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A COMPOSITE INDEX FOR THE EVALUATION OF STANDARDIZATION LEVEL OF MECHANIC SYSTEMS

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1. Introduction

Engineering design is characterized by the 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 *”an authorized model of a unit of measure or weight”*. In order to achieve successful design, appropriate standards are devised. These include national standards framed within guidelines agreed through the International Organization for Standards (ISO) [Toms 1988], [ASME 2003].
Measuring and estimating standardization of systems and products that are already operating is one aspect of the problem. Within this context, the problem of measuring the degree of standardization in an industry whose production facilities are as complex and multi-faceted as nuclear power stations was discussed within the barriers of a standardization measuring study [David and Rothwell 1996]. 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. Finally, performance weighted indexes that aggregate measures of standardization for each subsystem were computed. With suitable modifications, the degree of standardization of other technical systems could also be 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 industrial standards play is the reduction of amount of information that should be handled during design [Sharma and Purohit 2005]. This fact justifies to a large degree the past and current effort for developing standards in order to facilitate the design process and reduce design time and cost. According to 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.
Standardized components are 20% to 60% cheaper than customized components, and this contributes greatly to the reduction of the product cost [Technical University Dresden and the Fraunhofer Institute for Systems and Innovations 2000]. The importance of higher component part standardization has been recognized as a significant area of empirical investigation since it has been hypothesized to reduce inventory levels by reducing safety requirements, to reduce planned load through larger lot sizes as well as planning complexity through the reduction of the number of items to be planned [Wacker and Treleven 1986].
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 and Selen 2005]. In terms of component part standardization, commonality, i.e. using the same type of component in different locations of product structure trees, is frequently encountered in manufacturing industries [Fixson 2007].

The most traditional measure of commonality is the degree of commonality index (DCI), which indicates the average number of uses per component parts. Wu et al. state that the commonality index is a measure of how well the product design utilizes standardized components [Wu et al. 2006]. Wazed et al. consider the use of common components for different products in a company an important factor for managing product variety and maintaining competitiveness in this age of mass customization and supply chain struggle.

According to Hillier [2002], there should be a tradeoff between product performance and commonality within any product family. Focusing solely on the maximization of the standardized parts of a product during design and adhering to quality standards (standards conformance) could drastically affect design creativity and innovation and obstruct further suggestions and modifications. Therefore, great attention should be paid by the designers in order to resolve the tradeoff between too much commonality (i.e. lack of distinctiveness of the products) and insufficient commonality (i.e. higher production costs).

The representation and implementation of structural decompositions of mechanical systems in computers may be performed by hierarchical relations [Anastasopoulos and 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 copes with the problem of estimation of 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*.

While the commonality index DCI is a very effective instrument in the design of a new family of products (or the analysis of an existing one), lack of focus is observed in the analysis of the level of standardization of the system (as a whole) of its parts and assemblies. The commonality indexes provide standardization metrics that consider in general numbers of common components/part (as well as other relative parameters) without focusing on the standardization identity of each component/part. Therefore, the present paper aims to bypass this drawback by combining these two different standardization indexes, resulting into a more complementary and comprehensive standardization index that not only utilizes information concerning the commonality factor but also depicts the objective conformance and compliance of every part with the pertinent engineering standards. 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 could be the establishment of a systematic metric method for performing that estimation. The proposed composite index may be easily adapted in design cases where either *product families or highly customized products are being reverse-engineered or designed.*

2. Estimating the standardization level of mechanical system

According to the absolute standardization index methodology presented by Sinigalias and Dentsoras [2013], the basic idea for a first estimation of the standardization level of parts is based on the ratio of the number of standardized attributes of the part currently under consideration to the total number of the attributes it refers to. This basic idea is extended by introducing the degree of commonality index in the general estimation methodology and leads to the estimation of a composite standardization index. Figure 1 depicts this basic idea. A module decomposes recursively and iteratively the assemblies of a system into subassemblies and parts or composes them to subassemblies and assemblies, depending on whether a reverse engineering process or a design process takes place. These parts and assemblies can be either new or extracted from dynamically updated libraries. Irrespective of whether analysis or synthesis is performed, the parts are considered as the most significant entities that should be evaluated for standardization through systematic comparison to available standardization data.

