A Redesign Procedure to Manufacture Adaptive Façades with Standard Products

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Abstract
Although their potential for high environmental performance is largely accepted, adaptive façades have not yet become widespread in practice. Most of the current examples are developed by engineer-to-order design processes, as project-oriented, custom, and complex solutions. More simple and reliable solutions are needed to support the reuse of technical solutions between projects and increase the feasibility of adaptive façades. Therefore, this research aims to develop a procedure to design adaptive façades whose parts are based on engineered standard products with the least number of parts and layers. The research is initiated through the generation of concepts for designing adaptive façades to be manufactured using standard products. From several concepts, 'redesigning dynamic adaptive façades' has been selected for further investigation, as it pursues the goals for a solution determined for this research. A preliminary case study is conducted to redesign an adaptive façade to be manufactured with standard products. Its process steps are captured and analysed, and the steps that need improvement are revealed. To systematise and improve the captured redesign process, façade design and product design methodologies are analysed in the context of adaptive façade design. Redesign and reverse engineering processes used in product design are adapted and merged with façade and adaptive façade design processes, and a 5-phase adaptive façade redesign procedure is outlined. Each phase is developed based on mature tools and methods used in product and façade design. An iterative loop of development, application test, and review process is carried out for development of the process steps. Thus, a redesign procedure is generated by the combined application of DFMA and TRIZ in the synthesis of reverse engineering and redesign processes. Consequently, the application of the redesign procedure is demonstrated through a case study. The case study revealed that the procedure has the ability to generate a façade redesign that has a higher constructability index than the reference façade.

Keywords
adaptive façade, constructability, redesign, standard product, reverse engineering, DFMA

DOI 10.7480/jfde.2018.3.2530

1 INTRODUCTION

Adaptive façades are considered to be an important step in the development of façade technology. They are receiving increasing attention from researchers and professionals in the building sector, as they provide comfortable interior conditions with low energy consumption. Currently, there are more than five hundred building examples with adaptive shells, according to the climate adaptive building shells database (Loonen, 2013; Attia & Bashandy, 2016). However, these examples are mainly 'experimental, small-scale' or 'high-profile, high-budget' projects (Loonen, Trcka, Cóstola, & Hensen, 2013). Despite their accepted potential for high environmental performance and wide range of technology options from high-tech to low-tech, the practical application of adaptive façades is very limited. A comprehensive literature review is conducted to determine the problems causing this situation, and the findings are listed below:

- Adaptive façades are not clearly defined and resolved in the field of architectural research (Schnädelbach, 2010; Gosztonyi, 2015; Attia, Favoino, Loonen, Petrovski, & Monge-Barrio, 2015). Kolarevic (2015) states that change events are not adequately addressed or explored.
- Designers need to acquire experience and knowledge about designing adaptive façades (Meagher, 2015; Loonen, Favoino, Hensen, & Overend, 2017). However, detailed information about design and construction processes, performance, and post occupancy evaluations of existing cases are lacking in the literature (Attia & Bashandy, 2016; Attia, 2017). Decisions on how adaptive façades are designed, operated, maintained, and assessed remain a challenge (Attia, 2017). Questions such as: what sort of adaptation is needed, what type of behaviour results in the best performance, and what is the maximum acceptable rate of change are still being researched.
- Design and performance evaluation of adaptive façades is a complex task, and existing performance assessment tools are insufficient to evaluate the adaptive façade systems (Loonen et al., 2017; Boer et al., 2011; Struck et al., 2015).
- Standardised procedures, design support tools, and methods are needed for adaptive façade design (Bolbroe, 2014; Loonen et al., 2015)
- Majority of the current examples are project-oriented custom solutions that develop complex one-of-a-kind products and involve innovative technologies, resulting in challenging projects with relatively high risks (Loonen et al., 2013).
- There are social and psychological challenges and barriers related to user interaction (Loonen, 2010; Ogwezi, Bonser, Cook, & Sakula, 2011).

