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Design Optimization of Size-Adjustable Parts

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Abstract: This article is devoted to the design with size-adjustable parts approach which is used for mass customization. The article provides a framework for design optimization of size-adjustable parts which enable to achieve incessant adjustability on one or more dimensions of the product. The proposed framework is based on the analysis of size dependences between parts and the difficulty to assemble them addressed through a DSM approach. In addition, these two domains are moderated by the number of size-adjustable parts and the cost of the solution. The article includes a case study to demonstrate the application of the developed framework and a conclusion with a discussion of limitations and directions for further research.

Keywords: Product design, mass customization, design optimization, product variety, design for variety, size-adjustable parts, Design Structure Matrix (DSM)

1 Introduction

In recent decades we can observe the increased demand for customized products, and because of that, the mass customization approach has evolved significantly (Blees et al., 2010; Fogliatto et al., 2012). The core of mass customization is based on the modular design (Tu et al., 2007) and platform approaches (Simpson, 2004). Design objectives for these approaches are usually aimed to increase variety, shorten the lead time and reduce the cost (Simpson, 2004). Nowadays, studies about methods to increase variety emerged as a separate research direction called “design for variety” (Martin and Ishii, 2002).

Studies on variety concern about different parameters which change is required for customization. For example, the scope of adjustable parameters includes, but not limited to, a technology variety (Luh et al., 2011), an application variety (Krause and Eilmus, 2011), as well as size or dimensional variety (Kang and Hong, 2009). The most common approach to achieve variety for these parameters is to design the discrete predefined range of products to fulfill the demand by different configurations (Pahl et al., 2007) or to develop modular building blocks (like Lego bricks), which could be built up during the assembly process to create different variants (Martin and Ishii, 2002). In exceptional cases, adjustability can be achieved by inclusion of the additional functionality in the product architecture to establish adjustable parameter within limits, for example, the seat post clamp of a bicycle (Garneau et al., 2014). However, the dimensional variety represents significant challenges once the range for adjustability becomes uncertain or multi-dimensional variety is necessary. For example, the diversity of different layouts of premises tends manufactures of kitchen units to use parts produced by special order and have dimensions which can be incessantly changed (Figure 1). We refer to this approach as to the design with size-adjustable parts. Existing studies do not cover approaches related to incessant (multi)-dimensional variety and developers usually implement size-adjustable parts on the trial and error basis. The purpose of this article is to provide the framework for implementation of size-adjustable parts in a systematic way for mass customization, and thus, to introduce the new opportunity for developers to make better designs.

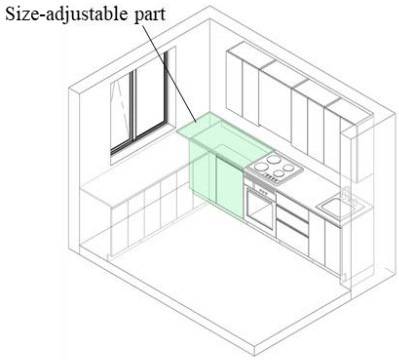


Figure 1. Example of the design with size-adjustable parts (adapted from www.archdaily.com)

To achieve this goal, we should make some deviation from traditional research practice in the design for variety field. Design for variety is mainly considered on a macro level, and the subject of study is a product architecture or a platform in general (Luh et al., 2011; Schmidt III et al., 2008; Suh et al., 2007). Results of these studies provide methods to determine the elements of the platform which should be designed in a way to achieve necessary variety (Li and Azarm, 2002; Simpson et al., 2001; Suh et al., 2007). In comparison to that, studies on a module level (micro level) are rare, for example (Eigner and Zagel, 2007). To have the possibility to consider the use of size-adjustable parts in more details we agreed to focus on a micro level.

