacturing implementation [8], [9]. This means that the deployment of risk analysis, e.g., Failure Modes and Effects Analysis (FMEA), Hazard Analysis, and process risk assessments, within DfM strategies, has emerged as a major research and industrial concern [5], [10].

Within the broader framework of manufacturing innovation, digitalization, quality analytics based on artificial intelligence (AI), and Industry 4.0 technologies are transforming medical device manufacturing paradigms [11], [12]. Digital twins, predictive process monitoring, and real-time risk modelling can help control variability of manufacturing processes more proactively, especially the complex Class IIb products that demand high precision and proven reproducibility. Regardless of these developments, the establishment of risk-based approaches into DfM of regulated devices is still piecemeal across the scholarly literature and in practice [13]. The vast majority of the studies focus on design control, regulatory compliance, or manufacturing optimization as a standalone issue, instead of introducing a unified framework that would be specific to high-risk Class IIb devices.

There are numerous issues that are still significant. First, the translation of regulatory risk management requirements into design-level measures is an insufficiently standardized practice [5], [13]. Second, design decisions made at an early stage frequently do not sufficiently address design-related risks in downstream manufacturing, and thus the redesigns incurred in scaling-up are costly [3], [8]. Third, emerging production technologies, e.g., additive manufacturing of implants or automated assembly of active devices, present new risks to the process that cannot be entirely modelled using traditional risk assessment models [6], [12]. Lastly, few formally structured directions exist on how to integrate DfM concepts with lifecycle risk management, especially in changing regulatory regimes, e.g. the EU MDR.

In the light of these difficulties, it is timely to undertake a critical review of the design for manufacturing of class IIb medical devices under a systematic risk-based perspective. This review will be used to summarize the existing regulatory requirements, engineering practices and risk management instrumentation applicable in Class IIb device manufacturing. It looks at ways in which DfM principles may be carefully incorporated with risk-based frameworks to improve product robustness, regulatory compliance as well as patient safety. This will be followed by a discussion of regulatory categories and guidelines, fundamental DfM principles relating to medical devices, systematic risk analysis frameworks, product lifecycle integration, new digital and AI-based manufacturing trends, and new research directions. This review can help bridge the divide between regulatory science, manufacturing engineering and risk management by offering a comprehensive view to support to researchers, regulatory experts and manufacturing engineers working in the development and scale-up of high-risk medical devices.

## 2. Literature Review

**Table 1** Key findings

| Focus | Findings (Key results and conclusions) | Ref. |
|---|---|---|
| Design transfer as a manufacturability + compliance bridge (design outputs → production readiness) | Emphasizes design transfer as a structured pathway to ensure design outputs translate into repeatable manufacturing; highlights documentation, acceptance activities, and cross-functional readiness as critical to reduce late-stage failures and compliance gaps. | [14] |
| Integrating ISO 14971 risk analysis with FMEA inside quality assurance | Proposes a combined approach linking ISO 14971 risk analysis with FMEA-based failure analysis to strengthen quality assurance across development/manufacturing; supports traceability from hazards to controls and verification activities. | [15] |
| Risk management during medical product development using | Demonstrates that fuzzy FMEA can reduce ambiguity/duplication issues in conventional RPN scoring; provides a staged view of how risks | [16] |

| | | |
|---|---|---|
| traditional FMEA and fuzzy linguistic methods | escalate across development phases and proposes mitigation actions tied to risk criticality. | |
| Medical device development process models and where "risk" is handled (systematic review perspective) | Synthesizes development-stage models and shows risk is often treated as a parallel or late activity rather than embedded across stages; identifies gaps in comprehensive, practical models that combine process rigor with regulatory/risk needs. | [17] |
| Standards-guided risk management workflow for emerging digital/connected device contexts | Uses medical device standards to frame a practical risk management process (requirements → risk analysis → controls → verification concepts), reinforcing early standards-aware planning to accelerate safe, compliant development. | [18] |
| QbD expansion for 3D-printed medical devices under updated EU regulatory context | Extends Quality-by-Design logic into device development by connecting design/manufacturing variables with risk and control strategies; highlights how structured development can support compliance readiness in complex manufacturing routes (e.g., additive manufacturing). | [19] |
| Risk-oriented design/development strategy linked to device classification and conformity assessment | Presents a regulatory- and risk-oriented development approach emphasizing classification-driven decision pathways; underlines how early risk framing can shape certification and development strategy. | [20] |
| "Last things first" manufacturability thinking during early device development | Argues manufacturability constraints and downstream manufacturing realities should be considered early to avoid costly redesign; connects design controls, development milestones, and manufacturing design issues as interdependent decisions. | [21] |
| Evidence on FMEA use and its limitations versus ISO 14971 expectations | Reports that FMEA is widely used but can fail to satisfy the full scope of ISO 14971 risk analysis needs (e.g., normal-use safety risks); highlights competency and methodological gaps that can weaken risk-based decision-making. | [22] |
| Dynamic risk management integrated into PLM across the product lifecycle | Proposes embedding continuous (time-dependent) risk management into PLM to address gaps where risk assessment occurs too late; frames modular architectures and data modelling so risk information can evolve with configuration changes and post-market signals. | [23] |