Considering the problems listed above, simple, flexible, and easily accessible solutions are needed with well-described procedures to achieve these solutions to increase the practical application of adaptive façades. Thus, a basis would be provided for adaptive façades to become customised industrial products like the majority of the regular façade systems on the market. In the context of this need, several approaches could be developed to achieve such solutions. One of these solutions is to simplify the design of adaptive façades using products that are based on engineered standard products with the least number of parts and layers. Within the scope of this approach, the term 'product' is used to describe all product levels of façades (Klein, 2013), between different levels of completeness, from material to component, within the building product hierarchy developed by Eekhout (2008). Likewise, the term 'standard product' covers all levels of products with unalterable characteristics and manufacturing processes, ranging from standard material to component (Eekhout, 2008).

In addition to enhancing the feasibility and constructability of adaptive façades, there are several other reasons for proposing the design of adaptive façades using standard products. Anderson (2014) states that standard products are less expensive to design and provide time savings, when design, documentation, prototyping, and testing processes are considered. The overhead cost of purchasing all the constituent parts and the cost of non-core-competency manufacturing can be reduced by using standard products. Suppliers are more efficient within their own specialty, more experienced in using their own products, continuously improve quality, have proven track records on reliability, have dedicated production facilities, produce parts at lower cost, offer standardised parts, and sometimes pick up warranty and service costs (Anderson, 2014). All these features of standard products support the maintenance, repair, and operation processes as well as the manufacturing process.

The aim of this research is to develop a design procedure to support designing adaptive façades with standard products that are available on market, to improve constructability through simplification. At first, a solution is sought for how to design adaptive façades to be manufactured with standard products. Possible solution paths, namely concepts, are identified and one of them is selected for elaboration. Following this, the selected concept is developed with the focus on identification of a design procedure. Various research methods are used within this research. A comprehensive literature review of both façade and product design is performed for concept generation and development. A research through design methodology is adopted, and an iterative loop of development, application test, and review process is carried out for development of process steps, checklists, and templates of the design procedure. Applicability of the design procedure is tested through a case study and evaluated by interviews with experts such as architects and manufacturers. Within this framework, Section 2 presents concept generation, selection, and development processes. Section 3 describes the phases and steps of the redesign procedure, developed for the selected redesign concept. Section 4 presents the application of the redesign procedure through a case study. Section 5 concludes the research with revealing characteristics, benefits, and limitations of the redesign procedure.

2 CONCEPT GENERATION, SELECTION AND DEVELOPMENT

Designing adaptive façades to be manufactured with standard products is an open-ended problem with multiple acceptable solutions. Indeed, a characteristic of architectural design problems is that there are numerous alternatives and many potentially acceptable solutions (Lawson, 1970). The challenge is to find the best solution in relation to the design objectives of the project.

When dealing with an open-ended problem, rather than concentrating initially on a specific solution, it is better to look for as many different solutions as possible (Dandy, Daniell, Foley, & Warner 2018). In this context, some researchers suggest subdividing and structuring the problem-solving process into three different levels: concept level, system level, and material level (Perino & Serra, 2015). From this point of view, this research starts from the concept level and continues down to the system level. The material level is outside the scope of this research, since material development is not intended.

The concept level aims to explore new ideas and visions, and analyses them from a theoretical point of view to obtain information on the working principles (Perino & Serra, 2015). An answer is sought for what would be done to solve the problem, without worrying about how to do it. Concept level studies respectively include collecting ideas and existing concepts, concept generation, and concept selection.

To reveal existing concepts and collect ideas, the mature principles from manufacturing industry are reviewed in the context of the aim of this research. At this stage, the need for customisation of façade design in each project depending on building specifications comes into prominence. In this context, strategies of designing customised products by combining standard products are reviewed from product development literature, to determine possible design approaches.

Ulrich (1992) demonstrated that product variety/customisation can be economically realised with product architecture strategies that provide flexibility in the final assembly process without changing the manufacturing process. In the context of product architecture, customisation by standard products is achieved by modular systems (Ulrich & Eppinger, 2012) and open systems (Koren, Hu, Peihua, & Shpitalni, 2013), and by the production approaches, mass customisation, and mass individualisation, which arise from these product architecture systems. Open systems and modular systems are embraced in architecture in a similar manner (Staib, Dörrhöfer, & Rosenthal, 2008). According to that information, it has been determined that concept studies should focus on the development of the product architecture.

