INDEX-BASED METRICS FOR THE EVALUATION OF EFFECTS OF CUSTOM PARTS ON THE STANDARDIZATION OF MECHANICAL SYSTEMS

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Abstract

The number and the attributes of custom parts affect significantly the standardization level of mechanical systems and determine their functional characteristics and their value. In the present study, a part classification scheme and a calculation procedure are introduced that enable systematic adaptation and standardization of custom parts during in-enterprise design and manufacturing processes. The level of standardization of the mechanical system under consideration is evaluated via metrics represented by a composite standardization index derived from the combination of two (2) partial indices, namely an index that represents the absolute attribute-based standardization of each part of the system and a second index that represents the degree of commonality for different parts and/or assemblies for the same system. The proposed approach leads to a more reliable evaluation of standardization levels by taking into account all in- and out-of-enterprise available standard resources and provides a framework that promotes design-for standardization processes. Additionally, it contributes towards more efficient and functional products and decreases design and manufacturing costs.

Keywords: Standardization index, Evaluation, Design for X (DfX), custom parts, design metrics

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1 INTRODUCTION

Engineering design is characterized by extensive use of standards. The term ”standard” may be perceived as *“an accepted or approved example of something against which others are judged or measured”* and/or as *”an authorized model of a unit of measure or weight”* (Collins English Dictionary, 2011). In order to achieve successful designs, appropriate standards are devised and used according to the guidelines agreed through the International Organization for Standards (ISO) (Pat Toms, 1988), (ASME, 2003).

Measurement and estimation of the standardization level of systems, machines and products form the basis of standardization metrics. Within this context, David and Geoffrey ((David, Rothwell, 1996) studied the problem of measuring the degree of standardization in an industry whose production facilities are as complex and multi-faceted as nuclear power stations. This study resulted in the introduction of performance-oriented measures that were based on operating downtime and the probability of shutdowns associated with reactor subsystems. Performance weighted indexes that aggregate measures of standardization for each subsystem were also computed. With suitable modifications, the degree of standardization of other technical systems could be also quantified.

The systematic consideration of standards during design is a practice that provides more time for creative and innovative work and reduces cost by minimizing both the number of items to be designed from scratch and the number of types of manufacturing processes needed (ASME, 2003). The most significant role that standards play is the reduction of amount of information that should be handled during design (Sharma, Purohit, 2005). This fact justifies to a large degree the past and current effort for developing standards in order to facilitate the design process. According to James G. Skakoon, (2000), a lot of work on standardization still remains to be done for other domains. These domains, however, do not refer to explicitly mechanical systems but to other processes, systems and products.

Commonality is strongly related to standardization and is defined as *“the number of parts/components that are used by more than one end product”* and is determined for all product families. Within a product/process family, commonality index is a metric to assess the degree of commonality (Ashayeri, Selen, 2005).

The representation and implementation of structural and functional decompositions of mechanical systems may be performed by hierarchical relations (Anastasopoulos, Dentsoras, 2009) and can now be considered as trivial task. However, measuring the standardization level of those systems is not so trivial. The present paper uses an already proposed method for estimating the standardization level of mechanical systems through a *composite standardization index* that consists of *an absolute standardization index* that could directly associate the mechanical parts of a system with available standardization data and a *commonality index* that represents the *intensity of use of common parts in different assemblies of a product* (Sinigalias, Dentsoras, 2014). The method is further extended in order to cope with the custom parts, whose presence reduces the value of the aforementioned composite index. The problem is methodological and belongs to a set of problems related to standardization issues that characterize the design and manufacturing of such systems; its solution is based on the systematic adaptation and standardization of custom parts and their registration to “internal” standardization libraries of the enterprise that undertakes the relevant design/manufacturing tasks. The new increased value of the composite index is the result of calculations that take into account both “external” and “internal” standards and reflects the importance of the correct consideration of custom parts.

