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# Developing quality indices for the management of product structure data across product life cycles

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## Abstract

A computational tool has been developed to highlight inconsistencies between design descriptions. This tool links these differences to a set of quality indices based on three types of inconsistencies between bills-of-materials based on the type, number and shape of parts. The indices are algorithmically calculated by parsing and analyzing computer-aided design models available as STEP AP214 files. They have been evaluated for a case study of a two-robots based welding system. The results indicate that the algorithm works well for products of varying granularities in the BoM descriptions and can support engineers in the efficient management of product structure data.

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**Keywords:** quality index; product structure; bill-of-materials (BoM); design configuration management; computational tool

## 1. Introduction

Despite the advances made in product lifecycle management tools, global firms have found it difficult to use them to carry out efficient configuration control that involves dealing with issues related to data access control, configuration context and release management [1]. The trend towards Industry 4.0 applications leveraging the Industrial Internet of Things (IIoT) to create digital twins of entire factories has also led to the increased density of electronics in products and systems, creating variants at a fast clip with tight turnaround times [2]. As such, the success of product development firms has depended on open and effective communication about design updates with key stakeholders and maintaining the consistency of design descriptions within the firm [3].

Given the complexity of modern product development processes, a multitude of people, systems and organizations may typically be involved in the design and development of new products, thereby creating a heterogeneity of design descriptions [4]. Sharing these descriptions across product life

cycles brings with it the added challenge of design reuse [5]. Typically, the design descriptions will include the product structure embedded in them which is often linked to a geometric model.

### Nomenclature

ITQI	inter-BoM type quality index
MTQI	multi-BoM type quality index
INQI	inter-BoM numerical quality index
MNQI	multi-BoM numerical quality index
ISQI	inter-BoM shape quality index
MSQI	multi-BoM shape quality index
ICPSQI	inter-BoM composite product structure quality index
MCPSQI	multi-BoM composite product structure quality index

Two types of product structures are usually present in these geometric models: i) the hierarchical tree structure of the parts and sub-assemblies that form the product and ii) assembly

mating conditions between the parts. The hierarchical structure is often also stored as a bill-of-materials (BoM) consisting of a list of components, sub-assemblies, raw materials and parts alongwith the quantity required of each [6].

Given the various lifecycle stages of a product and its evolution through the different divisions of a firm, several BoMs representing a single product and its variants may usually be present. This presents a critical challenge of keeping them in sync with one another. While this may be partly achieved by using product data management and product lifecycle management software tools, anomalies still occur frequently and work on handling such anomalies is limited [7].

In this work, efforts have been made to address the research gap in the management of product structure data available as BoMs by creating new computational tools together with a set of well-defined quality indices that can help maintain the quality of design descriptions within a firm by providing early indicators of emerging inconsistencies. First, we take a look at the background research that has motivated this work in Section 2. This is followed by an overview of the research methodology in Section 3. A case study conducted to apply the research methodology is presented next in Section 4, followed by results in Section 5. Finally, a critical discussion on the applicability of the current work and avenues for further work together with conclusions are discussed in Sections 6 and 7.

## 2. Background

The quality of design descriptions is crucial for the success of new product development processes, especially in tightly coupled and interacting phases of developing complex products with many stakeholders. Managing design configurations via the bills-of-materials is, therefore one critical step in maintaining the quality of the descriptions. This is discussed first followed by a discussion on quality indices in various application sectors in the industry that have motivated this work in Section 2.2. Then, the importance of delivering across product life cycles is covered together with the advantages and disadvantages of current product life cycle management (PLM) solutions in Section 2.3.