Concept generation study begins after re-stating the research problem in clear, general, and unambiguous terms, and collecting ideas and existing concepts. Within the set of possible solutions, concept alternatives are defined depending on certain variables that are mainly extracted from collected ideas and existing concepts. The number of these variables varies depending on the defined part of the solution set. In this context, nine variables stand out for concept generation to solve this research problem: design types, adaptive façade types, constructability improvement strategies, standard product ratio, functional requirements, performance requirements, demand for customisation, production volume and project budget (Emmitt, Olie, & Schmid, 2004; Charles, Crane, & Furness, 2001; Eekhout, 2008; Dieter & Schmidt, 2012; Jensen, 2014; Firesmith, 2015; Cantamessa & Montagna, 2016; Chen, Peng, & Gu, 2017; Başarır & Altun, 2017). Concepts are generated depending on the value of the choice spectrum for these variables. With respect to this, several concepts are generated, such as open system design, modular system design, and redesign of existing adaptive façades.

After a series of different concept solutions are created for the research problem, the next step is to evaluate, compare, and rank them to define the most reasonable concept for development at system level (Dandy et al., 2018). In evaluation, the ‘value’, ‘benefit’, or ‘strength’ of a concept is measured according to solution objectives of the research problem. In this research, the aim is to select a solution that leads to the fulfilment of following objectives: low development risk, high development capacity, high façade performance, technical availability, and high standardisation. With respect to these objectives, concept selection criteria are determined as development cost, development time, development capacity, performance, technological availability, and complexity level. Generated concepts are evaluated by a weighted decision matrix, and the concept of redesigning dynamic adaptive façades to be manufactured with standard products is chosen for further development.

The advantage of redesign is that the product architecture and a part of the new product is known in advance. There are most likely specific areas or problems to focus on, rather than a completely blank slate. Redesign solutions are generally more feasible and reliable, since they have already been used successfully in existing systems (Han & Lee, 2006). It generally focuses on resolving conflicts between current design objectives and reference design capabilities. Most techniques start by choosing a reference design that reduces conflicts as much as possible. Remaining conflicts, depending upon their degree, are resolved by changing component attributes, replacing components, or changing the structure of the original design (Li, Kou, Cheng, & Wang, 2006).

Concept level of the research is completed by selecting the concept. At the following system level, the selected concept is further investigated and developed with the focus on identification of the redesign procedure. For development of the redesign concept into a redesign procedure, a research-through-design methodology is used. A preliminary case study is conducted to redesign a dynamic adaptive façade to be manufactured with standard products. A systematic design method is not used in this case study. Design diary approach (Pedgley, 2007) is utilised to capture its process steps. Then, these process steps are analysed and grouped, with regard to their intended use and interrelationship. According to this preliminary case study, three fields that need to be improved in the captured redesign process are identified. These are (i) identifying existing parts to be redesigned, (ii) selecting new parts to be used in the redesign, and (iii) solving the contradictions or problems that arise from the reconfiguration process.