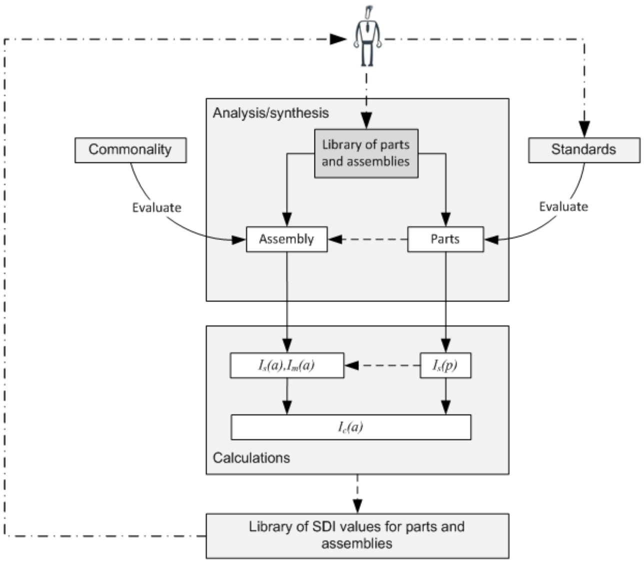

Figure 1. A general approach for estimating standardization levels and establishing metrics of standardization - the process for implementing the calculations of the composite index

An analysis about the method for calculating I_s and I_m *(commonality index)* is presented in the following section.

2.1 Calculation of the absolute standardization index

According to the absolute standardization index methodology presented by Sinigalias and Dentsoras [2013], each mechanical system can be structurally decomposed into *assemblies*, *subassemblies* and individual *parts*. Subsequently, for each such part, considerations of its *standardization level* can be carried out with respect to one or more distinct predefined standardized *attributes*. Then, the standardization level of a higher-level structure (subassembly, assembly, system) may be achieved by estimating the standardization levels of its components. It is imperative, when analyzing or composing hierarchical relationships among parts and assemblies that the engineer provides as much information as possible about all factors that refer to standardization issues such as nomenclature, dimensions, tolerances, materials, machining processes etc. This will ensure that the calculated values of (I_s)s for parts and assemblies reflect the real standardization level of the corresponding items. It is obvious that the process followed for measuring the standardization level of a part with respect to standardized attributes will be differentiated depending on the amount and the quality of the available data and information about standards.

In order to attain the standardization data required for the calculations of indexes, the configurations of standard parts were extracted from the toolbox of Solidworks© (or any PDM system capable of providing standards and technical specifications of mechanical parts) and were used as a point basis. The toolbox supports international standards, including ANSI, AS, GB, BSI, CISC, DIN, GB, ISO, IS, JIS, and KS. Each configuration of standards is described by specific standardized attributes with respect to the specific part. The set of these attributes is a representation of information and is accompanied by all necessary mechanisms and definitions that enable data exchange, use and update.

The basic idea for 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. In order to calculate that ratio, the (sub)-class (type) the part belongs to should be first identified. Class identification - through a similarity search algorithm influenced by the work of Wu et al. [2006] - will lead to the attributes that pertain to that (sub)-class and which will be used for the calculation of index I_s.

It is assumed that the values of standardized attributes for a class of parts are represented by standardization tables (of different dimensions depending on the part and the standard under consideration). The classification algorithm will classify – after extended text search – the current part

p to class c_p. If $A_c = \{a_{c.1}, a_{c.2}, ..., a_{c.n}\}$ is the set of all standardized attributes of class c, the comparison algorithm will compare all data and information inputted by the engineer for part p with those of A_c. 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:

$$I_s(p) \triangleq |A_p| / |A_c|, I(p) \in [0,1] \tag{1}$$

There may be cases where the deduction of the corresponding value is facilitated by the fact that there are available standards for that attribute; then the process will be straight and simple. Nevertheless, during the design phase, the assembly composition cannot always consist of fully or partially standardized mechanical parts (unique custom parts). If the classification algorithm for a part returns no results, then it is a non-standardized part, it is considered as a custom new part and the lowest value will be assigned to its index ($I_s(p) = 0$). On the contrary, for a fully standardized part, $I_s(p) = 1$. The flow chart depicting the main methodology for calculating the absolute standardization index for a part is shown in the Figure 2.