### 2.1. Bill-of-materials management

Bills-of-materials (BoMs) were first introduced by Orlicky as part of material requirements planning (MRP) systems [8]. Typically, they consist of assemblies, sub-assemblies and piece parts with their quantities that are required to create the product and may be represented as a list or a hierarchical tree [9]. The notion of the piece part is crucial here as for the sake of unambiguity, they must usually refer to an entity that is assembled with others to form an assembly, which forms part or whole of the entire final product. Several BoM management solutions have been proposed and used successfully over the years. For instance, a bill-of-materials-and-operations (BOMO) was used by Jiao, Tseng, Ma and Zou [10] to unify BoMs and routings for production planning and control. Van Veen [11] developed a generic BoM

structure to handle product variants and incorporate gozinto relationships where a product is consumed in the manufacturing or assembly of another product. BoMs have been used to form product families considering commonality of components, sequencing of operations and reusability [12]. The handling of multiple BoMs has also been facilitated using graph grammars [13] and hyperdimensional lattice structures [14]. Feature recognition methods and rules have been developed to transform BoMs from one domain to another such as from engineering BoM to maintenance [15]. A key issue in forming product families is that of matching BoM trees and this has been achieved using techniques such as the use of similarity measures [6]. Managing design configurations efficiently helps in managing products across their life cycles by helping manage changes, product variety and enhancement of downstream processes such as manufacturing, repair, maintenance and overhaul [3].

### 2.2. Quality indices

Quality indices provide a quick snapshot of the quality of a system or process that can assist with timely management decision making, putting remedial measures in place and compliance with standards and regulations. A review of indices used in various science and technological contexts reveals a wide range of mathematical measures that are in vogue. Air quality indices have been used for a long time to make measurements of pollutants in micrograms more meaningful to the public by using a scale from good to bad [16]. A fuzzy inference system was developed to create a service and design quality index of online shopping or e-commerce websites [17]. Weighted means of various influencing factors are a popular choice for developing a quality index and have been used in many sectors including water quality monitoring, manufacturing processes, etc. [18, 19]. Customer responses based on surveys are also useful in creating quality indices and has been used to develop sensory quality index for food products, lodging industry, etc. [20, 21].

### 2.3. Pros and cons of current product life cycle management software solutions

Managing products across life cycles is resource intensive and requires meticulous work despite the presence of several product life cycle management (PLM) solutions such as Teamcenter, Windchill, Enovia, etc. Typical advantages and capabilities offered by PLM tools include management of design data across workflow processes, enhanced use of simulation-based and model-based engineering in real time, compliance management, life cycle visualization, enabling multi-CAD product data management, cost estimation and ERP integration [5]. However, the three big problems with managing product data despite such tools occur due to data being out of control, in silos or with multiple definitions [22]. Implementing a PLM strategy in a company is usually a risky affair and often met with cost and schedule overruns. New skill sets and capabilities as well as cultural and strategic changes are often required to run a successful PLM project

[23]. Often, the PLM tool needs to be specifically tailored to the needs of the firm. A key aspect of implementation is organizational readiness and to assess that, various maturity models have been developed. Isolated aspects of PLM tools such as document management, parts classification, etc. have been used by organizations with low levels of readiness without considering whole life cycle aspects [24].

### 3. Methodology

This research used an action design research (ADR) methodology [25], involving the simultaneous development of theory in the form of mathematical constructs for quality indices, implementation as an IT software prototype, intervening with case studies and evaluating it concurrently. The case study related to a robotic manufacturing setup for which computer-aided design (CAD) models were created with three different bills-of-material corresponding to an engineering BoM (EBOM), a purchasing BoM (PBOM) and a shipping BoM (SBOM). Anomalies were introduced in the BoMs to generate the quality indices based on the developed mathematical constructs. The results were analyzed to evaluate and reflect on the usability of the indices and the software prototype for real life applications.

#### 3.1. Quality indices for product structure data

Due to frequent change management operations, temporal anomalies or errors can occur in BoM data lying in various divisions of a firm but relating to the same product. Three types of errors were analysed within this research. These are illustrated in Table 1, where each coloured square represents a part. Needless to state, while errors have been specified to be occurring at the very bottom of the hierarchy of part-whole relationships at piece part level, errors of the similar types could also occur higher-up at the sub-assembly or assembly level but have not been illustrated for the sake of simplicity. It may also be noted that engineers construct BoMs as they perceive the product and how its assembly should be organized. For the same product, BoM trees may have varying topologies from extremely flat to very detailed hierarchies. For the sake of this research, a consistent methodology was used in creating all the BoMs including the nomenclature of parts, sub-assemblies and assemblies.