2 ESTIMATING THE STANDARDIZATION LEVEL OF A MECHANICAL SYSTEM

According to the composite standardization index methodology presented by Sinigalias and Dentsoras, the basic idea for a first estimation of the overall standardization level of a mechanical system would be the *combination* of two separate and individually comprehensible and distinguishable indexes, the *absolute standardization index* and the *commonality index*. This combination is defined as a *composite standardization index* that provides valuable information about: a. the percentage of common parts being used in the system, b. the compliance of all parts with the pertinent standards and c. a sense about how different standardization data can improve or reduce the standardization level of the system under consideration. This index carries all above information, characterizes the standardization level of assembly mechanical system and is defined as (Sinigalias, Dentsoras, 2014):

$$\mathrm{I}_c(a) @ \frac{w_m \mathrm{I}_m(a) + w_s \mathrm{I}_s(a)}{w_m + w_s}, \mathrm{I}_c(a) \in [0,1] \qquad (1)$$

where $I_c(a)$ = composite standardization index, $\mathrm{I}_m(a)$ = the commonality index for the assembly *a*, $\mathrm{I}_s(a)$ = absolute standardization index for the assembly *a*, w_m = weight factor for commonality index of assembly *a* and w_s = weight factor for absolute standardization index of assembly *a*. In the present study, the value of the composite index is reconsidered by focusing on the custom parts of the system and, more specific, by taking into account their potential standardization. In the following paragraphs, the impact of these newly standardized parts on the design is examined.

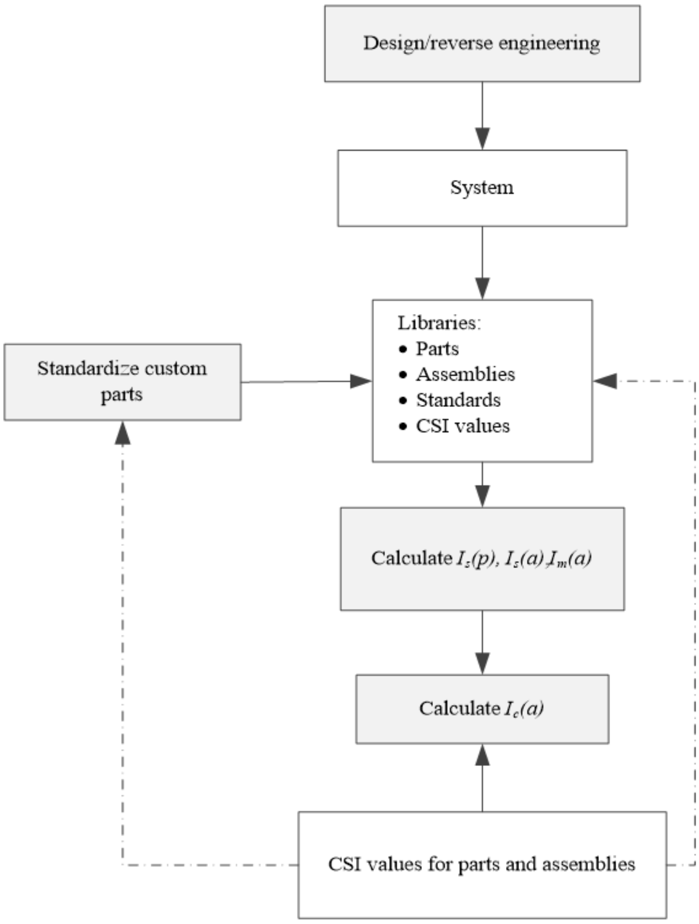

Figure 1. Establishment of standardization metrics and estimation of standardization levels for parts and assemblies.