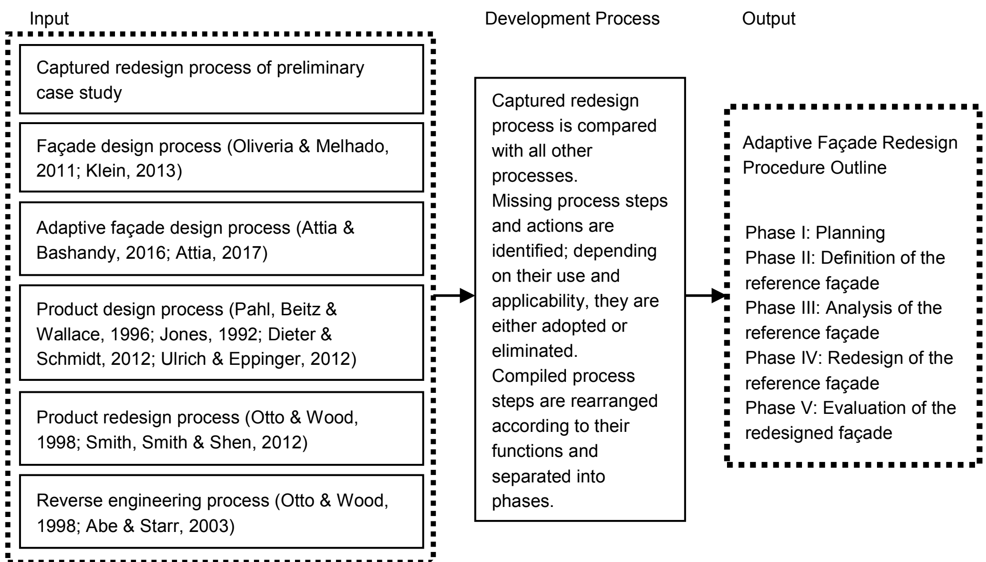


FIG. 1 Adaptive façade redesign procedure outline development

To systematise and improve the captured redesign process of the preliminary case study, façade design, adaptive façade design, and product design methodologies are reviewed first. Captured process steps of the preliminary case study are compared with the reviewed façade design, product design, and redesign process steps, and missing steps and actions are identified. These are subsequently either adopted or eliminated, depending on their use and applicability in the case of adaptive façade design, since not all process steps of product design/redesign are applicable to adaptive façades depending on different characteristics of development processes (Jones, 1992; Ichida & Voigt, 1996; Eekhout, 2008). Reverse engineering processes, which are used in product redesign to reveal the properties and working principles of the existing products, are adopted in the same manner. Compiled process steps are rearranged according to their functions and separated into phases. Thus, a 5-phase adaptive façade redesign procedure is outlined (Fig.1). Then each process phase is developed separately, according to the projected outputs of the phases.

After the redesign procedure has been outlined, studies are initiated on fields that need improvement according to the preliminary case study. Approximately sixty design methodologies have been reviewed in the context of this research problem (Tomiyama et al., 2009; Dieter & Schmidt, 2012; Tooley & Knovel, 2010; Eekhout, 2008; Ong, Nee, & Xu, 2008; Natee, Low, & Teo, 2016). Since the first field to be improved is the identification of the existing parts to be redesigned through elimination or replacement, research is initially focused on product simplification methods. Systematic problem-solving and design improvement methods related to manufacture and assembly are analysed to determine which of them could be utilised to improve constructability through simplification. Based on this, the design for manufacture and assembly (DFMA) method, which focuses on the same goals as the constructability concept, developed by O'Connor, Rusch, and Schulz (1987), and intended to adapt into architectural design in various researches to increase the constructability (Fox, Marsh, & Cockerham, 2001; Gerth, Boqvist, Bjelkemyr, & Lindberg, 2013), is selected to be adapted into the redesign process.

DFMA is a design-review method with two components: design for manufacture (DFM) and design for assembly (DFA). DFMA has three beneficial impacts on design: (i) reducing the number of parts, (ii) reducing the costs, and (iii) increasing reliability and quality of design through the simplified production process. In order to simplify a product's structure, the DFA method recommends a functional analysis of each part in the assembly to identify and eliminate parts that do not exist for fundamental reasons. Furthermore, DFMA manuals comprise comparison metrics for generic material, process, and component types and design evaluation metrics. (Otto & Wood, 1998)

Elimination or replacement of parts and reconfiguration of the system during the redesign process can lead to contradictions/problems which require design revisions. To support that process, systematic problem-solving methods are analysed. Theory of Inventive Problem Solving (TRIZ), which is claimed as a powerful support in tackling technical problems and increasing creativity (Chechurin & Borgianni, 2016), is selected for adaptation to the redesign process. The method works by restating the specific design task in a more general way and then selecting generic solutions from identified principles, previously-identified evolutionary patterns, and databases of designs and patents collected and abstracted from a wide range of technologies. TRlZ provides several problem-solving tools, such as Inventive Principles for overcoming technical contradictions, Separation Principles for overcoming physical contradictions, Inventive Standards or Scientific Effects for coping with a missing function, and Trends of Technological Evolution for solving technical and physical contradictions (Lucchetta Bariani, & Knight, 2005).

