Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220640

Design for Producibility: A Case Study on Theory, Practice and Gaps

Rohith ARETH KOROTH[1], Fredrik ELGH, Martin LENNARTSSON and Dag RAUDBERGET
School of Engineering, Jönköping University, Sweden

Abstract. Changing customer requirements, regulations, technology and regulations, shift to automated assembly and product variety are common challenges faced by many manufacturing industries and alignment between product and production system is critical for business success. Design engineers should be aware of production constraints and capabilities to ensure efficient manufacture and assembly of products that are developed. This requires different and detailed support to guide the work, evaluate different design solutions, enable continuous and concurrent work with design for producibility and production preparation. A study was conducted in three companies to understand alignment and integration of product development and production preparation processes. Also, utilization of production requirements, design for manufacture and assembly (DFMA) and failure modes and effect analysis (FMEA) to support design for producibility (DFP) was studied. Currently, production preparation is done through discussions between design and production engineers. Production preparation and work with DFMA and FMEA is skill and experience dependent. Definition, structuring and sharing of production requirements on different system levels, from production and product perspectives are identified as critical to supporting design for producibility and production preparation. The work with FMEA and DFMA can be developed and improved with systematic and structured way of working with production requirements.

Keywords. Production preparation, DFP, DFMA, FMEA, Production requirement, Transdisciplinary approach

Introduction

Product development process is characterized by a mix of uncertainties and design freedom leading to the gradual determination of product features, long lead times, high product complexity and uncertainty in the product [1, 2]. Increased demand for customized and personalised products both in business to business and business to customer markets is forecasted which can cause uncertainties [3–5]. Uncertainties can be managed to an extent if the design engineers knew the ability of the production process to materialize the design. It is essential that the design engineers are aware of the capabilities of production systems to create products of good quality, cost and value to the customers [6]. This knowledge becomes important as there is shift towards automated assembly to meet cost challenges and reshoring. To optimize the production process of a product, producibility engineering adopts a cross-functional approach [7] that can support the utilization of manufacturing knowledge during the whole product development process. However, many stakeholders and life-cycle aspects need to be

[1] Corresponding Author, Mail: rohith.arethkoroth@ju.se.

considered to address the design and manufacturing interface and design for producibility (DFP). Supports such as simulation tools are available for producibltiy assessment in later phases of product development but not for early design phases[8]. So, there is a need for developing such supports.

This research is part of a larger 3½-year project that brings together practitioners and researchers to address resource efficiency in industry and throughout the whole product life cycle. Three traditional manufacturing companies, two industrial house building companies and one IT solutions provider are involved in the project. At this point, more than fifty practitioners and thirteen researchers with competencies spanning from product management, engineering design, computational engineering, software development, production development and testing to quality, sourcing, and project management have been involved. The research is characterized by crossing borders, interactive research and transdisciplinary engineering where practitioners and researchers work together in the knowledge/solution creation process. The rationale for the composition of the group of industrial partners is that there is a learning potential between the different industry sectors. The traditional mechanical engineering industry is more mature when it comes to platform planning and development[9], and on the other hand, the selected housebuilders have the capability of delivering customer-specific products in low volumes. This work is based on the findings of research clarification study [10] including semi-structured interviews and workshops conducted earlier that identified tools of design for manufacturing and assembly, failure mode and effects analysis and production requirements as enablers for design for producibility which is explored further here.

1. Frame of reference

Different models of product development processes exist (e.g. [11], [12]), and making the product ready for production is an essential phase. This phase is known by different names such as production appraisal [12], production ramp-up [13] or production preparation [14]. Andreasen et al. [14] describe production preparation as those activities that demonstrate that the product can be produced. During this process the product is specified for production, the components are modified to suit the production and assembly and the suitability of the product for production is proven. The production preparation process aims at integrating the activities in product design and development with production planning and manufacturing [15]. Lukić et al. identify two phases to the production preparation process – technical and operational preparation, to address requirements related to product quality, variety, complexities etc [15]. The Lean-3P is another approach used for production preparation. It aims at the elimination of waste during product and process design through the use of cross-functional teams, rapid testing of ideas and embedding lean manufacturing concepts into the design [16].