Figure 1 depicts the procedure for the estimation of the composite standardization index. According to the absolute standardization index methodology presented by P.Sinigalias and A.J. Dentsoras (Sinigalias, Dentsoras, 2013), an early estimation of the standardization level of parts is based on the ratio of number of standardized attributes of the part currently under consideration to the total number of the attribute it refers to. Data about standardized parts is usually presented in a variety of forms and configurations and each one of them may contain one or more discrete attributes extracted from any PDM system capable of providing standards and technical specifications of mechanical parts. A classification algorithm classifies – after extended similarity text search – the current part *p* to a class c. If $A_c = \{a_{c.1}, a_{c.2}, \ldots, a_{c.n}\}$ is the set of all standardized attributes of that class, then a comparison algorithm compares all data and information provided by the engineer for part *p* with possible matching with those attributes. If $A_p, A_p \subseteq A_c$ is the set of attributes of part *p*, then the ratio of the numbers of cardinality of these two sets is called the *absolute standardization index for part p*, defined as:

$$I_s(p) @ |A_p| / |A_c|, I(p) \in [0,1] \quad (2)$$

The computations of absolute standardization indexes for the parts of a system are performed according to the structural hierarchical relationships, represented in the form of trees. Traversing such trees is a task that can be easily implemented through proper exhaustive search algorithms such as depth-first or breadth-first search (Bobrow, 1994), while the calculation of standardization indexes of parental nodes can be implemented by properly summing weighted mean values of standardization indexes of children nodes in a recursive manner. The absolute standardization index's methodology concerning a standard part is based on a trivial generic approach that can be applied to every standard regardless the source, origin of specification of the standard itself. Absolute standardization index is only affected by whether the part is a standard or a custom one. As long as the selected part belongs to a predefined standardized class, its absolute standardization index depends only on the values of the attributes and their availability during the examination of the part. Using multiple standards for a specific standardized type of parts such as fasteners will not affect the absolute standardization index of the parts directly but it will decrease system's commonality index.

In order to measure the degree of commonality, the relative modified version of Collier's index is used that has an absolute limit computed as (Collier, D.A, 1981):

$$\text{TCCI} = 1 - \frac{d-1}{\sum_{j=i+1}^{i+d} \varphi_j - 1} \quad (3)$$

In the context of the work presented, Collier's commonality index represents a crucial tool for the estimation of the composite index. The most traditional measure of component part standardization is the degree of commonality index (DCI), which indicates the average number of uses per component parts. Collier's research on commonality demonstrates that component part standardization may offer promise for future operations systems through better product designs. Therefore it was of high importance to implement in advance the modified version of Collier's commonality index for estimating the composite index.

The index represents the average number of common parent items (the term item here may refer also to assemblies and subassemblies) per average distinct part. It is a relative index that has absolute boundaries (Collier, 1981). Here $\sum_{j=i+1}^{i+d} \varphi_j$ represents the number of immediate parents for each part, d is the total number of distinct parts in the set of end items or product structure level(s) and i is the total number of end items or the total number of highest level parent items for the product structure level(s). The limits of this index range from 0 to 1, where 0 represents the state when no item is being used more than once in all product structures and 1 represents the state of complete commonality (one part is used everywhere). The index is a relative measure depicting the ratio of the number of times the item is used in the assembly to the maximum number of times such item could be used.

3 DESIGNING FOR INCREASING STANDARDIZATION - THE CUSTOMS PARTS

3.1 Increase of standardization indices

The absolute standardization index, as it has already been mentioned, depicts the conformance to engineering standards. Increasing the standardization level of the system through the maximization of the absolute standardization indices of its parts can be further studied.

The tasks of part declaration and assembly formation are of critical importance to the consistency of the provided standardization data for the system. Since the absolute standardization index depends directly on the data provided by the engineer for the standardized attributes of part p that belongs to a specific class c, one way of improving the comparison ratio for that part p would be the provision of more concise and standardized data.

Custom parts affect significantly the total standardization level of a mechanical system and great attention should be paid while estimating the standardization level of these parts. According to the method presented here, a solution to that problem would be the systematic provision of additional information for the class attributes for a specific part that would lead to an increase of the value of absolute standardization index. The main problem, however, is located in the originality of the custom part under consideration and the absence of conformance of its attributes with attributes of established part classes. By adapting an "in-company" (internal) standardization process, the custom nature of the part is reduced or eliminated, with its attributes conforming to company-introduced attributes of part classes. This leads finally to an increase of the values of both absolute and standardization indices (see above).