Also, we should take into account the difference between two types of variety: spatial (variety in current product) and generational (variety across generations, also known as a temporal variety) (Hsiao and Liu, 2005; Martin and Ishii, 2002). Many industries faced with the shortening of the product life-cycle (Fixson, 2005), for this reason, the generational variety seems to be more promising regarding the lead time and the cost reduction; thus, the dominance of research for generational variety is observed. However, the design with size-adjustable parts should be considered for the current generation of the product, and our contribution would be the rare example of a spatial variety investigation.

To sum up, this article is focused on the incessant dimensional spatial variety on a micro level, or in other words, it is aimed to provide the framework for design optimization of size-adjustable parts. However, the selection of narrow research niche does not prevent that the concepts can also be adapted to the generational variety on macro-level considerations. The rest of the article is organized in the following way, in section two the framework to optimize the design of size-adjustable parts is presented. Section three shows the case-study to demonstrate the application of the developed framework. Finally, in the conclusion section, we explain the results, limitations and future research directions.

2 Framework

This section is devoted to the establishment of the framework for the design optimization of size-adjustable parts. First, we will introduce the theoretical background in the form of causalities between selected design parameters. After that, we will use these connections to describe the optimization procedure for size-adjustable parts, therefore describe the framework.

2.1 Fundamental connections

The fundamental connections appear from the causalities between the number of size-adjustable parts, the number of size dependences per part, the difficulty to assemble for the individual part and the cost of the solution. In this contribution, we focus on the design optimization aimed at reducing difficulty to assemble by splitting size-adjustable parts to decrease the number of size dependencies, the second approach devoted to merging size-adjustable parts retaining the same difficulty to assemble still requires additional investigation and will be addressed in further research.

It is reliably investigated that the cost of the modular product or the platform increases as the number of different parts increases (Hernandez et al., 2003; Pahl et al., 2007; Tu et al., 2007). This artifact can be additionally explained for the case of size-adjustable parts; as we merge two size-adjustable parts on the one dimension we refuse from one machining operation, and in the opposite, the splitting in two parts require additional machining which causes an extra cost. Thus, the first fundamental connection can be stated as: the growing number of size-adjustable parts increases the cost of the solution due to the manufacturing expenses (Figure 2, link 1, "+" (means increase) and "-" (means decrease) notations are adapted from (Blessing and Chakrabarti, 2009)).

Merging (decreasing the number of parts) and splitting (increasing the number of parts) of size-adjustable parts can involve components with different size dependencies (for example, one part has size-adjustability aligned with the width only and second – with the depth only). Thus, the merged part can have greater or equal number of size dependencies, and the split parts can have a reduced or same number of size dependencies (Rajan et al., 2003). In that case, the splitting has a potential to reduce the number of size dependencies per part. Following this explanation for merging and splitting of size-adjustable parts we can formulate the second fundamental connection: by increasing the number of size-adjustable parts (splitting) it is possible to reduce the number of size dependencies per part (Figure 2, link 2).

The growing number of size dependencies for the part may cause the demand for different fastening methods, increase the number of various insertion directions and make assembly path more complex, as a result, the difficulty to assemble this part increases (Boothroyd and Alting, 1992; Sturges and Kilani, 1992). According to this, the third fundamental connection can be expressed as: the growing number of size dependencies per part increases its difficulty to assemble, or, by the reduction in the number of size dependencies for the part it is possible to reduce its difficulty to assemble (Figure 2, link 3).

Finally, the high difficulty to assemble may cause additional expenses for tools and increase the assembly time, thereby, that will enlarge the cost of the solution (Kuo et al., 2001). This observation leads to the fourth fundamental connection: the reduction of the difficulty to assemble may result in cost savings (Figure 2, link 4).