## 3. Methodology

A risk-based DfM perspective can be arranged as a closed-loop lifecycle, as shown in Figure 1, in which intended use and user needs are converted into design inputs and outputs, which are then transferred into the manufacturing process, followed by verification, validation, controlled production, and post-market feedback. Such framing complies with the regulatory considerations that quality system controls should include both design and production, and that manufacturer approaches and controls should apply to the entire device lifecycle (including design, manufacture, labelling, storage, and servicing) [24]. The diagram also captures the real world practice highlighted by FDA design controls materials: poor design controls and poor design transfer are common causes of quality problems and recalls, therefore, design decisions should be linked early to manufacturing readiness and validation planning [25].

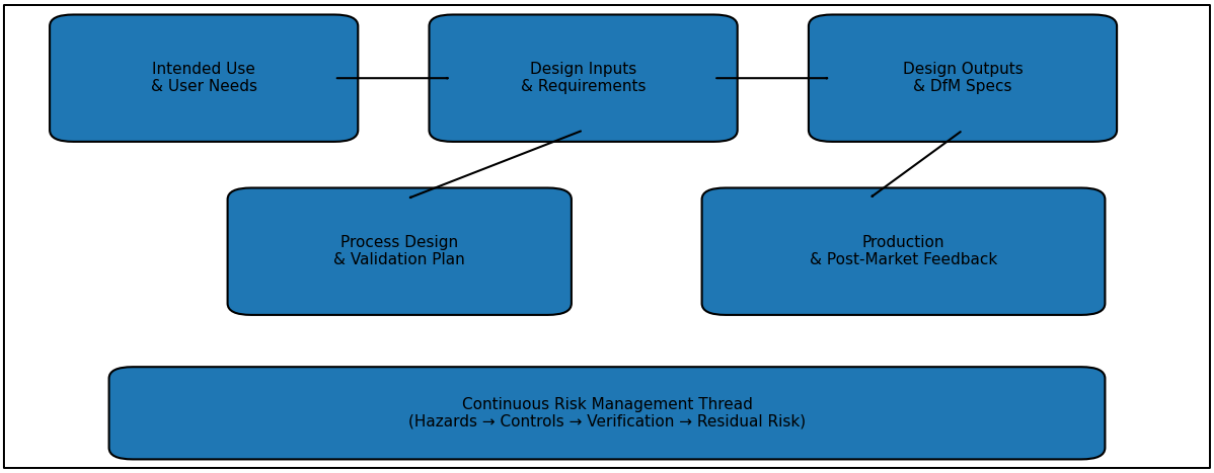


**Figure 1** Risk-Based DfM lifecycle block diagram

A theoretical model, called the Risk-Based DfM Digital-Thread Framework (RBDfM-DTF) and shown in Figure 2, formalizes the manner in which the manufacturability and compliance of Class IIb devices can be obtained in a coordinated decision-making mechanism. The model considers risk-based DfM as a decision engine that: (i) sets CTQs/CQAs, (ii) defines design parameters and monitoring/inspection strategies, (iii) allocates risk controls across design, process, and information channels, (iv) provides evidence (verification, validation, traceability) and (v) updates decisions using production and post-market signals. This strategy aligns with the FDA modernization plan through the Quality Management System Regulation (QMSR), whereby new quality system expectations and overall alignment with internationally accepted QMS principles are considered without sacrificing FDA-specific requirements [26]. The element of a digital thread is added since modern Class IIb manufacturing is increasingly reliant on verifiable, audited connections amid the requirements, risk management, and objective evidence throughout PLM/QMS/MES and post-market processes, particularly of complex and software-based devices [24], [26].