Literature shows that the production preparation can be done using tools such as Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Computer-Aided Process Planning (CAPP), Design for Excellence (DFx) guidelines, Failure Mode and Effects Analysis (FMEA) and 3P workshops. DFx aims at providing standard methodologies for aspects that provide excellence to design such as manufacturing, reliability, variability, assembly and producibility [17]. In the context of this paper, the focus is on manufacturing, assembly and producibility. Design for producibility (DFP) is the systematic method to attain functional requirements of the product while aligning to the manufacturing systems [18]. There is a lack of support in CAD systems for producibility assessment but tools such as CAD, CAPP and FMEA can support this [19]. DFP can be achieved using a knowledge-based approach through methods such as DFMA[20]. DFMA is a method proposed to support design engineers to get the full benefit of their production system through a combination of DFA and DFM principles [21]. DFA is done first to reduce the complexity of the product structure followed by DFM to reduce the manufacturing cost. DFM give inputs related to tooling, process, human factors, materials and equipment to designers [22]. FMEA is used to recognize and eliminate issues in a product during the product development process. It can be divided into three-system FMEA (sFMEA), design FMEA (dFMEA) and process FMEA (pFMEA) [23]. sFMEA is used to analyse the issues during the product's integration into the system and is carried out during the concept and design phases. dFMEA is used to identify risks related to design and is used in development phases while pFMEA is used to identify risks related to processes and is used in the realization phases.

DFMA and FMEA are widely used in the industry. Challenges in DFMA highlighted in the literature are lack of support for integrating knowledge from different sources in design, lack of manufacturability knowledge in early design phases, lack of support for the redesign of components after evaluation with DFMA tools, lack of integration with 3D CAD systems and capturing and sharing of knowledge within the company [24–27]. Challenges faced in FMEA are: it is a subjective process, knowledge and experience-dependent, lack of continuity as different people are involved in different stages of product development, large documentation, lack of integration to CAD systems and it is a single point failure analysis [23, 28–30]. Different methods have been proposed to overcome the challenges faced in DFP, DFMA and FMEA. Producibility assessment can be done using design automation [31] and tools of CAD, Computer-aided engineering (CAE) and Computer-integrated manufacturing (CIM)[8]. DFMA and FMEA can be improved by creating a knowledge base of pre-existing knowledge and guidelines and having information models which can be integrated into the CAD systems [27, 28, 32]. Combining DFMA and FMEA with other tools such as quality function deployment and multicriteria decision making tools, benefiting from opportunities of industry 4.0 will help to have more customer focus and reduce the data gathering and analysis bias currently faced [30, 33]. The concept of key characteristics (KC) is used both in DFMA and FMEA utilize knowledge [28, 32]. KC is defined as the features of materials, processes, parts or assemblies that can affect the product's performance and manufacturability [34]. KC can be used to communicate production requirements to early product development phases. Concepts such as manufacturing constraints [35] and manufacturing engineering requirements [36] can also be used for better communication between design and manufacturing. Test assemblies, risk assessment, DFA, QFD and CAD tools can be combined to the above concpets to improve communication.

2. Current industrial practice

This research project follows the design research methodology as a framework for conducting research [37]. An initial study revealed that improvement in the production preparation process is needed, including integrated information, digitalization, better communication methods and competence development to have better understanding between the design and production engineers. DFMA and FMEA along with the definition of production requirements were identified as tools that can support in developing the required understanding between the various disciplines and improve production preparation. This section presents the result of a subsequent in-depth descriptive study to understand the current status in production preparation, production requirement definition and use of DFMA and FMEA. Primary data source was semi-structured interviews and the secondary source was an analysis of company documents. A total of 12 interviews with three companies were conducted. Details about the companies and interviews are given in Table 1 below.

Table 1. Company description and interview details.

Company (Business)	Employee	Manufacturing Locations	Interview count	Interviewee roles
C1-Automotive Supplier	3303	9 (Global)	4	Design engineer (2No.s), Chief Engineer, Advanced quality planning
C2-Outdoor power products	14000	28 (Global)	4	Production engineer, Technical engineer, Mechanical engineer, Project manager
C3-Industrial house building	926	4 (Sweden)	4	R&D engineer, Development engineer, Production technician, Project manager-industrial development

2.1. Production Preparation

The case companies have production preparation embedded in their development processes. C2 and C3 have it throughout the process while C1 has it in the development and industrialization phases. They use supports such as DFx, 3P, lessons learnt, design guidelines and visualisation tools to support production preparation but is still dependent on individual knowledge and communication. Lack of manufacturing knowledge among design engieers and lack of manufacturing input in early phases of project have been highlighted as challenges which needs to be improved. Table 2 shows the supports, challenges and opportunities during production preparation in the case companies.