To develop the fields that were determined through the preliminary case study, the above-mentioned modules and tools of the DFMA and TRIZ methods, which are expedient for research purposes, are integrated into the redesign procedure outline. Furthermore, to support the selection of parts for replacement in redesign, part selection factors are compiled from literature. By adding checklists and templates to the design steps, improvements are made to facilitate the implementation of the redesign procedure. For a detailed examination, each phase of the procedure is subjected to application testing. An iterative loop of development, application test, and review process is carried out for development of the process steps. The steps that are taken in the development of the redesign procedure, depending on the phase development are shown in detail in the following figures (Fig. 2, Fig. 3, Fig. 4, Fig. 5, and Fig. 6).

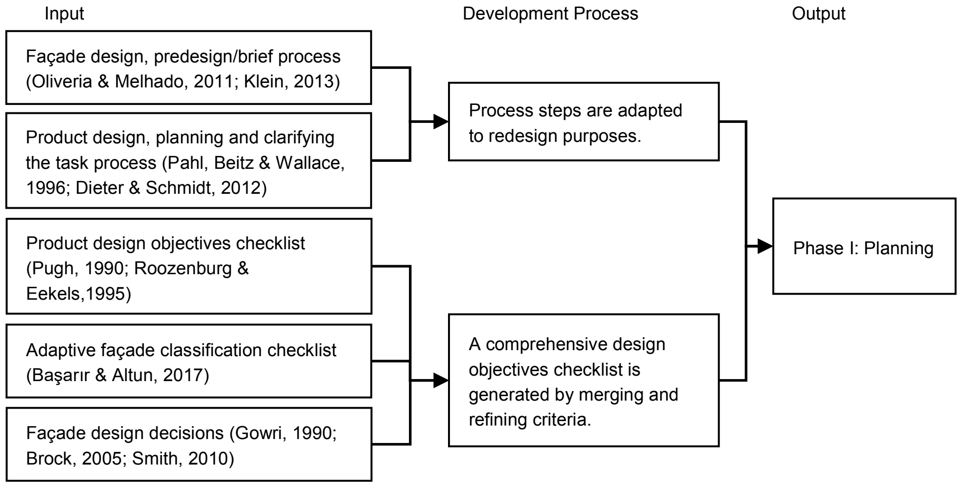


FIG. 2 Phase I: Planning, development of process steps

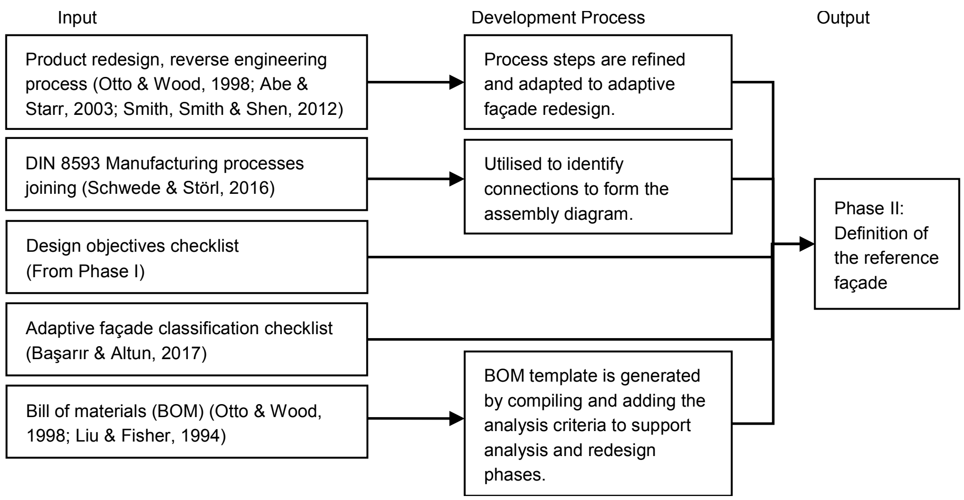


FIG. 3 Phase II: Definition of the reference façade, development of process steps