Based on three identified types of errors, a set of normalized quality indices have been constructed. These are presented below as a set of definitions. For shape mismatches of parts with identical labels, two different approaches were considered. One approach would be to find the geometric deviations between the mismatching parts. This is easily done by aligning the parts, treating one as nominal and evaluating deviations of the other part with respect to the nominal, similar to operations in point cloud processing software packages such as Zeiss Inspect Optical 3D or Nikon Focus Inspection. The geometric deviation metrics that are typically of interest are mean, standard, max and min deviation. The other approach that was considered was to use the count of parts that had a shape mismatch. The latter approach would yield indices similar to the ones for parts with ‘type’ mismatches based on their labels or names. It can be

anticipated that parts with type mismatch would often have shape mismatch as well.

Table 1. Errors in product structures

Error class	Original BoM	Altered BoM	Original shape definition	Altered shape definition
Type of parts				
Number of parts				
Shapes of parts				

#### Definition 1.

For two BoMs, each with ‘m’ parts, if ‘k’ mismatches are found in part type based on their ‘labels’ extracted from the ‘PRODUCT’ entity within a STEP AP214 file, then an inter-BoM type quality index (*ITQI*) is defined as:

$$ITQI = 1 - \frac{k}{2*m} \quad (1)$$

#### Definition 2.

For ‘n’ BoMs ( $BOM_1, BOM_2, \dots, BOM_n$ ), each with ‘m’ parts, if  $k_{ij}$  mismatches are found between  $BOM_i$  and  $BOM_j$  in part type based on their ‘labels’ extracted from the ‘PRODUCT’ entity within a STEP AP214 file, then a multi-BoM type quality index (*MTQI*) is defined as:

$$MTQI = 1 - \frac{\sum_{i=1}^n \sum_{j=1, j \neq i}^n k_{ij}}{2*m*nC_2} \quad (2)$$

#### Definition 3.

For two BoMs,  $BOM_1$  and  $BOM_2$ , one with ‘ $m_1$ ’ parts and the other with ‘ $m_2$ ’ parts, an inter-BoM numerical quality index (*INQI*) is defined as:

$$INQI = \begin{cases} 1, m_1 = m_2 = 1 \\ 1 - \frac{|m_1 - m_2|}{\max(m_1, m_2) - 1}, \text{ for all other cases} \end{cases} \quad (3)$$

#### Definition 4.

For ‘n’ BoMs ( $BOM_1, BOM_2, \dots, BOM_n$ ), with number of parts equal to  $m_1, m_2, \dots, m_n$  respectively, a multi-BoM numerical quality index (*MNQI*) is defined as:

$$MNQI = 1 - \frac{\sum_{i=1}^n \sum_{j=1, j \neq i}^n \frac{|m_i - m_j|}{\max(m_i, m_j) - 1}}{nC_2} \quad (4)$$

$$\text{where } \frac{|m_i - m_j|}{\max(m_i, m_j) - 1} = 0 \text{ if } m_i = m_j = 1 \quad (4)$$

#### Definition 5.

For two BoMs, each with ‘m’ parts, if ‘k’ parts with shape mismatches are found, then an inter-BoM shape quality index (*ISQI*) is defined as:

$$ISQI = 1 - \frac{k}{2*m} \quad (5)$$

#### Definition 6.

For ‘n’ BoMs ( $BOM_1, BOM_2, \dots, BOM_n$ ), each with ‘m’ parts, if  $k_{ij}$  parts with shape mismatches are found between  $BOM_i$  and  $BOM_j$ , then a multi-BoM shape quality index (*MSQI*) is defined as:

$$MSQI = 1 - \frac{\sum_{i=1}^n \sum_{j=1, j \neq i}^m k_{ij}}{2*m*nC_2} \quad (6)$$

#### Definition 7.

A weighted inter-BoM composite product structure quality index (*ICPSQI*) is constructed using the above indices as:

$$ICPSQI = w_t ITQI + w_n INQI + w_s ISQI \quad (7)$$

where,  $w_t + w_n + w_s = 1$ . The weights  $w_t, w_n, w_s$  signify the relative importance of each type of error in the product structure based on the specific product development activity or life cycle phase.