For the development of this typical standardization process, the identification and classification of the part to a specific category/class of parts (such as the already existing ones) should take place first. Thus, a *part classification scheme* is introduced that provides the engineer with a framework to classify the part to a specific class of parts with same characteristics and different sub categories. That classification scheme is a *descriptive arrangement of parts into groups based on common characteristics such as geometry, material type, manufacturing processes, assembly, etc.* This is a complex approach and, for simplification matters, the data necessary to define this set of expressions and variables are derived from the integrated CAD/CAM environment and the CAD model developed during the detailed design phase.

By grouping parts based on such types of attributes, the designers are able to compare parts, not only within each product, but also across multiple products (product family dissection). Thevenot et al. (2005) proposes a product family redesign method using commonality indices and genetic algorithm. The method uses data that can be collected through product dissection or estimated as input: a list of parts in each product with related information (cost, material, manufacturing process, etc.), as well as the redesign strategy (which parts to keep unique, etc.). Using a genetic algorithm, this metric is then maximized, and recommendations on how to improve the redesign of a product family are provided. Other commonality indexes such as the DCI and more specifically the TCCI Collier index only consider the parts in each product and compare them to see if they are common, variant, and/or unique.

Ashby (1999) proposes taxonomies at different levels for material and manufacturing process selection. Each material can be characterized by different sets of attributes at different levels of granularity. During product dissection, all the information needed to progress to lowest level of detail may not be available or easy to obtain; therefore, an appropriate level of granularity should be defined and used across all the products during dissection. The methods for product redesign and product family redesign rely on relevant data on the products to redesign. If this information is not available, companies must use product dissection to collect data; this process is often subjective and qualitative. On the other hand, replacing more unique parts with equivalent similar and common ones will result to the increase of the commonality index in each assembly and in system totally. However, factors such as part costs, production volume, materials, manufacturing processes, etc, that could provide cost-savings benefits of commonality within a product family, would not be taken into account.

The geometry of the product plays a central role in all phases of design because of its immense utility. Standards are also available for the geometry of simple parts and are extensively used in production and assembly drawings, in strictly standardized forms. Standards are used to transfer the geometry data to different functions of the computer-integrated manufacturing (CIM) environment. These standards originate from international, national, and professional standards-developing organizations. Geometry attributes have essentially great impact on the final standardization of product and therefore comprise one of the most significant factors for standardization estimation that should be always taken into account very carefully.

The main steps of the present part classification scheme are:

1. Part class definition
2. Sub type definition for the selected class
3. Embedded standard used for this selected class

The objective of above scheme is to establish geometrical recognition patterns in order to determine the critical features/attributes for the standardization of a totally new part being designed. Once the new part is categorized according to the classification scheme (see Figure) and parameterized according to the determined attributes, its composite standardization index can be re-estimated. The newly standardized part is considered as a standard part – regarding its geometry - in the standardization tables provided after the application of the classification scheme and its

standardization index can potentially contribute to a desired increase in the total standardization level of both the assembly it belongs to and of all parent assemblies. From a secondary point of view, this partial standardization does not have a substantial impact on the calculation of commonality index, since the latter simply counts how many times a part participates in different assemblies without taking into account its absolute standardization index. The composite standardization index, however, is modified since the absolute standardization index is recalculated. Additionally, the designer is capable of providing new standardization information and processing part standardization data that was totally unaware of in previous standardization index estimations' attempts.
In the present paper, the new parts' classification functionality was established and adapted to the existing commonality index metric software. This adaptation provides to the designers the capability to manipulate custom parts so that the total standardization level of the system under consideration is improved.

3.2 Implementation of index calculations

In the work by P.Sinigalias and A.J. Dentsoras (Sinigalias, Dentsoras, 2014), a software tool was presented as a standalone application for implementing calculations of absolute standardization indexes, commonality indexes and the composite standardization index. Its main interface holds the basic controls and is divided in 3 main modules (see Figure 2). The first module depicts the structural tree of the system and provides extensive editing facilities for its components. Here the designer has the ability to load an existing tree structure or to create a new one from scratch by adding and editing nodes, by forming the hyper- and sub- assemblies of the structure and by defining the final parts.