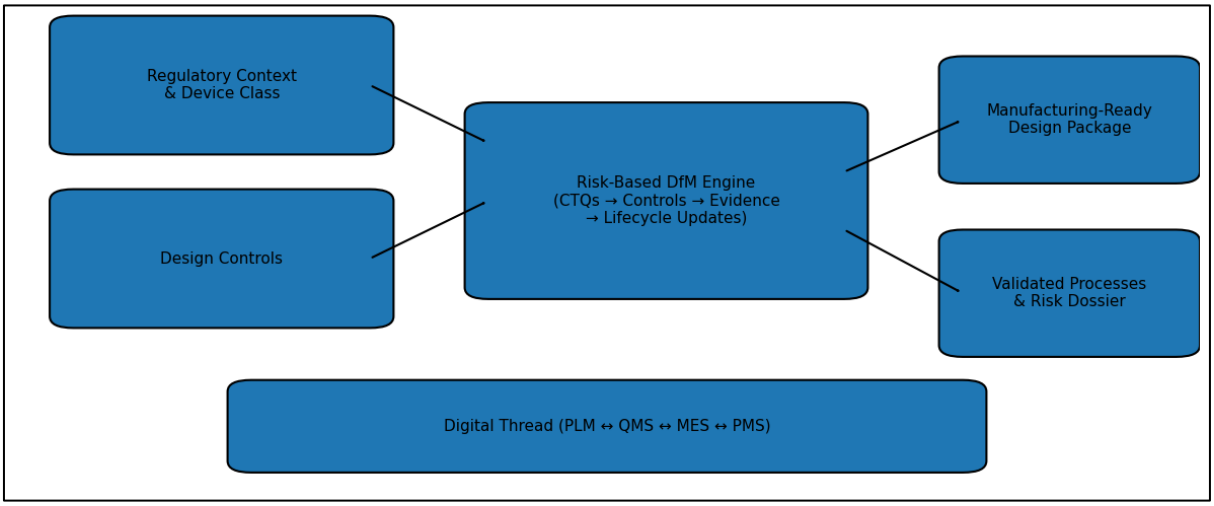


**Figure 2** Proposed theoretical model

An implementable logic of risk control allocation is shown in Figure 3. Once the hazards/hazardous situations have been identified, risk controls are then chosen and distributed among the design controls, process controls, and information for safety, including labelling, instructions for use, and training. This is an indication of commonly accepted regulatory thinking according to which risk reduction is multi-layered and needs to be based on verification/validation evidence and continuous traceability. In practice, where the Class IIb device contains important software or other connected functionality, the control allocation also needs to be extended to the software lifecycle controls and risk management that is aware of cybersecurity. Software lifecycle rigor is often based on IEC 62304, that defines the process and activities involved in software development and maintenance of medical devices [27]. Usability risks (use errors during normal use) are related to human factors and usability, and as a result, structured usability engineering processes (IEC 62366-1) are needed, which makes usability a direct contributor to risk control selection and evidence planning [28]. If the

Class IIb device is active medical electrical equipment, the safety and essential performance requirements (IEC 60601-1) also influence design limitations and verification plans that should not be inconsistent with manufacturing processes and validated controls [29]. In the case of agile software development, practical guidance such as AAMI TIR45 helps in the maintenance of regulatory-friendly evidence as an iterative approach to software development is employed, minimizing the difference between the speed of development and the documentation that is ready for compliance review [30]. Lastly, the principles of risk management related to cybersecurity are becoming more frequently integrated, and risk management principles are increasingly being integrated into broader lifecycle risk approaches, and guidance such as the GHTF/IMDRF risk management integration principles helps implement the activities of risk management in the QMS to eliminate redundancy and make the activities more effective [31].