As a result, we have introduced four fundamental connections for design with size-adjustable parts (Figure 2). As we can observe, there is no obvious way to set the optimization path, for example, the growing number of size-adjustable parts, on the one hand, increases the cost, on the other hand, decreases the cost through a reduction of the difficulty to assemble by decreasing the number of size dependencies. To mitigate this contradiction, we will consider the optimization task in a way to find the suitable tradeoff between difficulty to assemble, the number of size dependencies per part and number of size-adjustable parts while assessing the optimized solutions through the cost (Figure 2, dash lines). In such arrangement, the optimization procedure is built around links 2 and 3 (Figure 2) and driven by splitting the size-adjustable parts into several. The results of the optimization are assessed by the cost of the solution (the transition to this stage is made through links 1 and 4) and, if the result of the assessment is successful, the next iteration of the optimization is possible – another size-adjustable part can be split to reduce the difficulty to assemble.

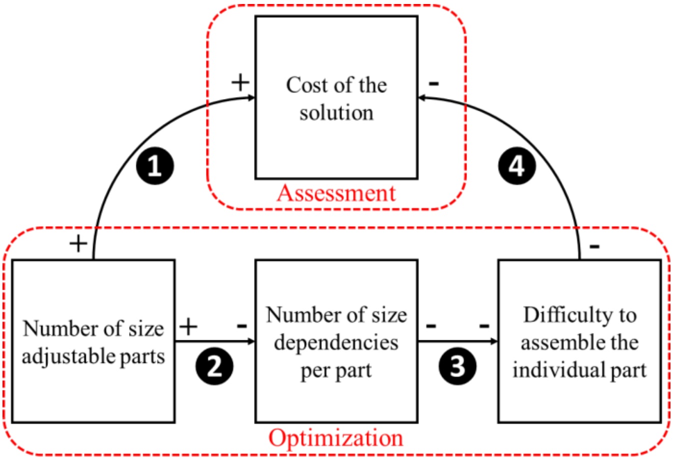


Figure 2. Fundamental connections for design with size-adjustable parts

2.2 Optimization procedure

To arrange a systematic approach for splitting size-adjustable parts to reduce the difficulty to assemble we established the optimization procedure as an iterative process (Figure 3). One iteration of the optimization procedure is devoted to a redesigning one size-adjustable part to reduce the difficulty to assemble by decreasing the number of size dependences for the selected part. The cost is evaluated after each cycle and optimization finishes as size-adjustable parts do not cause difficulties for the assembly process.

The starting point for the optimization procedure depends on the current development phase. If the case is devoted to the design from scratch, then we suggest designing the first version with a minimum number of size-adjustable parts, as the optimization is driven by splitting; else, the current design version can be used as a subject for the optimization.

Cost requirements should be checked before looking for any changes in size-adjustable parts as the optimization driven by splitting can cause additional manufacturing costs. If the solution is out of the budget, then the cost minimization should be performed upfront the optimization (Asiedu and Gu, 1998; Duray et al., 2000; Pahl et al., 2007; Tseng, 1996).