#### Definition 8.

A weighted multi-BoM composite product structure quality index (*MCPSQI*) is constructed using the above indices as:

$$MCPSQI = w_t MTQI + w_n MNQI + w_s MSQI \quad (8)$$

### 3.2. Software prototype development

A software prototype, PROSTRAN (PROduct STRucture ANalyzer), was developed in MATLAB to demonstrate and test the applicability of the quality indices presented in Section 3.1. This software package takes as input STEP AP214 files and parses it based on instances of the PRODUCT\_DEFINITION entity, which inherits from the NEXT\_ASSEMBLY\_USAGE\_OCCURRENCE entity in the STEP file. A snapshot of the user interface of PROSTRAN is shown in Fig. 1. The BoMs are visualized using the uitree function in MATLAB. Quality indices in PROSTRAN are calculated based on Equations (1) – (8). The flowchart of the software is shown in Fig. 2.

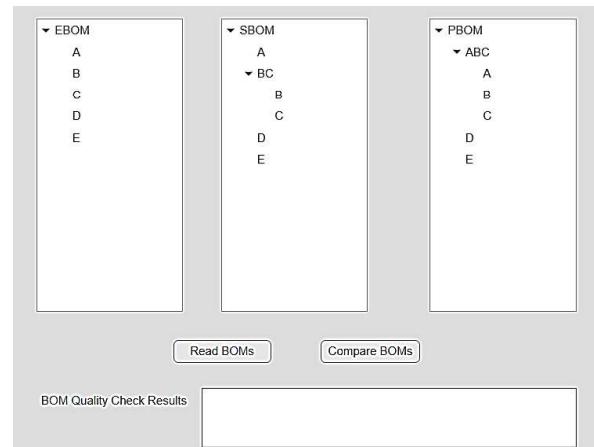


Fig. 1. User interface for the developed software prototype, PROSTRAN, showing three BoMs, corresponding to the engineering, shipping and purchasing bills of a hypothetical product ABCDE, that have been parsed from STEP AP214 files

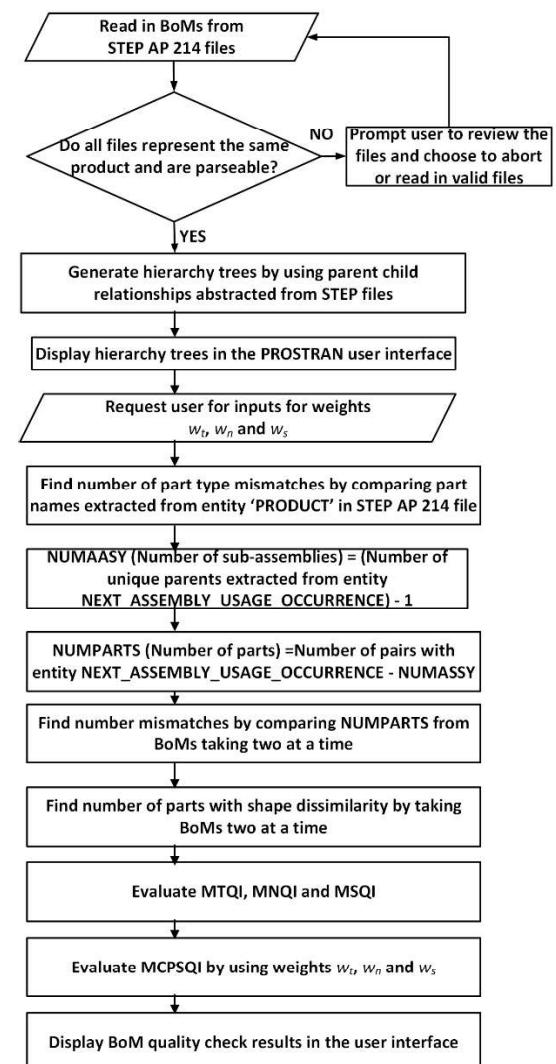


Fig. 2. Flowchart for calculating quality indices

### 4. Case Study

A two-robots based welding system, shown in Fig. 3, was used as the case study. This system has 14 individual piece

part components. The experiments for testing and validating the software prototype consisted of creating erroneous BoMs by introducing changes to the type, number and shapes of the parts. Three different BoMs were created to conduct experiments on the developed software prototype.