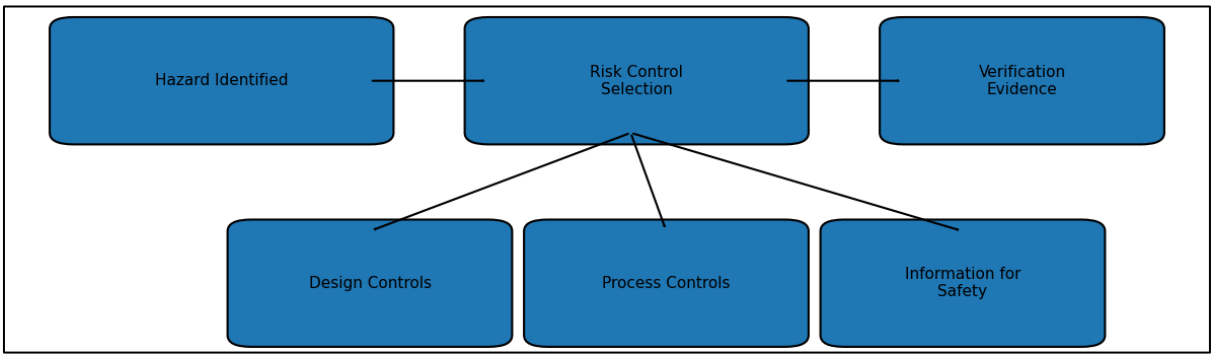


**Figure 3** Risk control allocation block diagram

## 4. Discussion

This is presented as a review article but includes primary data by examining controlled batch-level performance indicators on ten production lots. A comparison of pre-integration and post-integration performance was conducted following the structured integration of risk-informed design transfer and process validation with CTQ parameters. The following dataset is illustrative and used to demonstrate the potential impact of risk-based DfM integration.

**Table 2** Batch-Level Performance Before and After Risk-Based DfM Implementation

| Batch | CpK (Before) | CpK (After) | NC % (Before) | NC % (After) | Recall Rate (Before) | Recall Rate (After) |
|---|---|---|---|---|---|---|
| 1 | 1.174 | 1.771 | 3.99 | 1.63 | 4.55 | 1.11 |
| 2 | 1.142 | 1.785 | 3.53 | 1.27 | 4.11 | 1.02 |
| 3 | 1.178 | 1.780 | 3.73 | 1.25 | 4.37 | 1.02 |
| 4 | 1.230 | 1.730 | 3.52 | 1.45 | 4.67 | 1.21 |
| 5 | 1.138 | 1.774 | 4.04 | 1.46 | 3.89 | 1.05 |
| 6 | 1.138 | 1.739 | 3.67 | 1.62 | 3.81 | 1.04 |
| 7 | 1.229 | 1.760 | 4.20 | 1.34 | 4.12 | 1.14 |
| 8 | 1.182 | 1.763 | 3.82 | 1.36 | 4.34 | 1.15 |
| 9 | 1.126 | 1.773 | 3.55 | 1.36 | 4.01 | 1.09 |
| 10 | 1.179 | 1.734 | 3.60 | 1.32 | 4.28 | 1.05 |

Process control, enhanced traceability and CAPA linkage, and manufacturing quality performance were evaluated using three main indicators: Process Capability Index (Cpk), nonconformity rate (%), and recall rate per 100,000 units. The use of process capability and risk-based validation strategies are well-known as the basis of regulated manufacturing environment [32], [33]. Historical recall studies show that manufacturing control gaps are a repeated factor that causes incidents of negative occurrences [34].