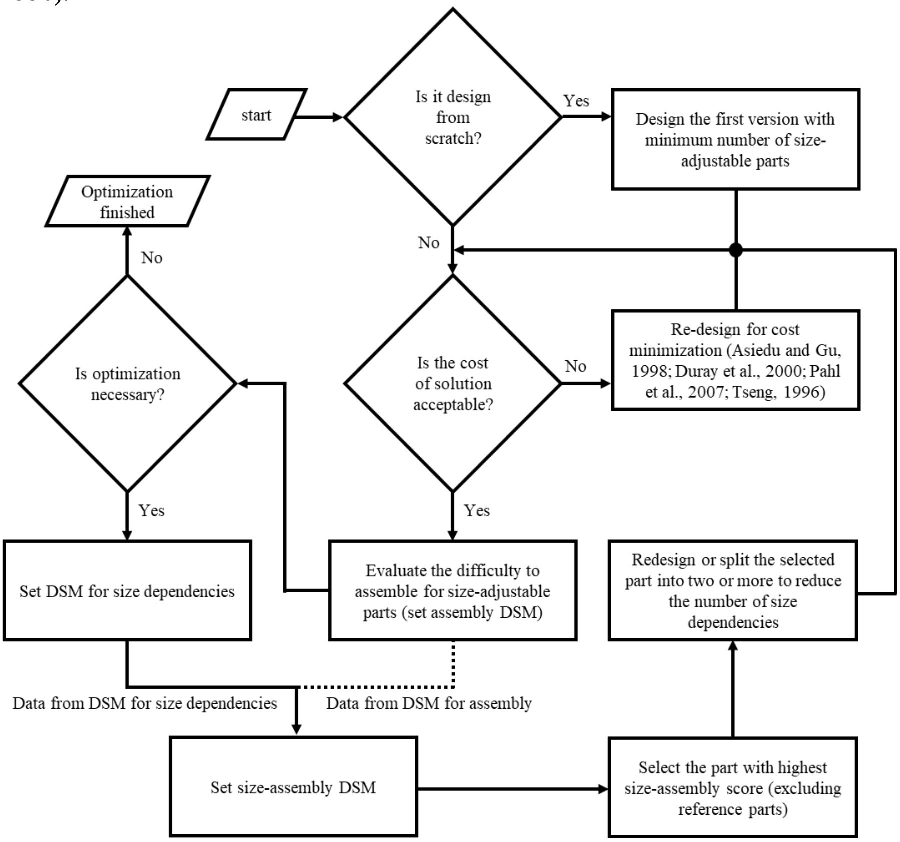


Figure 3. Optimization procedure for size-adjustable parts

The evaluation of the difficulty to assemble serves as a trigger for the optimization. To assess the difficulty, we propose to use the Dependency and Structure Modelling (DSM, also known as the Design Structure Matrix) (Eppinger and Tyson, 2012). Parts in the order of the assembly flow are allocated as headers for columns and rows of the matrix, and then intersection represents the difficulty to assemble between different parts. The four-grade scoring system is adapted from the study of Gunnar Erixon (Erixon, 1996). Each connection is weighted in a color scale, red (= high difficulty to assemble, the assembly path is complex, an additional machining is necessary or tools out of the specification are used), yellow (= moderate difficulty to assemble, tools are required according to the specification), green (= minor difficulty to assemble, no tools are required, or parts are attached indirectly) and blank if parts do not have a connection. The assembly score for each part can be calculated as:

$$\textit{Assembly score} = 9 \times (\#\ red) + 3 \times (\#\ yellow) + 1 \times (\#\ green), \qquad (1)$$

applied to the row of the part ((# color) is the count of color markings in the row). In addition, the average difficulty to assemble is introduced as a mean of assembly scores and can be used to compare design versions. The example of the DSM for the difficulty to assemble can be observed in the case study section (Figure 4a). The markings should be placed based on CAD model investigations, sub-assemblies and prototypes, and several different sizes of the solution should be checked. The red color signals for the necessity of the optimization, however, the difficulty to assemble cannot be used to set optimization path as it is a subjective rating made by few people involved in a design process.

To avoid subjectivity issue and set the optimization path, the DSM for size dependences between parts is introduced (Figure 4b). To acquire data for size dependences, the reference parts should be selected. These parts have only one adjustable dimension. The size dependencies are evaluated in relation to the reference parts and to each other by the following scale, 3 (= parts share the same dimension and geometrically attached), 1 (= the dimension of the part can be calculated from the other, however, parts do not have a direct connection) and 0 if parts are size independent, this procedure gives the objective report about design.