In one BoM, only piece parts are present. This may be thought of as an engineering BoM. In the second BoM, base plates of the two robots have been combined into a sub-assembly, the robot links, weld arm and robot support have formed a second sub-assembly and the slider base and the robot support on the second robot has been combined to form a third sub-assembly. This second BoM was created to be representative of a shipping BoM. The third BoM only combines the slider base and robot support for each robot into a sub-assembly each, and is representative of a purchasing BoM, where these two components come in a single package, while the remaining components are fabricated individually in-house.

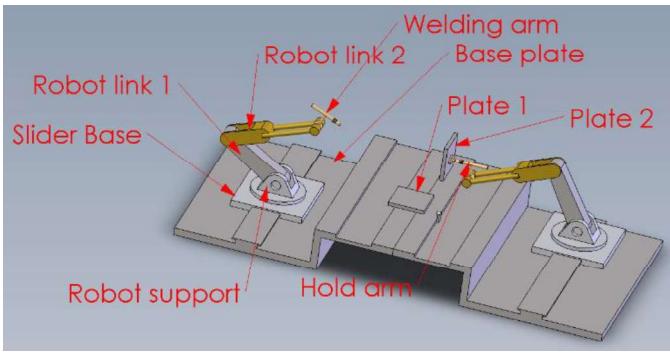


Fig. 3. Annotated view of the two-robots welding system; the left robot has a welding arm with a torch while the right one holds up the plated to be welded

## 5. Results

The original BoMs, as seen within PROSTRAN, are shown in Fig. 4. Keeping the EBOM anchored and fixed, the PBOM and SBOM were changed to introduce type errors and number of parts errors in experiment sequences 1 and 2 respectively. This resulted in 4 erroneous STEP files, which created mismatches as shown in Tables 2 and 3. The type error files were evaluated with respect to the anchored EBOM in the first experiment while the number error files were evaluated in the second experiment. The calculated quality indices from PROSTRAN are presented in Table 4. By introducing part label errors in experiment sequence 1, there were no changes to the numbers of parts and hence, the indices corresponding to those come out to be 1. However, the change to part numbers in experiment sequence 2 led to discrepancies in part types between the BoM hierarchies and as such, the type quality indices are lower than 1.

Table 2. Type mismatches introduced for the experiments

Table 3. Part number mismatches introduced for the experiments

Experiment sequence	EBOM part nodes	PBOM part nodes	SBOM part nodes	Part number mismatches		
				EBOM-PBOM	PBOM-SBOM	EBOM-SBOM
1	14	14	14	0	0	0
2	14	13	15	1	2	1

Table 4. Results showing quality index calculations based on mismatches

Expt sequence	ITQI1	ITQI2	ITQI3	MTQI	INQI1	INQI2	INQI3	MNQI	MCPSQI
1	0.786	0.571	0.714	0.690	1.000	1.000	1.000	1.000	0.794
2	0.964	0.929	0.964	0.952	0.923	0.857	0.929	0.903	0.936

## 6. Discussion

It was noted that introducing only 3 part name changes in the PBOM (baseplate to rightplate, baseplate\_WithoutSensor to rightplate\_WithoutSensor and holdarm to articulatedarm) led to 6 mismatches in the hierarchies between the EBOM and PBOM, as the corresponding parts in the EBOM also go out of sync and do not find an equivalent in the PBOM. Likewise, making 4 changes to the SBOM created 8 mismatches with the EBOM.