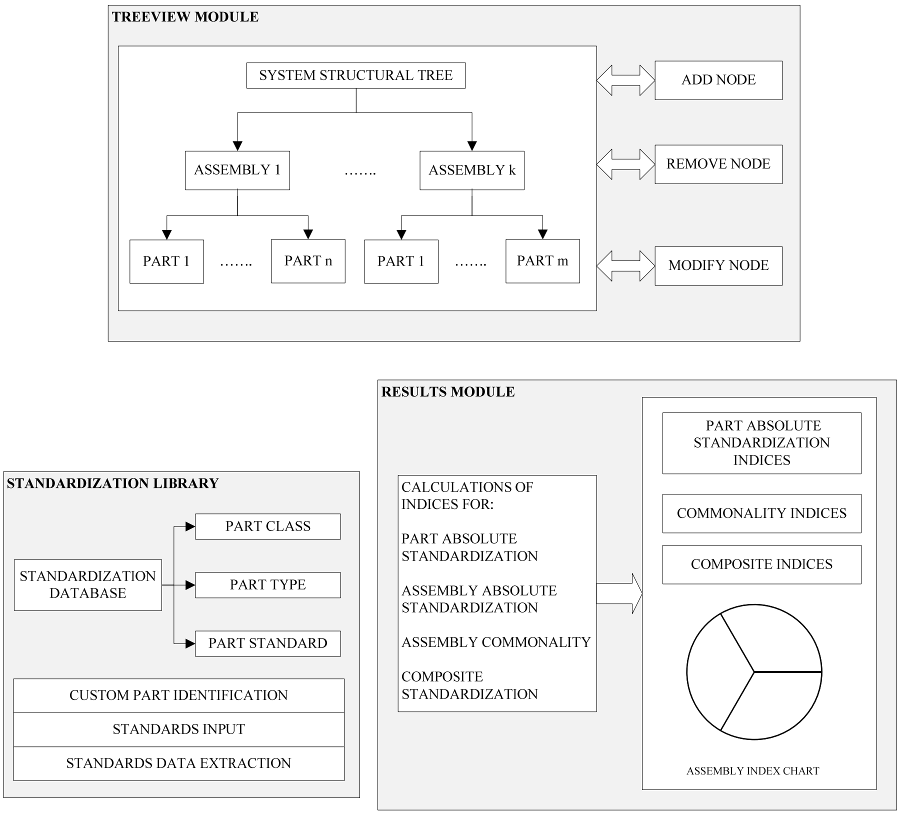

Figure 2. Software main modules and functions

The second module is dedicated to standardization attributes related to the absolute standardization index. Once the structure of the system has been established and visualized, the designer is able to proceed with calculations of absolute standardization indexes for every leaf node of the structural tree. Before any calculation is prompted for execution and after such a node has been selected, the designer may need to update the standardization library with all tables that contain standardization data and information that pertain to the case under consideration. Next, the software will attempt to extract the necessary data from the node name and proceed with classification. If values have been assigned to the standardization attributes, the absolute standardization index will be calculated and then stored. If the selected part stands for a new custom part, it is labeled as such and the lowest permissible value for absolute standardization index ($I_s(p)=0$) is assigned.

In the current updated version of the software, a supplementary function capability has been added in order to cope with custom parts. The designer is able to identify and classify these parts and then to take into account the so standardized new parts for further (re)design activities and calculation of standardization indexes. The third module of the software presents standardization data and results obtained by calculations of the absolute standardization indexes of tree nodes as well as the commonality indexes (except for the leaf nodes). On-demand information can be always provided to the designer regarding the selected node, its properties and its sub-tree within the overall tree structure. The software has been supplied with extended file I/O and printing operations and is capable of producing graphical visualization for the results in the form of pie chart diagrams (Petroutsos, 2002). In these diagrams, the allocation percentage of the absolute standardization index for the assemblies and the parts composing the selected hyper assembly can be viewed. This offers great versatility and permits direct and easy comprehension of the distribution of values of the absolute standardization indexes of system assemblies and parts. It also assists undertaking of proper actions in order to improve – either partially or totally - its standardization level.