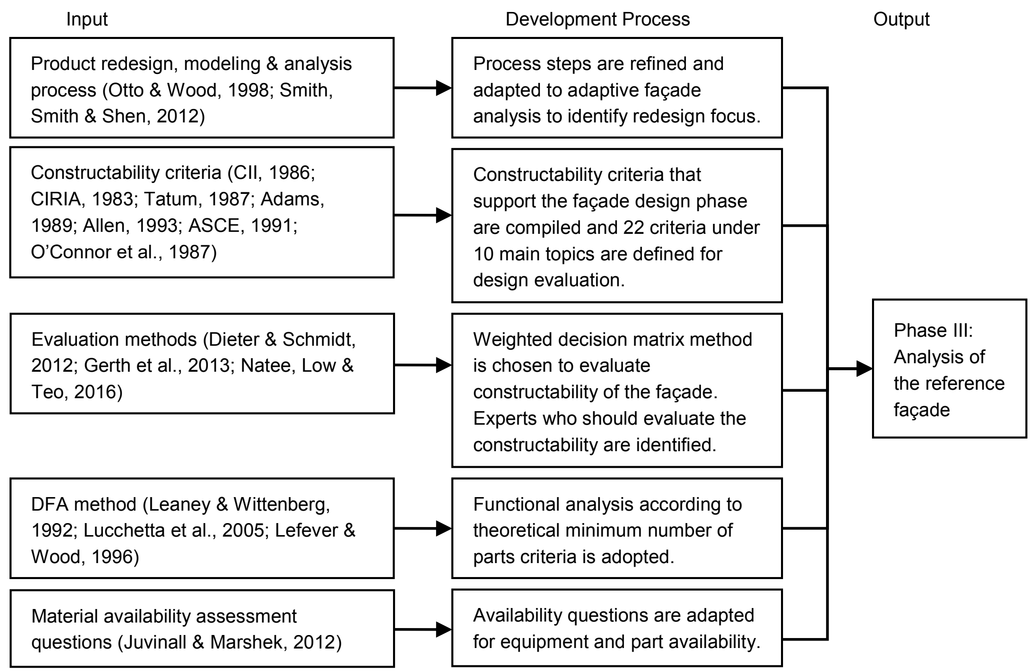


FIG. 4 Phase III: Analysis of the reference façade, development of process steps

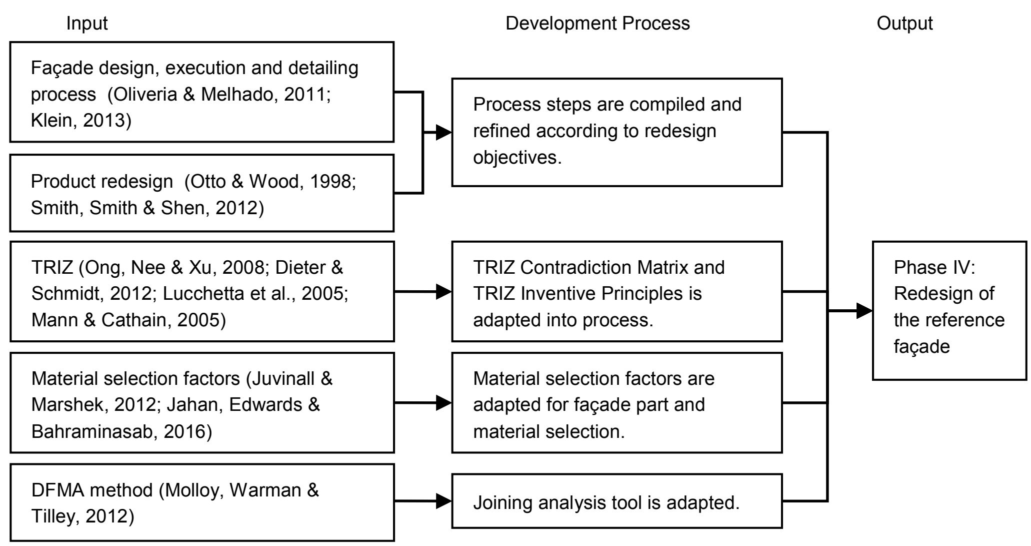


FIG. 5 Phase IV: Redesign of the reference façade, development of process steps

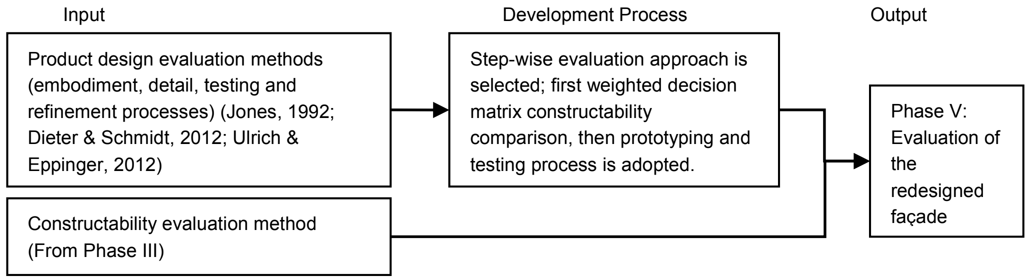


FIG. 6 Phase V: Evaluation of the redesigned façade, development of process steps

3 A REDESIGN PROCEDURE TO MANUFACTURE ADAPTIVE FAÇADES WITH STANDARD PRODUCTS

A redesign procedure with a structured approach towards manufacturing adaptive façades with standard products is developed as presented in Section 2. It is based on the organisation of form, elimination, replacement or addition of parts, and reconfiguration, depending on the design objectives. It consists of five phases and their application steps. Even though the process is linear theoretically, there is a back coupling between and within the phases in practice. Application steps and outputs of each phase are explained in the following sections.

3.1 PHASE I: PLANNING

The aim of this phase is to determine the design objectives and constraints of the façade required for the developing architectural project, and in this context selecting the most proper existing adaptive façade for redesign. First, factors, namely the design objectives, affecting the decisions of façade design and defining the characteristics of the façade, are revealed. A checklist approach is adopted for that purpose. The checklist consists of a comprehensive list of design objectives with 22 factors, such as built environment conditions, performance requirements, material properties, regulations, standards, building and façade characteristics, aesthetics, and cost per unit. Based on the data obtained from the checklist, an existing adaptive façade that most closely meets the design objectives is selected as the reference façade for redesign.

3.2 PHASE II: DEFINITION OF THE REFERENCE FAÇADE

An extensive understanding of the reference façade is needed to lead the redesign process. This phase intends to provide an understanding of the design rationale that motivated the existing design and physical system of the reference façade. It leads to a comprehension of the “whys” that motivated the “hows” of the reference façade. Definition of the reference façade is achieved through the concept of reverse engineering. Reverse engineering, wherein a product is observed, disassembled, analysed, and documented in terms of its form, components, physical principles, functionality, manufacturability, and assemblability, initiates the redesign process. Definition studies are based on the design, production, and installation details obtained from the designers, contractors, and manufacturers.