Table 2. Production preparation.

	C1	C2	C3
Support	DFx, Production part approval process(PPAP), guidelines	3P, templates, lessons learnt, handbooks, PPAP	meetings, guidelines, test builts, visualisation tools
Challenges	- Different documents, templates, guidelines - Experience-dependent - Prototype-based evaluation different from actual production - Lack of resources - Less manufacturing input in the beginning	- Design engineers lack knowledge on production aspects - Deviations in tools, logistic issues -information from mature products may be wrong - Automation and productplatform shift	- Constrained by equipment suppliers, regulations and laws. - Changing customer needs creates uncertainty - Pushing boundaries to accommodate design
Opportunities	D and p fmea should highlight as much as possible	3P link to technology and manufacturing readiness level (TRL & MRL)	Decision making support, process flow simulations, CAM

2.2. DFMA and FMEA

C1 uses DFMA separately as DFM and DFA and C2 uses it as a part of the DFx tool. FMEA is used by both C1 and C2 for removing risks in functions from a user perspective, to evaluate engineering work to identify challenges and risks related to safety and quality. Both use dFMEA and pFMEA. C3 does not use either DFMA or FMEA tools at present but identifies an opportunity in implementing them. Data collected showed that there is overlap in roles of people involved in DFMA and FMEA activities and used supports such as templates, guidelines, lessons learnt, PLM and documents from previous projects. Challenges faced were change to automation, lack of manufacturing input in early phases, dependency on experience and lack of resources. Table 3 and table 4 below gives details of DFMA and FMEA implementation in the case companies.

Table 3. DFMA implementation.

	C1	C2
Role	Project manager, production engineer, test engineer, simulation engineer, design engineer, chief engineer,	Design engineer, Manufacturing engineer, Operations, quality, purchasing, project manager, industrial designers
Support	Guidelines, templates, Checksheet, Product Lifecycle Management tool (PLM), Sharepoint, project folder	3P Guidelines, carryover parts, prototype, mockup workshops, checklists, templates, simulation and cad, lessons learnt, PLM
Challenge	Lack of clarity, need adaptation for certain products, time pressure, lack of resources, documentation and lack of participation in early design phases by manufacturing.	They need to review the supports as they are converting from manual to automatic assembly. Dfx documents are at a high level and need to be smaller manageable parts.
Opportunity	More structured DFMA tools will enable early manufacturing input. Semi-automated can benefit from the tool.	Templates are good for sum up and communication. Design for automated assembly and simulation tools can support.

Table 4. FMEA implementation.

	C1	C2
Role	DFMEA: Project manager, test engineer, simulation engineer, design engineer, chief engineer, project purchaser, industrial design, external experts PFMEA: Project manager, production engineer, design engineer, chief engineer, advanced quality planning engineer,	DFMEA: Design Engineers, mechanical engineers and quality engineers PFMEA: Design Engineers, quality engineers, test engineers, material technician, process preparation engineers, supplier.
Support	User study and user functionality of similar products, old FMEAs, FMEA templates, guidelines, instruction manuals, lessons learnt documents and PLM.	DFMEA starting point for pFMEA. Estimations and mockups based on TRL, external expert, old fmea, input from field issues, standardised template, PLM
Challenge	Skill dependent, summarized risk assessment, downplaying numbers, a large number of documents	Skill dependent, common template irrespective of size, focus on documents can lead to missing details
Opportunity	Family FMEAs, integrating dFMEA and pFMEA, training	Software tools and visual supports for problem identification, integration of dFMEA and pFMEA

2.3. Production Requirements

Production requirements are mostly communicated through meetings based on the knowledge possessed by individuals. However, there is no structured definition of production requirements at present. The companies identify the potential benefits as: supports manufacturing input in early design, improves communication, sets limits to design and can be used for the testing plan. It should be standardised, flexible, valid and testable. The requirements should be clear and not upon interpretations. Also, putting down all the requirements on paper can be a challenge. Information handling and sharing can be a constraint in working with production requirements. Digital processes for information handling such as linking CAD/CAM and ERP to production systems can be useful. Table 5 below shows the aspects to be considered and tools support that exists for managing production requirements.