4 A CASE STUDY: SEMIAUTOMATIC ICE PACKAGING MACHINE - BAG FILLER ASSEMBLY

In order to provide more in depth information about the proposed method, a particular type of packaging machinery, specifically designed and manufactured for the filling of a prefabricated plastic bag with ice cubes, is studied. The machine can be classified into the general category of Vertical Form Fill Seal machines (VFFS) and have been mandatorily modified in order to comply with the special end-user needs and requirements. The term “form fill seal” means producing bags or pouches from a flexible packaging material, inserting a measured amount of product to each one of them and then closing its top. Two distinct principles are utilized for this type of packaging: horizontal (HFFS) and vertical (VFFS) (Kit, 2010).

Due to the customization and the semiautomatic functional mode of the machine and in order to implement the production cycle, the user must manually provide the bag to be filled and then wrap it around a tube. Once the bag is wrapped, mechanical parts stabilize its position and the filling process starts. As soon as the bag is filled, it is automatically released from the holders and advances to a specific predetermined point and remains in that position. Then the sealing jaws contact and hold the top part of the in place long enough as for the sealing process to be completed successfully (uniform top seal of a filled bag). When the jaws open, the filled bag is released and the production cycle is completed.

Figure 3 shows – among others - a 3D-representation of the bag filler assembly. This assembly was structurally decomposed and all its assemblies and parts were registered in the software tool and the hierarchical tree was created. One hundred and fifty three (153) mechanical parts and sixteen (16) system assemblies were recorded. After that, the process of calculating the absolute standardization index for each part of the system was initiated. For each node element (part), the designer inserted the available standardization data in the form of tables (see Figure 3). Finally the values of absolute standardization indexes for all participating parts as well as of their assemblies were calculated. In order to conform to restrictions set by the length of the paper, a subset of the overall set of computations and results are shown in figure 3.

Particularly, for the hyper assembly *Bag Holding and Filling Mechanism for Semiautomatic Ice Packaging Machine*, the composite standardization index was found equal to *0.4625* with equally weighted values for the attributes for absolute standardization index I_s equal to *0.611* and for commonality index I_m equal to *0.314* (see Figure 3). All subassemblies of that system were thoroughly examined to distinguish the most important parts that affect the resulted value. During the calculations, sixteen (16) parts were detected that could not be classified. Therefore, they were considered as custom parts and for all of them an absolute standardization index equal to 0 was assigned. Nevertheless, despite being unable to be classified and extract a certain level of standardization knowledge that will affect the product's final design, these parts would reappear in the total product assembly in different sub assemblies therefore having an direct impact on the commonality index for a specific selected assembly. These parts were considered the most crucial for further investigation regarding their possible standardization.