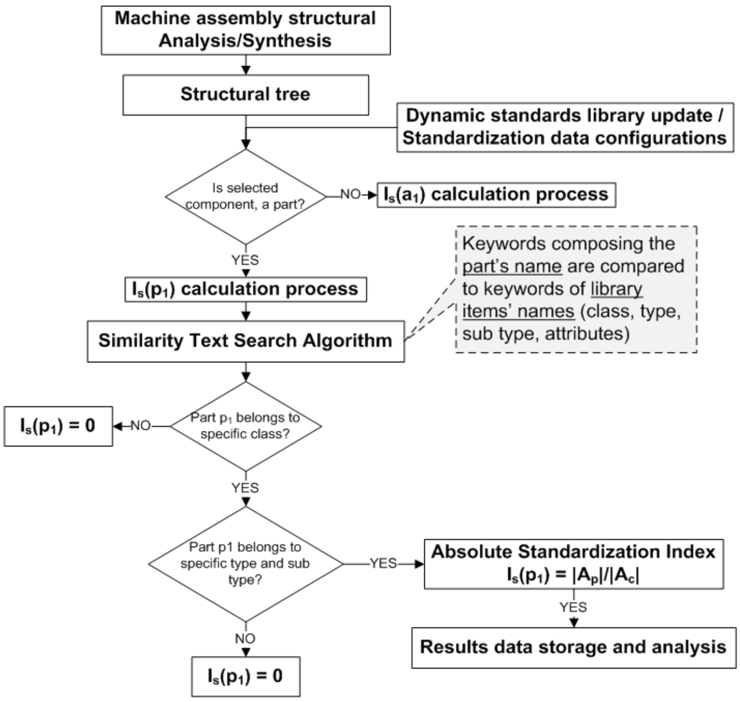

Figure 2. Flow chart showing the calculation of absolute standardization index

The computations of absolute standardization indexes 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. Given that the recursion will eventually reach leaf nodes of the tree, their standardization indexes should already be available. In Figure 3, a simplified example of recursive calculation for an assembly that consists of two (2) parts and one (1) subassembly is analyzed. In order to calculate the absolute standardization index for assembly a_1, the standardization index for each child node must be first calculated. Following a depth-first search strategy (see arrows in the figure), the algorithm locates a new node (part p_1) in level 1. Since it is not a parental node, focus is redirected to node of subassembly a_2. Here children parts p_3 and p_4 are located in level 2. Thus, the algorithm returns to the previous level and the calculation process commences by already calculated standardization indexes for those parts. Therefore, the weighted mean value (equal unary weight factors are assumed) is $I_s(a_2)$ = (0.7*1 + 0.5*1)/2 = 0.6. Finally, the algorithm returns to level 0 and calculates the weight mean value $I_s(a_1)$ = (0.6*1 + 0.6*1 + 0.5*1)/3 = 0.56 which is the absolute standardization index for assembly a_1. The directional arrows in the Figure 2 show the recursive process that is being followed.

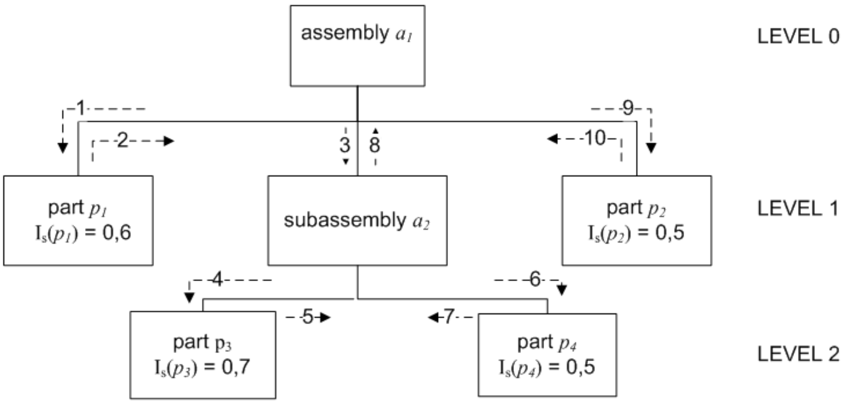

Figure 3. A simplified example of recursive calculation for an assembly

2.2 Calculation of degree of commonality index

The most common measure of the degree of commonality is the average places used for a distinct component, or the average number of parent items per distinct component part [Collier 1981], [Sheu and Wacker 1997]. This measure is known as the degree of commonality index (DCI) and it reflects the average number of common parent items (the term item can be used as a more general reference to the assemblies and subassemblies) per average distinct part. For comparisons between sets of products (product lines, product groupings, etc.), it would be more useful to have a relative index that has absolute boundaries. Therefore, the methodology makes use of the modified version of Collier's index that is relative and has an absolute limit as follows [Collier 1981]:

$$\mathrm{TCCI} = 1 - \frac{d-1}{\sum_{j=i+1}^{i+d} \varphi_j - 1} \tag{2}$$

Here φ_j is the number of immediate parents component j has over a set of end items or product structure level(s), 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 values 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.