Table 5. Aspects and Tools for production requirements.

	C1	C2	C3
Aspects	Output, quality and scrap levels, poka-yoke, safety, environment aspects, dimensioning related, packaging requirements, process-related requirements, outcomes of the pFMEA	KPIs, approach in assembly, the direction of fastening, label placement surface, software download time, certification demands, assembly and test time	Process information, dimensions, storage, JIT demands, regulations and equipment
Tools/ supports	Control plans, drawings, FMEA, guidelines, PPAP documents and instructions	Mockup products, previous projects, guidelines, lessons learnt, PLM, meetings	Forums, information n the CAD system, control files, drawings

3. Analysis

The product development process in the companies can be generalized into a stage-gate process as discussed by Cooper et al.[38]. The production preparation process in the case companies is carried out to meet the cost, output and quality targets. C2 and C3 have production preparation throughout the process while C1 has it at the beginning of the development phase. Current implementation of DFMA, FMEA and use of production requirements to support production preparation were investigated in the case companies. C1 and C2 use DFMA and FMEA tools while C3 does not. However, C3 use platforms and existing knowledge to support production preparation but sees opportunity in implementing DFMA, FMEA and production requirements as it can support collaboration between design and production.

Dependence on individual knowledge, lack of manufacturing input in the early phases, abundance of documentation, changing product concepts, the difference in technology readiness levels (TRL), regulations, lack of production knowledge among design engineers, geographical dispersion of suppliers, possibility of missing information due to discontinuity in process and people involved, mismatch between prototype and actual production part hinders the process of production preparation, DFMA and FMEA in the case companies. These were in line with the challenges identified in the literature. Existing DFA methods rely on the design engineers' knowledge to create solutions [25] and lack of manufacturing knowledge can limit design engineers from assessing the producibility of the product [24]. Weakness of FMEA methods lies in dependence on experience, discontinuity in the process, resource-intensiveness, subjective method and lack of support for cross-functional integration [23, 28].

DFP aims at achieving the functional requirements while aligning to the manufacturing systems. C1 and C2 uses FMEA to assess risk to end users and DFMA to check the conformance to the production system. Success of these tools to support producibility was dependent on knowledge and maturity of the product. This may result in producibiltiy failures. The companies also raised concerns that the shift to automated assembly and loss of knowledge when experienced individuals leave the company can affect producibility. Better systems for capturing and sharing production knowledge and managing variants in existing lines is important to overcome these issues. It was understood from the case studies and literature that an improvement in the way of working with DFMA and FMEA, their integration with digital tools and combination with tools such as quality function deployment can better support producibility and integrated product development [28, 33]. Based on this, multiple areas have been identified for future work:

1. Defining and structuring of production requirements for improved support for design for producibility: Production requirements can be visualized as a combination of process variables and logistic variables [39], manufacturing requirements[36], manufacturing constraints [35] and key characteristics. Data collected from the interviews showed that a structured definition of production requirements can help to better communication between the different disciplines and overcome the lack of manufacturing inputs in the initial stages. The production requirements could support the alignment of product and production development.
2. Improvement of the FMEA tool for combining design and process FMEAs and supporting DFMA aspects: The second development area is to have the design and process FMEAs as a more parallel process based on the projects. This may help to overcome the issues of missing information and save resources.
3. Knowledge-based applications for DFMA and FMEA: Major challenges faced by both DFMA and FMEA are the dependence on experience and documentation. Knowledge-based systems could help the design engineers to evaluate the designs easily and also improve accessibility to earlier DFMAs and FMEAs.
4. Tools like quality function deployment (QFD) for combining information from production requirements, DFMA and FMEA: Repurposing existing tools is easier for acceptance than success of new tools. Quality function deployment is a tool already in use. New dimensions may be added to this, considering the aspects of production requirements, DFMA and FMEA. This could support integrated information and make the decision process easier during the early design phases.
5. Feature-based CAD tools to define interfaces capturing production requirements: CAD systems can store libraries of standardised components with information embedded into it. This can be used to capture production related information and make them available to design engineers.