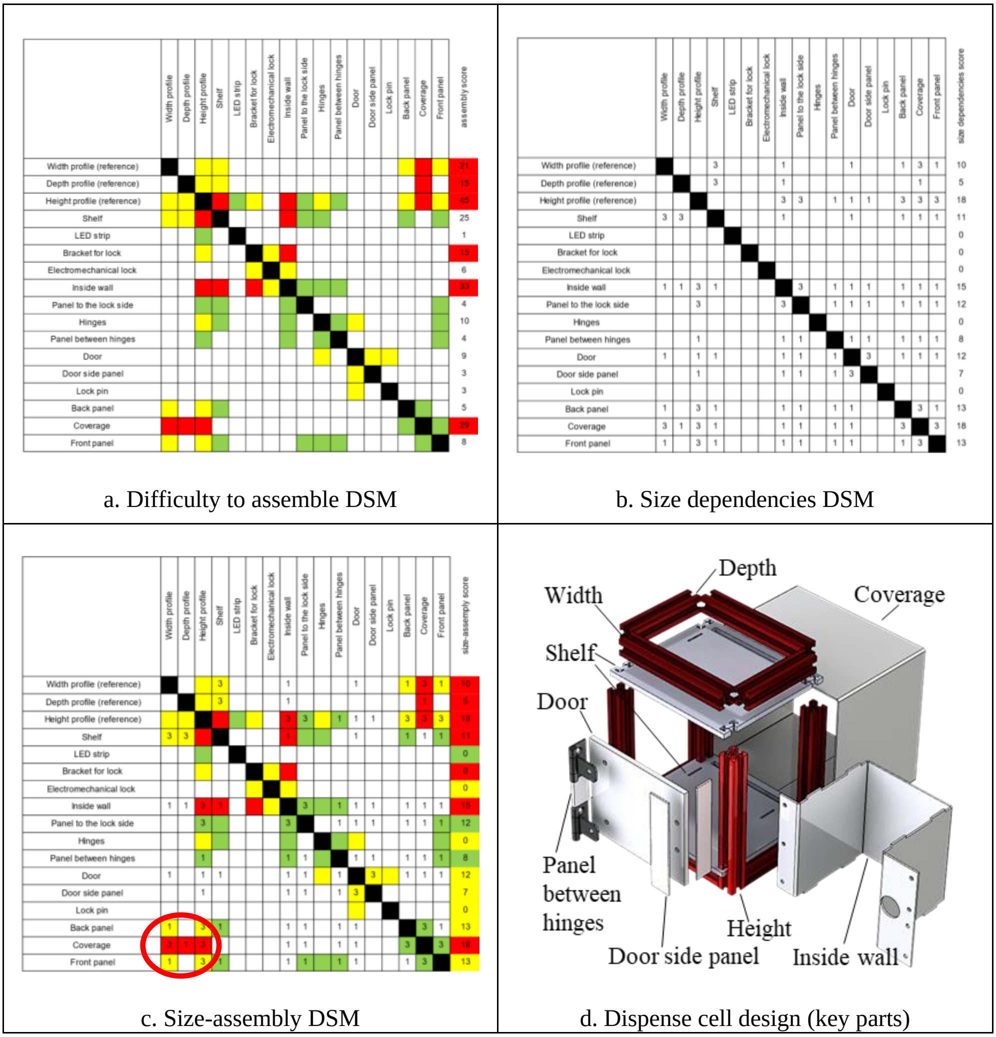
To have a comprehensive picture and select the part for optimization iteration, the two-dimensional size-assembly DSM is introduced (Figure 4c). One dimension is devoted to the assembly difficulty and represented in the color scale, and the second dimension is obtained from the DSM for size dependences between parts. As the size-assembly matrix is set, the size-assembly scores can be calculated as the sum of markings for the individual part and highlighted with the color referred to the highest difficulty to assemble met (red, yellow, then green) (Figure 4c). The part for optimization is selected based on the highest size-assembly score, color then sum of points.

The selected part should be redesigned or split in two or more to reduce the number of size dependences, and the markings in the size-assembly DSM are used to determine design alternatives. After the alternative design was found, the next cycle of the optimization can be started with the cost requirement checking and setting new size-assembly DSM. Once all cases of the high difficulty to assemble for size-adjustable parts are iteratively resolved, the optimization procedure is finished.