While numerous other advanced commonality indexes have been registered covering specific weak points of the simple DCI presented by Collier, the purpose of the present paper is the adaptation of commonality index in its simplest form and a significant contributor in forming the aforementioned composite index. In future work, more complex commonality indexes will be used in the calculations to provide more concise and accurate results concerning the component part standardization of a selected system. Within the context of the present work, the modified version of Collier's index will be identified as the newly introduced term $I_m(a)$ that will represent the commonality index for an assembly a.

2.3 Calculation of composite standardization index

Having acquired the standardization index for each part and/or assembly and the commonality index for each assembly, the engineer attains wider information and details concerning the standardization of the system under consideration. These two standardization indexes may be combined to one more insightful standardization index that could provide valuable information concerning the percentage of common parts being used in the system, an ascertainment for the compliance of the standards being used in the system and a sense about how different standardization data can improve or deteriorate a design. The combination of these two indexes contributes to the calculation of a composite one thus providing the engineer with helpful design information concerning the standardization level of the system. This index carries all above information, characterizes the standardization level of an assembly and is defined as:

$$\mathrm{I}_c(a) @ \frac{w_m * \mathrm{I}_m(a) + w_s * \mathrm{I}_s(a)}{w_m + w_s}, \mathrm{I}_c(a) \in [0,1] \tag{3}$$

where $\mathrm{I}_c(a)$ = composite standardization index of assembly *a*, $\mathrm{I}_m(a)$ = the commonality index, $\mathrm{I}_s(a)$ = absolute standardization index, w_m = weight factor for commonality index and w_s = weight factor for the absolute standardization index.

The idea of applying weight factors to both commonality and absolute standardization indexes is derived from the necessity to highlight their importance. There would be cases where the designer would prefer to focus on either how many common components (or unique respectively) are being used in the system or focus on each of those components and of their conformity to given standards. Therefore, the weight value sets a design constraint, rendering the calculations even more credible. As a conclusion and as far as calculation processes are concerned, the following comments should be made:

1. An absolute standardization index can be assigned only to individual parts; assemblies acquire their standardization indexes via recursive calculations of standardization indexes of children parts and subassemblies;
2. The method is capable of performing calculations even with missing assignments of standardization indexes (custom parts). In that case, the standardization index presents restricted validity;
3. Since a degree of commonality index provides component part standardization information, it can be assigned only to assemblies. Therefore, although the absolute standardization index relates standards and standardization details to the components of the lowest level of a product structure, the final composite standardization index can only be related to an assembly level.

2.4 Description of the calculation software

In the work by Sinigalias and Dentsoras [2013], a software was presented as a standalone Visual Studio© application for implementing the calculations of absolute standardization indexes. Its main interface holds the basic controls and is divided in 3 main sections. The first section depicts the structural tree of the system and provides extensive editing facilities for its components. Here the user 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.

The second section is dedicated to standardization attributes related to the absolute standardization index. Once the structure of the system has been established and visualized, the user 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 user must update the standardization library with the appropriate standardization tables that contain the predefined standard values.

Next, the software will attempt to extract the necessary data from the node name and proceed with classification. If the selected node belongs to a predefined class of standard parts, the calculation of the standardization index will be initiated. If values have been assigned to the standardization attributes, the absolute standardization index will be calculated and then stored. Otherwise, the user will be prompted to update values before commencing calculations. If the selected part stands for a new custom part then the software labels it as such and assigns the lowest permissible value for absolute standardization index that is $I_s\left(p\right)=0$. After the estimation of all standardization indexes for the parts, the activation of calculation process for each assembly will automatically provide the values of their absolute standardization indexes and that of the overall assembly as well.
The calculation of commonality index for every assembly of the structure is a more simplified procedure since an identification/ similarity algorithm may be applied and, as soon as the sum of every distinct component node (part) and the sum of their immediate parent nodes in the selected node structure are computed, the commonality index is directly calculated.
The third section 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 user 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 in undertaking of proper actions in order to improve – either partially or totally - its standardization level.