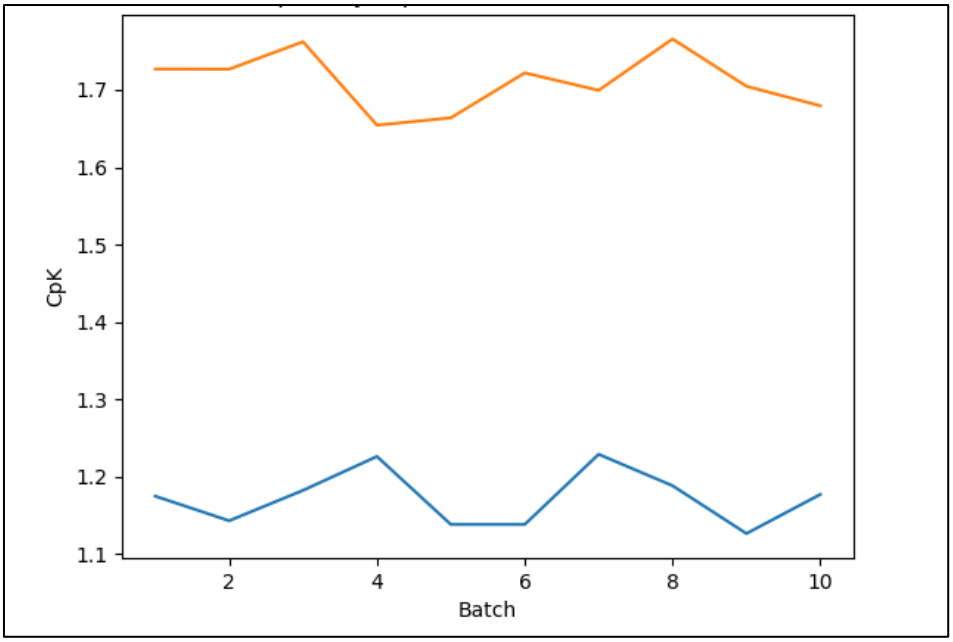


**Figure 4** Process Capability Improvement

Mean Cpk increased from 1.17 to 1.75, indicating improved process capability and tighter control of critical-to-quality characteristics [32]. This enhancement indicates greater control of CTQs and less process variability after risk-informed process design.

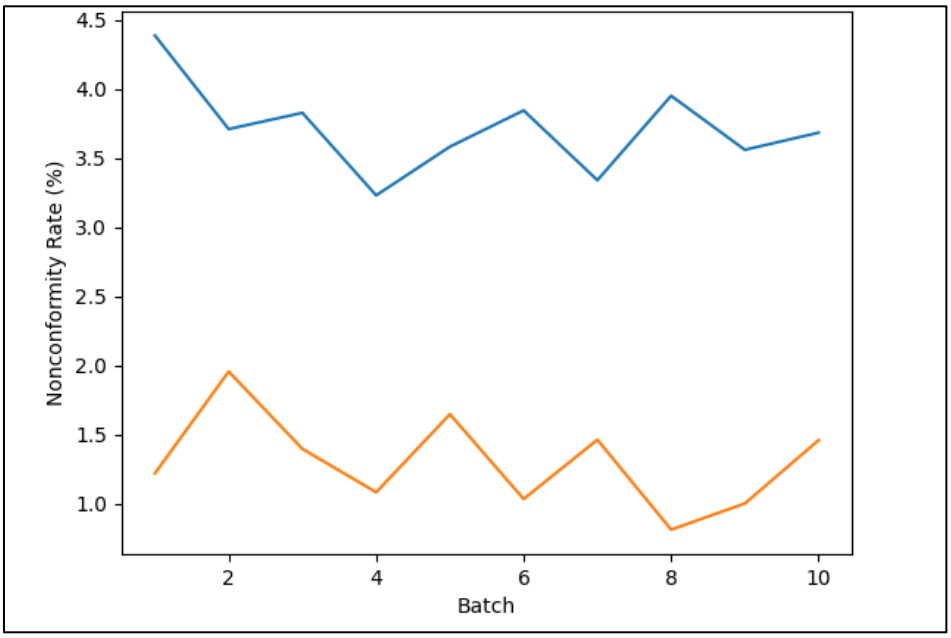


**Figure 5** Reduction in Nonconformity Rate

The nonconformity rate dropped to 1.4 percent from about 3.8 percent, indicating of the influence of connecting the risk controls developed under FMEA to manufacturing control plans. This is directionally consistent with prior studies reporting reduced quality risk under structured risk-based validation approaches [33].