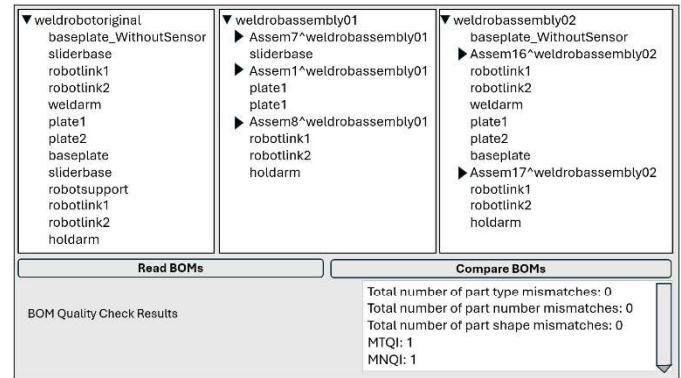


Fig. 4. BoM hierarchies as seen within PROSTRAN prior to quality index experiments

This highlights the compounding effects of even minor changes to product structure hierarchies in terms of the quality of the design descriptions and the knock-on effects that can have on downstream processes in a firm. The type quality indices for one-to-one BoM comparisons varied between 0.571 and 0.786, while the multi-BoM index stood at 0.69. Such a deterioration in the quality of the product data can then become immediately visible to the product managers and the product development teams, who can take necessary actions to remedy the situation. The effects of varying part numbers had an impact on the type quality indices as well. This is because the additional part or the lack of a part introduces automatic discrepancies in the part labels as well, when the BoMs are compared. As only one change each was introduced in the PBOM and SBOM, the effects are less pronounced than in experiment 1 and the quality indices have stayed above 0.9.

The implications of these two experiments are that in real life scenarios, where both new parts may be added to a design

Experiment sequence	EBOM part nodes	PBOM part nodes	SBOM part nodes	Type mismatches		
				EBOM-PBOM	PBOM-SBOM	EBOM-SBOM
1	14	14	14	6	12	8
2	14	13	15	1	2	1

definition as well as obsolete parts removed, and additionally, part name changes are introduced to a certain number of BoMs, this can quickly translate into significant confusion about the most reliable design definition that can be used for day-to-day operations such as manufacturing, assembly, packaging and shipping. As such, early indicator alerts from the quality indices can help in addressing such issues by timely communication between the stakeholders to synchronize the multiple definitions.

## 7. Conclusions and future work

A new method for developing quality indices for product structure data was presented in this work. These indices have been incorporated within a software prototype which provides the detailed quality check results in an elegant manner. The novelty of this work lies in deconstructing the information lying in BoMs in an efficient manner to be able to manage product data better. The implications of the work cascade through the entire life cycle of the product and can be used as dashboard indicators for product teams. The developed method relies on modelling BoMs as hierarchical trees and builds on existing literature on similarity measures for matching such trees. The quality indices were tested using experiments by creating a case study on a hypothetical robotic welding system that uses two robots. As this system was chosen to be of a reasonable complexity with a granularity that allowed the incorporation of an adequate number of sub-assemblies in addition to piece parts, the results of this study indicate that the developed software prototype holds significant promise.

Further work can involve looking into understanding shape discrepancies in product data better and incorporating intelligent algorithms to highlight shape changes in isolated definitions that may not have cascaded to the other definitions of the same product. Also, past work has investigated realigning BoMs based on effectivities for specific product lines and this can be incorporated into a more holistic quality measure that takes into account such usage of BoM data.