3 Case study

The case study is devoted to the dispense cell module of a vending machine (Figure 4d, 5d). Initial marketing investigation revealed 560 different goods which can be potentially sold by the device. Analysis of the package dimensions for these goods provided requirements for inner dimensions of the dispense cell, and the attempt to satisfy these requirements with the multiple size ranges approach would involve the designing of at least 180 size versions. The building block and functional adjustability approaches could not be applied due to security challenges. For these reasons, the design with size-adjustable parts approach was selected, and the goal is to design the dispense cell module that can be produced by special order according to the dimensions of the good to store in this cell.

The initial configuration included 12 types of size-adjustable parts (Figure 4d, three reference parts (highlighted with red color) and nine size-adjustable parts (highlighted with white, front and back panels are not presented)). The prototype revealed several cases where the difficulty to assemble is high (Figure 4a); however, the cost requirements were fulfilled, and thus, the optimization was necessary and possible. The DSM for size dependence was filled (Figure 4b), and it was supplemented by data from the assembly test to set the size-assembly DSM (Figure 4c).



a. Difficulty to assemble DSM

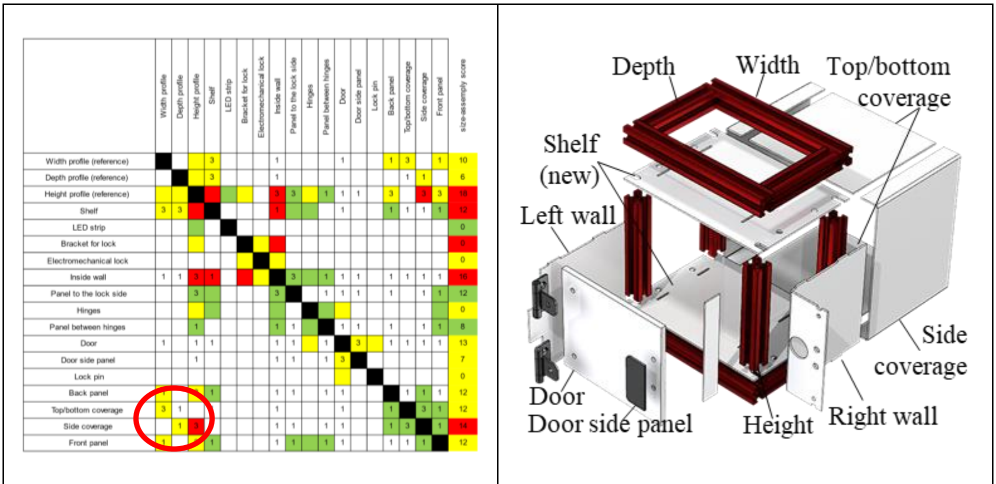
b. Size dependencies DSM

c. Size-assembly DSM

d. Dispense cell design (key parts)

Figure 4. Analysis of the design before the optimization procedure

The "coverage" had the highest size-assembly score =18 and was selected for the first iteration of the optimization (Figure 3). Looking at the row for "coverage" (Figure 4c, circled) we can observe that it has size dependencies with all reference parts, however, the dependency aligned with depth has score "1" compare to "3" for the rest references. Based on this, we can propose splitting into two parts: a first should have dependencies with "width + depth" and a second - "depth + height." Several design alternatives aligned with this suggestion were generated, and the possible one was implemented. As a result, the "coverage" was split into 2 types of size-adjustable parts (Figure 5c, 5d): the "top/bottom coverage" (determined by width and depth) and the "side coverage" (determined by depth and height). After the "coverage" redesign, the size-assembly DSM for new design version was set (Figure 4c). According to it the "top/bottom coverage" has size-assembly score =12, the "side coverage" =14, compare to 18 for the original "coverage" design.



c. Size-assembly DSM

d. Dispense cell design (key parts)

Figure 5. Analysis of the design within the optimization procedure, c. Size-assembly DSM after the first iteration of the optimization procedure ("coverage" redesign), d. The design of the dispense cell after all iterations of the optimization procedure.