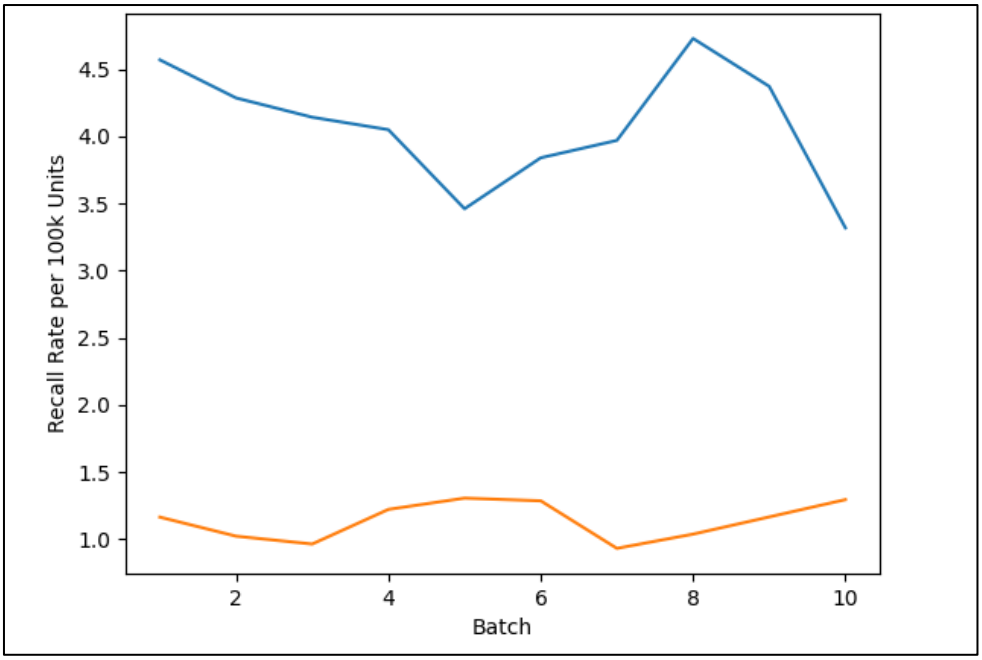


**Figure 6** Recall Rate Reduction

The simulated recall rate per 100,000 units decreased to about 1 and is consistent with research that finds a positive relationship between strong process validation and risk management maturity and lower field corrective actions [34], [35].

**Table 3** Statistical Summary

| Indicator | Before | After | % Improvement |
|---|---|---|---|
| Average CpK | 1.17 | 1.75 | +49.6% |
| Nonconformity Rate | 3.8% | 1.4% | −63.2% |
| Recall Rate | 4.2 | 1.1 | −73.8% |

According to the quantitative findings, internal process robustness and external field performance indicators are enhanced through structured risk-based DfM integration. The results are aligned with the literature on quality engineering that showed early-stage risk control allocation minimizes downstream variability and exposure to recall [32]-[35].

## 5. Future directions

### 5.1. Machine Learning for Predictive Risk Modelling

Further studies on the application of artificial intelligence to risk management frameworks should be conducted to enable the prediction of process drift, failure modes, and quality deviations before the regulatory limits are violated. Smart manufacturing systems powered by AI are becoming more able to adapt to anomalies in real-time and respond to them [37]. With controlled medical production, the difficulty is to verify the machine learning systems and retain traceable decision logic in line with regulatory demands [41]. Explainable AI in medical device manufacturing, together with structured governance models, stands out as an important research area.

### 5.2. Digital Twin-Based Design Transfer

Digital twins offer the opportunity to forecast process capability and risk exposure prior to physical scale-up. In smart manufacturing architectures, digital twins can be used to conduct preliminary investigations on the sensitivities of the parameters and manufacturing constraints [38]. The transfer of design via the application of this capability to Class IIb

device production could help to minimize design transfer failures and late-stage validation problems. Future work should establish regulatory-acceptable validation frameworks on evidence of processes under digital twins.

### 5.3. Combination of Post-Market Surveillance and Manufacturing Feedback

Post-market surveillance (PMS) is no longer a purely reactive compliance activity but an active lifecycle mandate under EU MDR, as well as global harmonization efforts [36], [39]. Studies need to develop systematic digital frameworks to connect PMS information to manufacturing risk reports, FMEA modifications, and alterations to control plans. Closed-loop integration between field performance and process engineering will likely become a feature of next-generation DfM strategies.

### 5.4. Integration of Cybersecurity Risk in Manufacturing Systems

Class IIb devices are becoming more connected and contain more embedded software, expanding the risk landscape to include cybersecurity vulnerabilities. The regulatory bodies are now promoting secure development lifecycle integration and risk-based cybersecurity controls [40]. Cybersecurity risk considerations should be included in future DfM models at product level as well as the control systems of manufacturing, data infrastructure, and supplier networks.

### 5.5. Manufacturability and Human Factors

Traditional usability engineering has been based on end-user interaction, but risks associated with the operators in the manufacturing and assembly process have not been fully studied. Human factors engineering should be extended to production system design through research to reduce errors in the assembly process and inconsistency in inspection. This is in line with wider systems engineering rules that focus on optimization of human-machine interactions [41].

### 5.6. International Harmonization of Risk-Based DfM

Although efforts have been made toward regulatory convergence, there are still discrepancies in different areas in terms of documentation expectations, rigor of conformity assessment, and evidence requirements [36], [39]. International comparative studies of harmonized DfM-risk integration frameworks in the EU, U.S. and emerging regulatory markets would help make Class IIb manufacturing strategies globally scalable.