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## References

- [1] Trythall, S., 2015, "The Opportunity-Improving Aerospace Configuration Management," No. 0148-7191, SAE Technical Paper.
- [2] O'Connell, E., O'Brien, W., Bhattacharya, M., Moore, D., and Penica, M., 2023, "Digital Twins: Enabling Interoperability in Smart Manufacturing Networks," *Telecom*, 4(2), pp. 265-278.
- [3] McKay, A., Rice, H. P., Chau, H. H., and de Pennington, A., 2021, "Maintaining consistency across design descriptions in engineering product development," *Proceedings of the Design Society*, 1: 1987-1996.
- [4] Behera, A., McKay, A., Chau, H., and Robinson, M., "Embedding multiple design structures into design definitions: a case study of a collision avoidance robot," *Proc. DS 84: Proceedings of the DESIGN 2016 14th International Design Conference*, pp. 119-128.
- [5] Behera, A. K., McKay, A., Earl, C. F., Chau, H. H., Robinson, M. A., de Pennington, A., and Hogg, D. C., 2019, "Sharing design definitions across product life cycles," *Research in Engineering Design*, 30, pp. 339-361.
- [6] Kashkoush, M., and ElMaraghy, H., 2016, "Product family formation by matching Bill-of-Materials trees," *CIRP Journal of Manufacturing Science and Technology*, 12, pp. 1-13.
- [7] Schramm, S., Pieper, M., and Vogl, S., 2023, "Orthogonal Procrustes and Machine Learning: Predicting Bill of Materials errors on time," *Computers & Industrial Engineering*, 185, p. 109606.
- [8] Orlicky, J. A., 1973, "Net change material requirements planning," *IBM Systems Journal*, 12(1), pp. 2-29.
- [9] Orlicky, J. A., Plossl, G. W., and Wight, O. W., 1972, "Structuring the Bill of Material for MRP," *Production and Inventory Management*, 13(4):19-42.
- [10] Jiao, J., Tseng, M. M., Ma, Q., and Zou, Y., 2000, "Generic bill-of-materials-and-operations for high-variety production management," *Concurrent Engineering*, 8(4):297-321.
- [11] Van Veen, E. A., 1991, "Modelling product structures by generic bills-of-materials."
- [12] Galan, R., Racero, J., Eguia, I., and Garcia, J., 2007, "A systematic approach for product families formation in Reconfigurable Manufacturing Systems," *Robotics and Computer-Integrated Manufacturing*, 23(5), pp. 489-502.
- [13] Du, X., Tseng, M. M., and Jiao, J., "Graph grammar based product variety modeling," *Proc. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers: 73-85.
- [14] McKay, A., Chau, H. H., Earl, C. F., Behera, A. K., de Pennington, A., and Hogg, D. C., 2019, "A lattice-based approach for navigating design configuration spaces," *Advanced Engineering Informatics*, 42, p. 100928.
- [15] Liu, M., Lai, J., and Shen, W., 2014, "A method for transformation of engineering bill of materials to maintenance bill of materials," *Robotics and Computer-Integrated Manufacturing*, 30(2), pp. 142-149.
- [16] Van den Elshout, S., Léger, K., and Nussio, F., 2008, "Comparing urban air quality in Europe in real time: A review of existing air quality indices and the proposal of a common alternative," *Environment International*, 34(5), pp. 720-726.
- [17] Şimşek, H., and Güvendiren, İ., 2023, "Soft computing based e-commerce website service quality index measurement," *Electronic Commerce Research and Applications*, 61, p. 101303.
- [18] Sutadian, A. D., Muttal, N., Yilmaz, A. G., and Perera, B., 2017, "Using the Analytic Hierarchy Process to identify parameter weights for developing a water quality index," *Ecological Indicators*, 75:220-233.
- [19] Diao, G., Zhao, L., and Yao, Y., 2016, "A weighted-coupled network-based quality control method for improving key features in product manufacturing process," *Journal of Intelligent Manufacturing*, 27:535-548.
- [20] Imm, B.-Y., Lee, J. H., and Lee, S. H., 2011, "Sensory quality index (SQI) for commercial food products," *Food quality and preference*, 22(8): 748-752.
- [21] Knutson, B., Stevens, P., Wullaert, C., Patton, M., and Yokoyama, F., 1990, "LODGSERV: A service quality index for the lodging industry," *Hospitality Research Journal*, 14(2), pp. 277-284.
- [22] Stark, J., 2022, "Product lifecycle management (PLM)," *Product Lifecycle Management (Volume 1) 21st Century Paradigm for Product Realisation*, Springer, pp. 1-32.
- [23] Vezzetti, E., Violante, M. G., and Marcolin, F., 2014, "A benchmarking framework for product lifecycle management (PLM) maturity models," *Int J Adv Manuf Technol*, 71, pp. 899-918.
- [24] Kulkarni, K., Kulkarni, V. N., Gaitonde, V., and Kotturshettar, B., "State of the art review on implementation of product lifecycle management in manufacturing and service industries," *Proc. AIP conference proceedings*, AIP Publishing.
- [25] Sein, M. K., Henfridsson, O., Purao, S., Rossi, M., and Lindgren, R., 2011, "Action design research," *MIS quarterly*, pp.37-5