The size-assembly DSM after the first iteration (Figure 4c) is used to find the next candidate for optimization – the "inside wall." It had the highest size-assembly score for current optimization iteration. Following the same logic as for the "coverage," the "inside wall" was divided into the left and right parts; thus, the dependency aligned with the width was neglected (compare Figure 4d, 5d). Next iterations of the optimization procedure (Figure 3) were devoted to the "side coverage" (the size dependency with "height profile" was reduced by changing of the connection between profiles), the shelf (the shape was changed to reduce size dependency with "depth profile"). After these four iterations, all cases with the high difficulty to assemble were resolved.

The design optimization of size-adjustable parts made with the help of the optimization procedure in Figure 3 allowed to introduce the design which has 14 types of size-adjustable parts (Figure 5d) and the cost of the solution increased within 1% depending on the size. However, the most important is the fact that the average difficulty to assemble (average assembly score) was reduced almost twice, from 14 (Figure 5a) to 8, and this allowed to shorten the assembly time and minimize the number of defective products.

The case-study also reveals two promising applications for the DSM driven optimization of size-adjustable parts. The first discovery is devoted to the possibility to determine size-adjustable parts which should be redesigned as “one size fits all” or as a set of multiple sizes. The “door side panel” represents the example of such case. According to size-assembly DSM (Figure 4c, 5c), only one cell for the “door side panel” part – the intersection with the “door” part, is devoted to the assembly difficulty and simultaneously represents the highest marking for size dependencies. Based on this observation, we can propose that the parts with only a few markings, which comprise the assembly difficulty and size dependency, in a row of size-assembly DSM are the first candidates to become fixed parts. The second idea relates to merging several size-adjustable parts into one. In comparison to splitting, the merge operation also requires information about materials and manufacturing methods. With this information, it is possible to cluster the DSM to search for merging opportunity. The case study had an intuitive example were the merge was necessary, however, this decision can be also explained with the help of size-assembly DSM. Once the “inside wall” was split into two parts, and a new size-assembly DSM was set, it was observed that the markings in the row for the “left wall” include all markings for the “panel between hinges.” It means that the merging of these parts will not increase the difficulty to assemble, but it will reduce the number of parts, and thus, the cost. These two propositions require in-depth, detailed research to become a part of the optimization procedure for design with size-adjustable parts.

4 Conclusion

This article introduces the design with size-adjustable parts as a solution for the incessant dimensional spatial variety on module level. Analysis of the connections between four objectives of the design with size-adjustable parts revealed the optimization path contradiction (Figure 2). To resolve it, the optimization framework which comprises the optimization procedure (Figure 3) has been developed. The case study of the dispense cell module (Figure 4d) has demonstrated the practical implications of the developed optimization approach. The proposed approach allows systematic implementation of size-adjustable parts for mass customization and introduces the new opportunity for developers to make better designs.

The optimization procedure can be adapted for a generational variety and macro level considerations, however, that may require additional investigation for the size dependencies assessment. The current scale for size-assembly DSM does not distinguish the full scope of cases but serves as a good indicator of the optimization order on module level and supports the search for design alternatives. Transition to macro level or generational variety considerations will require more precise calculations as the number of parts will grow significantly.

Moreover, the current optimization procedure is built upon the splitting of size-adjustable parts to reduce the number of size dependencies, thereby reducing the difficulty to assemble. The merge operation for size-adjustable parts has a potential to reduce the cost of the solution by manufacturing savings and should be investigated in more details. In addition, some of the size-adjustable parts can be redesigned as “one size fits all” and DSM based approach has a potential to determine such parts. These two ideas form a promising research avenue with an aim to establish comprehensive DSM based design optimization for size-adjustable parts.

Finally, during this research, we found that the evaluation of the difficulty to assemble has not been investigated systematically. Individual approaches are available in the literature, and systematic clarification of them will make a significant contribution.

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