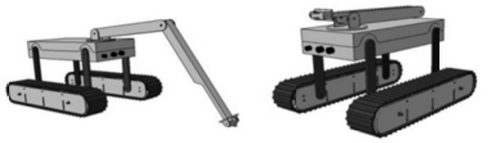

Figure 4. The CAD models of the mobile platform with the manipulator

Figure 5. Structural analysis of the manipulator of the robot

3. A case study: The Polymechanon robot – Manipulator assembly

The Polymechanon Robotics Team is a part of the Robotics Group of the Mechanical Engineering and Aeronautics Department (MEAD) of University of Patras (UoP). The case study selected for presentation and explanation of the present paper methodology is the robot proposed, designed, constructed and assembled from the Robotics Club students of University of Patras for the Robocup Rescue 2013 competition. It is based on a realistic mechanism with several moving parts/assemblies which constitutes a non extensive, easily structurally decomposable mechanical system, capable of providing explanatory information on the paper's main idea (see Figure 5). The Polymechanon Robot [Synodinos et al. 2013] is a tracked platform with a five-degree freedom manipulator and two extra degrees of freedom that connect the main body to the tracks (see Figure 4). The case study presented here focuses on the manipulator assembly.
The manipulator of the robot was structurally decomposed and all its assemblies and parts were first distinguished (see Figure 5 as a reference for the manipulator of the robot). Then all parts and assemblies were registered in the software and the hierarchical tree was created. Sixty one (61) mechanical parts and nine (9) system assemblies were recorded. After analysis, the process of calculating the absolute standardization index for each part of the system was initiated. For each node

element (part), the user inserted the available standardization data in the form of tables. Finally the values of standardization indexes for all participating parts as well as of their assemblies were calculated. Flow chart in Figure 6 depicts an example of calculation of the standardization index of a selected part. 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.

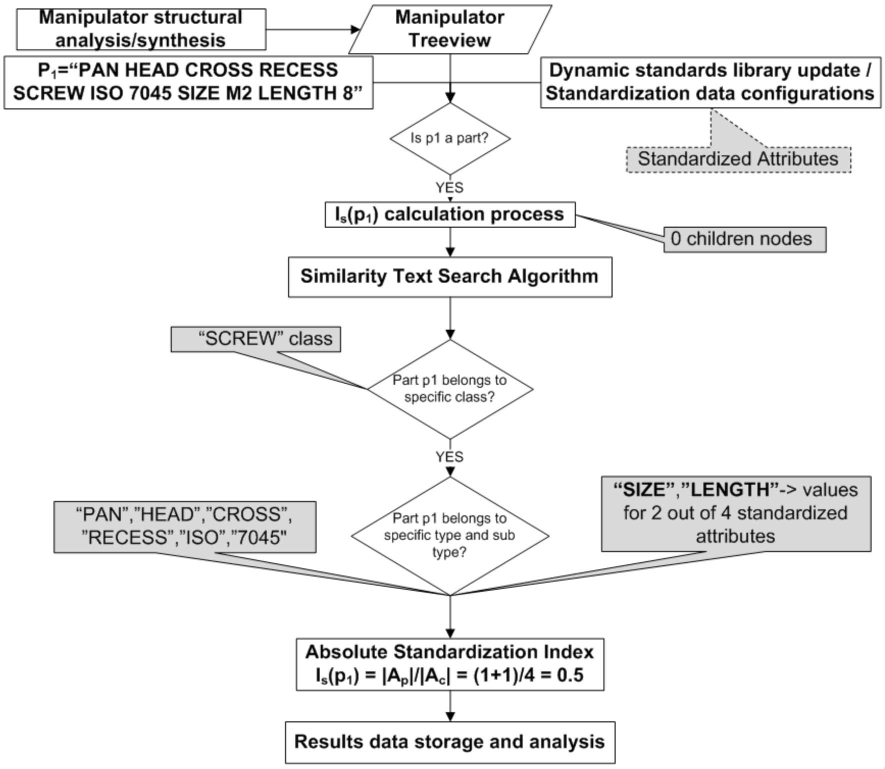

Figure 6. Flow chart showing the calculation steps for a selected part of the robot arm