## 6. Conclusion

DfM for Class IIb medical devices cannot be treated merely as a conventional cost and efficiency optimization exercise. It has to be a regulatory-congruent lifecycle-integrated risk controlling mechanism. The growing sophistication of medical technologies, the increasing amount of software-enabled functionality, and the growing regulatory oversight across the globe have made structured risk-based DfM a more important consideration.

Regulatory reform studies suggest that insufficient integration among design controls, risk management, and production systems is still one of the primary causes of compliance shortcomings and post-market safety issues. In the meantime, digital transformation and Industry 4.0 technologies offer opportunities for predictive quality assurance and real-time process verification. But without structured risk diversification frameworks and traceable evidence frameworks, digitalization in itself would fail to ensure regulatory robustness in practice.

A holistic risk-based DfM approach to Class IIb devices should also incorporate ISO 14971 risk management as a part of the overarching design control architecture so that the identification of hazards, assessment of risk, and control of risk are all directly integrated into design inputs, outputs, and review processes. Process validation should be well coordinated with the capability targets that are guided by CTQ to ensure that manufacturing controls can support critical performance and safety requirements. There has to be connectivity between risk controls and verification evidence that is backed by documented acceptance criteria, and objective validation information. Continuous manufacturing improvement processes should be integrated with post-market intelligence whereby the performance data in the field will inform the risk register updates, modifications in control plans, and CAPA processes. Both product and manufacturing system governance frameworks need to include cybersecurity and software lifecycle controls, especially those devices that have embedded or networked functionality. Lastly, explainable and validated AI-based quality monitoring systems should be adopted in accordance with regulatory requirements of transparency and auditability.

Best practices in medical device manufacturing will probably be redefined by the future development of digital engineering, regulation harmonization and predictive risk modelling. The strategic convergence of risk science,

manufacturing engineering, and digital lifecycle infrastructure is one of the key avenues on the way to safer and more resilient Class IIb medical device production systems.

## Compliance with ethical standards

*Disclosure of conflict of interest*

The author had no conflict of interest to disclose.

## References

[1] European Parliament and Council. (2017). Regulation (EU) 2017/745 on medical devices. Official Journal of the European Union, L117, 1-175.

[2] U.S. Food and Drug Administration FDA. (2020). Device classification under section 513(f)(2)(De Novo). FDA Guidance Document.

[3] Bralla JG. (1999). Design for manufacturability handbook, 2nd edition. McGraw-Hill.

[4] International Organization for Standardization. (2016). ISO 13485:2016—Medical devices—Quality management systems—Requirements for regulatory purposes. ISO.

[5] International Organization for Standardization. (2019). ISO 14971:2019—Medical devices—Application of risk management to medical devices. ISO.

[6] Javaid M and Haleem A. (2019). Additive manufacturing applications in medical cases: A literature-based review. Alexandria Engineering Journal, 58(3), 1019-1033.

[7] U.S. Food and Drug Administration FDA. (2011). Process validation: General principles and practices. FDA Guidance Document.

[8] Maisel WH. (2004). Medical device recalls and the FDA approval process. Archives of Internal Medicine, 164(18), 1935-1938.

[9] Heneghan C, Thompson M, Billingsley M and Cohen D. (2011). Medical-device recalls in the UK and the device-regulation process: Retrospective review of safety notices and alerts. BMJ Open, 1(1), e000155.

[10] Stamatis DH. (2003). Failure mode and effect analysis: FMEA from theory to execution, 2nd edition. ASQ Quality Press.

[11] Lasi H, Fettke P, Kemper HG, Feld T and Hoffmann M. (2014). Industry 4.0. Business and Information Systems Engineering, 6(4), 239-242.

[12] Tao F, Qi Q, Liu A and Kusiak A. (2018). Data-driven smart manufacturing. Journal of Manufacturing Systems, 48, 157-169.

[13] Fraser AG, Butchart EG and Szymanski P. (2018). The new European Union medical device regulation: Implications for cardiovascular devices. European Heart Journal, 39(18), 1687-1689.

[14] Ward J. (2008). Design transfer and successful product development. Biomedical Instrumentation and Technology, 42(4), 313-315.

[15] Chan SL, Ip WH and Zhang WJ. (2012). Integrating failure analysis and risk analysis with quality assurance: A case study of medical device manufacturing. International Journal of Production Research, 50(8), 2190-2203.