These areas aim at creating different support that can enable the design engineers to assess the producibility of their designs easily within the systems they use. Having a well-defined set of production requirements can support better communication and the knowledge base of DFMA and FMEA can reduce the dependency on experience. Case study analysis shows that there is an overlap between the aspects and supports for production requirements, DFMA and FMEA which indicated the possibility of working together. Existing digital tools such as PLM and platform thinking in the case companies provide opportunities for linking the three tools and streamlining the production preparation process. The platform thinking can help to develop production requirements, DFMA and FMEA as knowledge assets[40] which can be used and reused based on if the product is new or a variant. Existing PLM support could provide common storage for these knowledge assets and access irrespective of the discipline and experience.

Figure 1 illustrates alignment of production requirements, DFMA and FMEA for design for producibility with respect to product development process and production development process [41] based on the future areas identified. Production requirements serve as a backbone and is used to define the production aspects of the products. The set of requirements matures along with the product. DFMA and FMEA are done as per the required stages. Production requirement assessment (PRA) is suggested after each stage to evaluate the conformance and critical areas. The production requirements act as input to these. Subscripts in the figure represents the stages. Future work focuses on how the identified areas could support design for producibility.

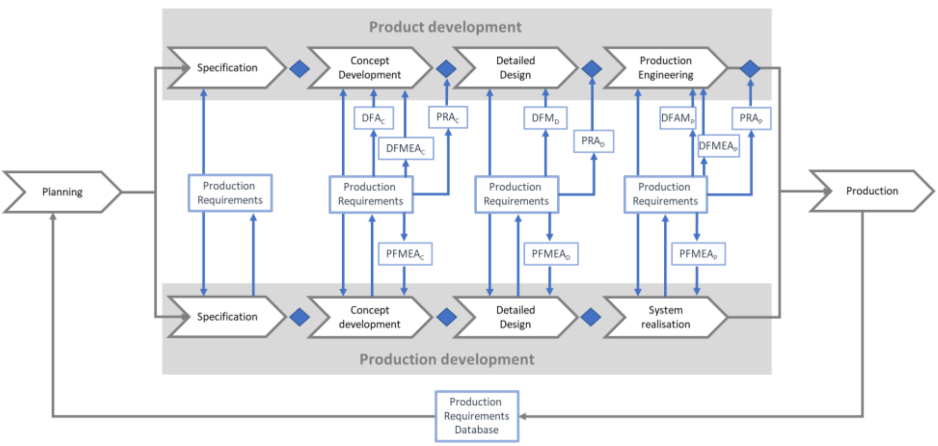

Figure 1. Proposed alignment of tools to development processes.

4. Conclusions

This paper presents and discusses the findings of a case study conducted to understand the production preparation process, use of DFMA and FMEA, scope of implementing production requirements in design and future development. The study was done in three companies with semi-structured interviews as the primary data source. Though DFMA and FMEA are useful tools to support design for producibility, there were challenges to implementing such as dependence on experience, a large volume of documentation and reduced accessibility due to the lack of integration with the existing software tools. Analysis of literature and data collected helped to identify the possible areas for future work as defining and structuring of production requirements, improvements of the

FMEA, knowledge-based applications for DFMA and FMEA, use of tools like quality function deployment (QFD) for combining information and feature-based CAD tools to define platform-based interfaces to capture production requirements. This study forms the foundations for the next phase of research with the aim of developing a method for improved integration in the design-production interface and support development phases with manufacturing knowledge thereby supporting design for producibility.

Acknowledgements

The research work presented in this paper is supported by the IDEAL project group, the Swedish Knowledge Foundation and the SPARK environment at Jönköping university.