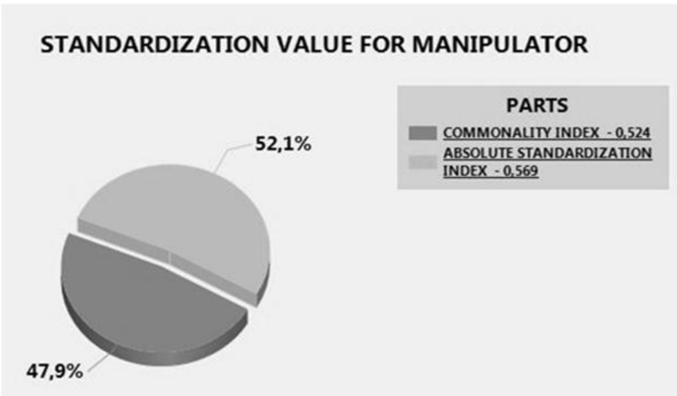

Figure 7. Pie chart for Manipulator - Assembly depicting allocation percentage and the contribution of each index in the total composite standardization index

Particularly, for the hyper assembly *Manipulator*, the composite standardization index was found equal to 0.5465 with equally weighted values for the attributes for I_s equal to 0.569 and for I_m equal to 0.524 (see Figure 7). All subassemblies of that system were thoroughly examined to distinguish the most important parts that affect the resulted value. During the calculations, three (3) parts were detected that could not be classified. Therefore, they were considered as custom parts and for both of them a standardization index equal to 0 was assigned. These parts were considered the most crucial for further investigation regarding their possible standardization.

As already mentioned, the performance of the software basically relies on a similarity text search based on keywords affecting the absolute standardization index calculation as well as the commonality index calculation. Through this search, conclusions can be deduced for a selected part of system tree regarding the percentage of conformance to engineering standards (absolute standardization index). A low standardization level may be possible due to the insufficient standardization data provision by the engineer during part declaration and assembly formation. This is expected to affect the calculations of the indexes. Furthermore, during the design phase the engineer may introduce a part to the system that is so poorly standardized that it will have to be considered as a new custom part for which standardization information is totally absent. In this specific point, the true value of the program is being highlighted.
The similarity text search of commonality index can be affected only by the structural tree node declaration. Therefore, after the assembly formation, the commonality index is available for examination for the system under consideration. The implication for engineering standards will not be apparent until the engineer has proceeded to the estimation of the absolute standardization index for the system. Despite the use of a variety of common parts in a mechanical system - which means vast commonality among its components - it is not whether these parts conform to obligatory and standard regulations rendering them as unique and not standardized parts. In order to improve design efficiency, the use of standard parts – whenever this is possible - is encouraged, bearing always in mind the aim to maintain a balance between an excessive use of standard parts and (lack of distinctiveness in the system) and a preferable use of custom parts (lack of standards). For already existing and operating systems, the composite standardization index will show the need to proceed with proper actions that will improve the global standardization level of the system either with greater need of using same components in the system as well as using more standard parts in the system.

4. Conclusions

In the present paper, a new composite standardization index is introduced, which includes commonality index that focuses mainly on product families and highlights the usefulness of the common components in system assemblies and absolute standardization index that provides supplementary objective quantitative standardization metrics for every component/part/assembly. When used, the composite standardization index provides a better understanding of the standardization process and helps designers to balance between excessive use (too much commonality and absolute compliance to national standards) and poor use of standards (not enough commonality – higher productions costs).
There is a critical mass of available digital standards for mechanical parts. In the present paper and for the purposes of the case study, some tables of standards from the toolbox of SolidWorks© were used and all calculations of standardization indexes were performed with respect to these tables. In order to illustrate the method, a mechanical subsystem of a mobile manipulator base assembly was analyzed. The analysis of the system resulted to a structural tree consisting of 61 parts and 9 assemblies. Each part was examined, its absolute standardization values were estimated and the composite standardization index values were calculated. The proposed method may function effectively in reverse engineering processes as an assisting tool for examining the standardization levels of existing mechanical systems and can also contribute to applications aiming at improving the standardization of parts and assemblies during design. It is also expected that its extension will enhance it further by providing: a. a reasoning mechanism for knowledge-based estimation of the standardization levels and b. a second mechanism capable of providing - more or less automatically – advices about the steps that should be followed towards a direction of increasing the standardization levels of the system or of one or more of its parts.
Future work is expected to consider the present contribution as part of a framework for establishing a new “design-for-standardization” consideration of design process through software that could dynamically provide all the necessary information about standardization from early design phases. It could also validate the relevant decisions and provide advice about how to increase the standardization level of the product being designed from every aspect of component part standardization. The advice could lead either to increasing the common parts or establishing more standard components.

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