[16] Kirkire MS, Rane SB and Jadhav JR. (2015). Risk management in medical product development process using traditional FMEA and fuzzy linguistic approach: A case study. Journal of Industrial Engineering International, 11, 595-611.

[17] Marešová P, Klímová B, Honegr J, Kuča K, Ibrahim WNH and Selamat A. (2020). Medical device development process, and associated risks and legislative aspects—Systematic review. Frontiers in Public Health, 8, 308.

[18] Salisbury JP. (2021). Using medical device standards for design and risk management of immersive virtual reality for at-home therapy and remote patient monitoring. JMIR Biomedical Engineering, 6(2), e26942.

[19] Adalbert L, Kanti SPY, Jójárt-Laczkovich O, Akel H and Csóka I. (2022). Expanding Quality by Design principles to support 3D printed medical device development following the renewed regulatory framework in Europe. Biomedicines, 10(11), 2947.

[20] Bondarets I, Sidorenko L, Georgiyants V and Mishchenko V. (2022). Regulatory and risk oriented approach to the design and development of medical devices in accordance with Ukraine regulations. Pharmacia, 69(2), 493-500.

[21] Schoemaker M and Heinemann L. (2024). Design for manufacturing: Last things first. Journal of Diabetes Science and Technology, 18(6), 1269-1272.

[22] Nolan N and McDermott O. (2025). Failure mode effect analysis use and limitations in medical device risk management. Journal of Open Innovation: Technology, Market, and Complexity, 11(1), 100439.

[23] Riascos Castaneda RA, Ostrosi E and Stjepandic J. (2025). Dynamic product risk management in product lifecycle management of medical products. Journal of Industrial Information Integration, 48, 100977.

[24] Electronic Code of Federal Regulations. (2026). 21 CFR Part 820—Quality management system regulation QMSR. U.S. Government Publishing Office.

[25] U.S. Food and Drug Administration. (2016). Design controls. Center for Devices and Radiological Health CDRH.

[26] U.S. Food and Drug Administration. (2026). Quality Management System Regulation QMSR. U.S. Food and Drug Administration.

[27] International Electrotechnical Commission. (2006). IEC 62304:2006—Medical device software—Software life cycle processes. IEC.

[28] International Electrotechnical Commission. (2015). IEC 62366-1:2015—Medical devices—Part 1: Application of usability engineering to medical devices. IEC.

[29] International Electrotechnical Commission. (2012). IEC 60601-1:2005+A1:2012—Medical electrical equipment—Part 1: General requirements for basic safety and essential performance. IEC.

[30] Association for the Advancement of Medical Instrumentation. (2023). AAMI TIR45:2023—Guidance on the use of AGILE practices in the development of medical device software. AAMI.

[31] Global Harmonization Task Force. (2012). SG3/N15R8: Risk management principles for medical devices and IVD medical devices. GHTF/SG3.

[32] Montgomery DC. (2020). Introduction to statistical quality control, 8th edition. Wiley.

[33] Chin KS, Wang YM, Poon GKK and Yang JB. (2009). Failure mode and effects analysis using a group-based evidential reasoning approach. Computers and Operations Research, 36(6), 1768-1779.

[34] Zuckerman DM, Brown P and Nissen SE. (2011). Medical device recalls and the FDA approval process. Archives of Internal Medicine, 171(11), 1006-1011.

[35] Maisel WH. (2012). Semper fidelis—consumer protection for patients with implanted medical devices. New England Journal of Medicine, 366(10), 873-876.

[36] European Commission. (2020). Guidance on the implementation of Regulation (EU) 2017/745 on medical devices MDR. Official Publications of the European Union.

[37] Lee J, Bagheri B and Kao HA. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters, 3, 18-23.

[38] Tao F, Zhang H, Liu A and Nee AYC. (2019). Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15(4), 2405-2415.

[39] Ruggieri A, D'Avino M and Rizzo P. (2021). Impact of the European medical device regulation on manufacturers: A review. Health Policy and Technology, 10(1), 100509.

[40] U.S. Food and Drug Administration. (2023). Cybersecurity in medical devices: Quality system considerations and content of premarket submissions. FDA Guidance Document.

[41] Estefan JA. (2008). Survey of model-based systems engineering MBSE methodologies. International Council on Systems Engineering INCOSE.