References

[1] B. Christensen, T.D. Brunoe, Product Configuration in the ETO and Capital Goods Industry: A Literature Review and Challenges. In: S. Hankammer, K. Nielsen, F. Piller, G. Schuh, N. Wang, (eds.) *Customization 4.0. Springer Proceedings in Business and Economics*. Springer, Cham. https://doi.org/10.1007/978-3-319-77556-2_26.
[2] C. Levandowski, D. Raudberget, H. Johannesson, Set-based concurrent engineering for early phases in platform development. *Advances in Transdisciplinary Engineering*, 2014, Vol. 1, pp. 564–576.
[3] N.N., *2020 World Manufacturing Report: Manufacturing in the Age of Artificial Intelligence*, World Manufacturing Foundation, 2020. www.worldmanufacturing.org
[4] N.N., *Factories of the Future: Multi-annual roadmap for the contractual PPP under Horizon 2020*, 2020, European Commission. http://ec.europe.eu/research/industrial_technologies, doi:10.2777/29815.
[5] O. Isaksson, C. Eckert, Product Development 2040: Technologies are just as good as the designer's ability to integrate them. 2020. https://doi.org/10.35199/report.pd2040
[6] S. Gedell, M.T. Michaelis, H. Johannesson Integrated model for co-development of products and production systems - A systems theory approach, *Concurrent Engineering Research and Applications*, 2011, 19(2), pp. 139–156, doi:10.1177/1063293X11406751.
[7] D.T. Koenig, Producibility Engineering. In: *Manufacturing Engineering: Principles for Optimization*, Third Edition. ASME Press; 2010. p. 141–168. doi:10.1115/1.802493.ch6.
[8] J. Madrid, J. Landahl, R. Söderberg, H. Johannesson, J. Lööf, Mitigating risk of producibility failures in platform concept development. *31st Congress of the International Council of the Aeronautical Sciences*, 2018, https://www.icas.org/ICAS_ARCHIVE/ICAS2018/data/papers/ICAS2018_0101_paper.pdf.
[9] D. Popovic, S. Thajudeen, A. Vestin Smart Manufacturing Support to Product Platforms in Industrialized House Building. *Modular and Offsite Construction (MOC) Summit*. 2019 May 24, 284–292. doi:10.29173/MOCS105
[10] R. Areth Koroth, M. Lennartsson, D. Raudberget, F. Elgh, Product Platforms and Production – Current State and Future Research Directions Targeting Producibility and Production Preparation. *Advances in Transdisciplinary Engineering*, 2021, Vol. 16, pp. 332-341.
[11] T.W. Simpson, J.R.R.A. Martins, Multidisciplinary design optimization for complex engineered systems: Report from a national science foundation workshop, *Journal of Mechanical Design, Transactions of the ASME*. 2011, Vol. 133(10), pp. 1–10, doi:10.1115/1.4004465.
[12] R.G. Cooper, Stage-Gate Systems: A New Tool for Managing New Products. *Business Horizons*, 1990, Vol. 33, Issue 3, pp. 44-54.
[13] K.T. Ulrich, S.D. Eppinger, *Product design and development*. 5th ed. McGraw-Hill, Irwin, 2012.
[14] M.M. Andreasen, L. Hein, *Integrated product development*, IFS, Bedford, 1987.
[15] D. Lukić, V. Todić, M. Milošević, Model of Modern Technological Production Preparation. *Proceedings in Manufacturing Systems*, 2010, Vol. 5(1), pp. 15-24.
[16] S. Ramakrishnan, M.V. Testani, An integrated lean 3P and modeling approach for service and product introduction. *61st Annual IIE Conference and Expo Proceedings*. 2011, pp. 1-8.
[17] W. Lu, T. Tan, J. Xu, J. Wang, K. Chen, S. Gao, F. Xue, Design for manufacture and assembly (DfMA) in construction: the old and the new, *Architectural Engineering and Design Management*, 2021, Vol. 17(1–2), pp. 77–91. doi:10.1080/17452007.2020.1768505.