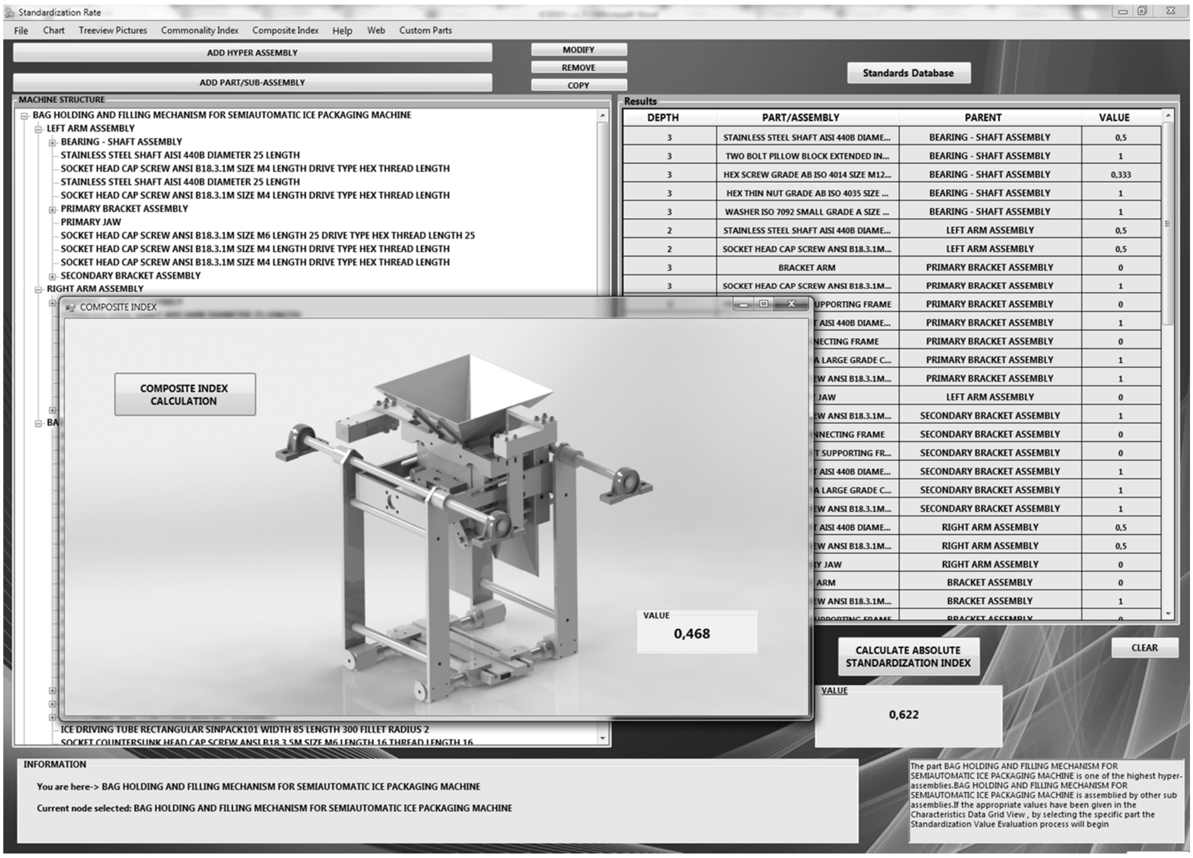

Figure 3. Calculation of composite index and visual representation of software environment

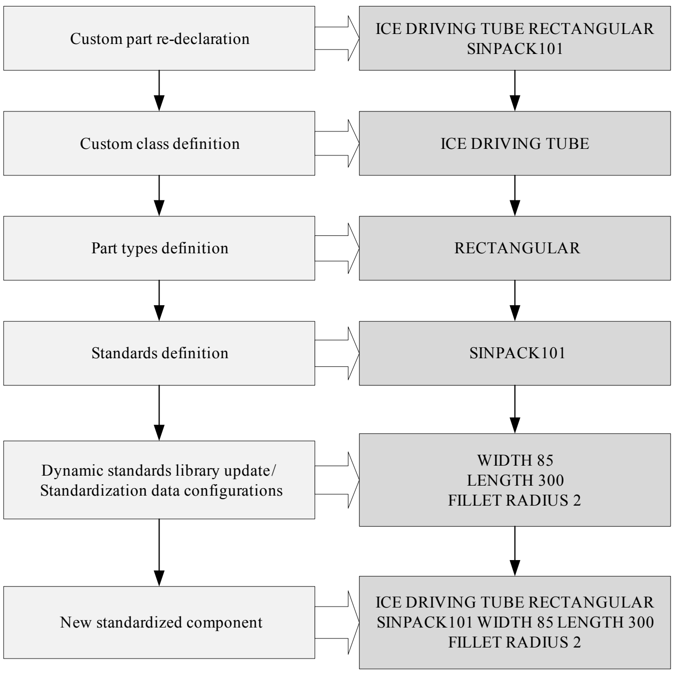

Figure 4. Classification scheme and custom part standardization methodology -Indicative example of the methodology