[18] F. Elgh, *Computer-Supported Design for Producibility: Principles and Models for System Realisation and Utilisation*, PhD thesis, Chalmers University of Technology, 2007.
[19] J. Landahl, *Platform Design for Producibility: Early-Stage Modeling and Assessment Support*, PhD thesis, Chalmers University of Technology, 2018.
[20] N.P. Suh, Keynote Papers: Basic Concepts in Design for Producibility. *CIRP Annals - Manufacturing Technology*, 1988, Vol. 37(2), pp. 559–567, doi:10.1016/S0007-8506(07)60753-7.
[21] G. Boothroyd, P. Dewhurst, W.A. Knight, *Product Design for Manufacture and Assembly*, 3rd edition, CRC Press, Boca Raton, 2010, doi:10.1201/9781420089288.
[22] C. Poli, *Design for Manufacturing: A structured Approach*, Butterworth-Heinemann, Oxford, 2001.
[23] A. Breiing, A. Kunz, Critical Consideration and Improvement of the FMEA, *Proceedings of the TMCE*. 2002, pp. 519–530. https://doi.org/10.3929/ethz-a-006042074.
[24] R.F. Harik, N. Sahmrani, DFMA+, A Quantitative DFMA Methodology, *Computer-Aided Design & Applications*, 2010, Vol. 7(5), pp. 701–709. doi:10.3722/cadaps.2010.701-709.
[25] L.H. Iwaya, R.S.U. Rosso, M.D.S. Hounsell, A Design for Assembly application with dynamic information retrieval from case database. *IFAC Proceedings*, Vol. 46, Issue 7, May 2013, pp. 186-191.
[26] J. Montali, M. Overend, P.M. Pelken, M. Sauchelli, Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends, *Architectural Engineering and Design Management*, 2018, Vol. 14(1–2), pp. 78–94, doi:10.1080/17452007.2017.1364216.
[27] F. Campi, C. Favi, M. Germani, M. Mandolini, CAD-integrated design for manufacturing and assembly in mechanical design, *International Journal of Computer Integrated Manufacturing*, 2022, Vol. 35(3), pp. 282–325, doi:10.1080/0951192X.2021.1992659
[28] L.Y. Zheng, Q. Liu, C.A. McMahon, Integration of process FMEA with product and process design based on key characteristics, *Advances in Intelligent and Soft Computing*, Vol. 66, Springer, Berlin, Heidelberg; 2010, pp. 1673–1686, doi:10.1007/978-3-642-10430-5_125.
[29] N.N., *The FMEA Handbook: Failure Mode and Effects Analysis*. Automotive Industry Action Group; 2019. https://www.aiag.org/
[30] J.M.M. De Andrade, A.F.C.S.M. De Leite, M.B. Canciglieri, A.L. Szejka, E.F.R. De Loures, O. Canciglieri, A multi-criteria approach for FMEA in product development in industry 4.0, *Advances in Transdisciplinary Engineering*, 2020, Vol. 12, pp. 311–320, doi:10.3233/ATDE200090.
[31] F. Elgh, M. Cederfeldt, Concurrent cost estimation as a tool for enhanced producibility-System development and applicability for producibility studies, *International Journal of Production Economics*, 2007, Vol. 109(1–2), pp. 12–26, doi:10.1016/J.IJPE.2006.11.007.
[32] V.H. Torres, J. Ríos, A. Vizán, J.M. Pérez, Approach to integrate product conceptual design information into a computer-aided design system, *Concurrent Engineering Research and Applications*, 2013, Vol. 21(1), pp. 27–38, doi:10.1177/1063293X12475233.
[33] R. Ginting, A. Ishak, A.F. Malik, Product development and design with a combination of design for manufacturing or assembly and quality function deployment: A literature review, *AIP Conference Proceedings*, 2020, 2217(June). doi:10.1063/5.0000739.
[34] N.N., *Aerospace Standard AS9103. Variation Management of Key Characteristics*. SAE, 2001.
[35] S. Bix, P. Witt, Introducing Constraints to Improve New Product Development Performance, *Research-Technology Management*, 2020, Vol. 63, Issue 5, pp. 29-37, doi:10.1080/08956308.2020.1790238.
[36] M. Nafisi, M. Wiktorsson, C. Rösiö, A. Granlund, Manufacturing engineering requirements in the early stages of new product development-a case study in two assembly plants. In: M. Ram and J. P. Davim (eds.), *Advanced Applications in Manufacturing Engineering*. Woodhead Publishing; 2018, pp. 141–167. doi:10.1016/B978-0-08-102414-0.00005-7.
[37] L.T.M. Blessing, A. Chakrabarti, *DRM, a design research methodology*, Springer, New York, 2009. doi:10.1007/978-1-84882-587-1.
[38] RG. Cooper, What's next? After stage-gate, *Research-Technology Management*, 2014, Vol. 57(1), pp. 20–31, doi:10.5437/08956308X5606963.
[39] J. Jiao, T.W. Simpson, Z. Siddique, Product family design and platform-based product development: A state-of-the-art review, *Journal of Intelligent Manufacturing*, 2007, Vol. 18(1), pp. 5–29, doi:10.1007/s10845-007-0003-2.
[40] D. Robertson, K. Ulrich, Planning for Product Platforms. *Sloan management review*. 1998, Vol. 39(4), pp. 19–31, http://repository.upenn.edu/oid_papershttp://repository.upenn.edu/oid_papers/266, accessed Mar, 22 2021.
[41] M. Bellgran, K. Säfsten, *Production development: Design and operation of production systems*, Springer-Verlag, London, 2010. doi:10.1007/978-1-84882-495-9.