After evaluating the design of the existing product - as it has been already analyzed and studied beforehand - custom parts should be considered for standardization in order to achieve a more efficient system design from that aspect. In order to exemplify the relevant approach, the absolute standardization and commonality indexes for a specific selected custom part was considered. The part has a primary part declaration designation as *ICE DRIVING TUBE* and an absolute standardization index equal to 0 has been assigned to it. The part was modified and redefined for standardization according to an individual classification scheme that included part class, subtype and standard data (see figure 4). All this information was introduced in the standardization library; the latter was subsequently adjusted in order to host the specific part. The part was labeled so that it could be recognized and identified as standardized for all subsequent index calculation procedures. Its standardization should be considered as "internal" in the sense that it refers to a library that pertains to the enterprise and is used for facilitating design and manufacturing processes. Based on the main idea that governs the present method and in order to complete the standardization process, the configuration of standards must be provided for the aforementioned specific newly standardized part. This configuration will contain both the parametric attributes of the part and their corresponding values as well.

The features of the *ICE DRIVING TUBE RECTANGULAR SINPACK101* part to be selectively defined and standardized are: *WIDTH, LENGTH* and *FILLET RADIUS* (see figure 4). The new part's declaration designation to the system will be: *ICE DRIVING TUBE RECTANGULAR SINPACK101 WIDTH 85 LENGTH 300 FILLET RADIUS 2* (all in mm), with absolute standardization index equal to 1. The absolute standardization index for the parent assembly of this part *BAG FILLER MAIN ASSEMBLY* will become – after recalculation – equal to 0.65 (previous value was 0.6335). The absolute standardization index I_s for the system will increase (new value = 0.622, old value = 0.611) and the new composite standardization index I_c will become equal to 0.468.

5 CONCLUSIONS

In the present paper, within the framework of design and manufacturing of mechanical systems, the calculation of standardization indices is reconsidered by taking into account the custom, non-standardized parts that participate in forming system assemblies. In order to increase the number of standardized parts and – as a consequence - the values of the indices associated with them, a method is proposed that can provide a solution for the decreasing effects that these parts exert to the standardization of the system under consideration. Within this context, designers can assign standardization data for those parts and create records in new standardization libraries that pertain to the enterprise.

The analysis of the system considered in the case study resulted to a structural tree consisting of 153 parts and 16 assemblies. From the 153 parts of the system, 16 custom parts were identified during the assembly decomposition of the case study. These 16 custom parts contributed in the innovativeness of the design but simultaneously affected the positive effects of a technologically competitive design that can be accomplished though the increase of the standardization level of the system. The new *ICE DRIVING TUBE RECTANGULAR SINPACK101 WIDTH 85 LENGTH 300 FILLET RADIUS 2* standardized part not only increased the standardization level of the system with all of its beneficial results but also it didn't hinder the innovation factor of the design.

In general, although the commonality index is not influenced directly by this standardization process, there may be a noticeable impact for the level of absolute standardization. Since the value of the absolute index affects directly the value of the composite index, the overall standardization level of the system will increase. This implies that: a. the standardization libraries will be extended and enriched, b. the implementation of design and manufacturing processes will be facilitated and c. the cost– as far as manipulation of standardization during developing new machines and systems in the future - will lower.

In the future, it is expected that the proposed standardization process for the custom parts - that leads to increased values of both absolute and standardization indices - would be incorporated in a new "design-for-standardization" consideration of design process. With this perspective, new libraries of standardized "in-enterprise" custom parts and assemblies would be created. These libraries, in combination with libraries of "external" general standards and regulations could form a framework which - throughout all design phases - could provide data, information and knowledge to: a. reasoning mechanisms for knowledge-based estimation of standardization levels and b. automatic advice-providing tools in order to achieve the desired standardization indices.

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