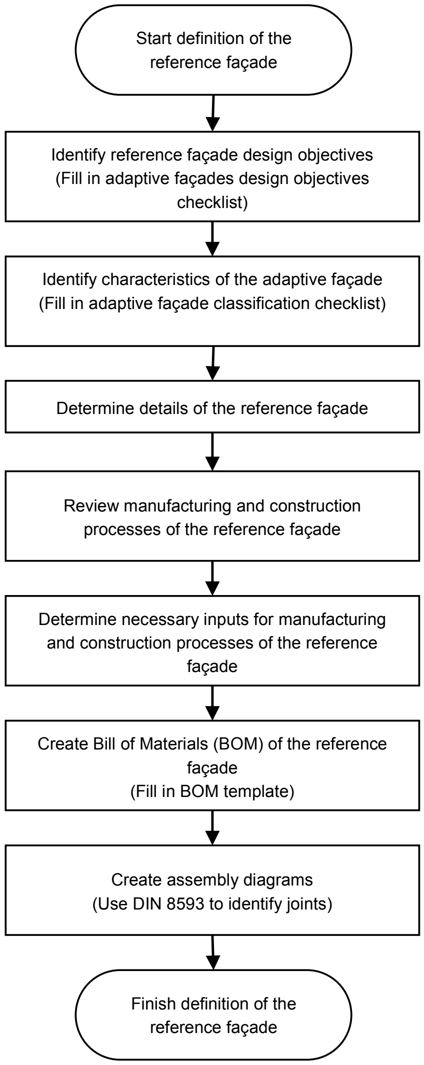


FIG. 7 Phase II: Definition of reference façade, process flowchart

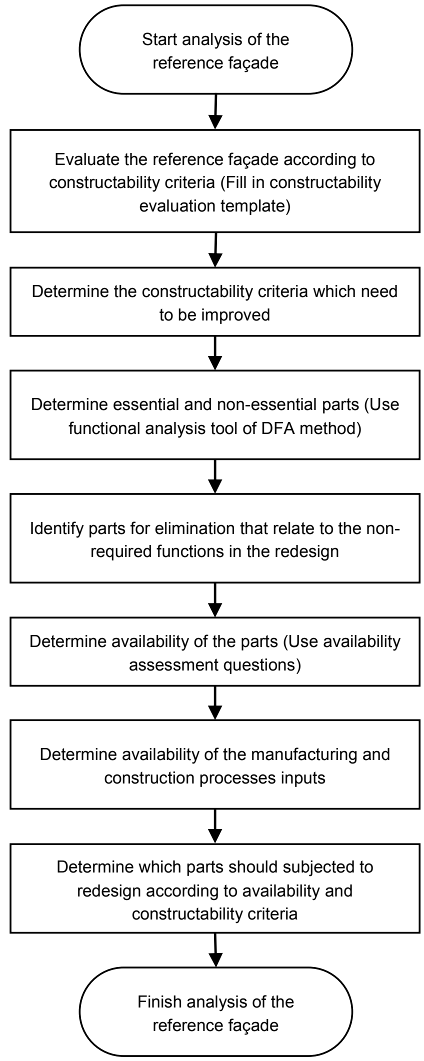


FIG. 8 Phase III: Analysis of reference façade, process flowchart

A comprehensive collection of information on the reference façade is undertaken at this phase. The adaptive façade design objectives checklist structured in the planning phase is utilised to establish the factors that motivated the reference façade design. The adaptive façade classification checklist is used to identify adaptive façade characteristics. Details of the façade system are identified and examined. Manufacturing and construction processes of the façade system are reviewed and the necessary inputs, such as equipment, labour, and funds for these processes are determined.

One of the most important steps in this phase is generating a bill of materials (BOM) for the reference façade. BOM is used for displaying data inputs and outputs, defining key characteristics of parts and structuring part relationships in the manufacturing industry. The BOM of the reference façade is generated according to BOM template to support redesign decisions. The BOM template contains information about sub-assemblies, parts, part numbers, functions, quantity, unit of measure, materials, manufacturing process, production, and procurement type, which describes if a particular part has been purchased or manufactured.

As well as identifying the parts that form the façade system, connections of the parts with each other and with other building components should be identified. Type of joints between façade parts are identified by assigning manufacturing processes according to DIN 8593, and assembly diagrams are created.

The flowchart showing all process steps of the phase is given in Fig. 7. Upon completion of this phase, all the information necessary for the analysis of the reference façade is defined.

3.3 PHASE III: ANALYSIS OF THE REFERENCE FAÇADE

As a characteristic of redesign, the product architecture and a fraction of the redesigned façade system is known in advance, and conversely, the parts that need to be eliminated or replaced by standard products must be determined. Identifying which parts are the focus of the redesign is important, as well as recognising the redesign objectives.

Analysis of the reference façade starts with the constructability evaluation, which is made according to 22 constructability criteria used in the detailing process in architectural design, such as the use of minimum number of parts and the use of readily available products in common sizes and configurations. A constructability evaluation template is generated according to a weighted decision matrix method to support this step. A constructability index is calculated by the constructability evaluation; as the index value converges from zero to one, the level of constructability increases.

An important issue to be considered is that the nature of the constructability evaluation mostly depends on the level of expertise of the evaluator (cf. Dorst, 2004), therefore choice of the evaluator should be done very carefully. At this point, level of expertise of the designer who is responsible for the redesign should be identified according to the knowledge required about the design, manufacturing and construction processes of the reference façade. If necessary, experts should be identified on subjects that require deeper knowledge. Consequently, the evaluation should be carried out by the designer together with an expert team.

The purpose of the evaluation is to clarify to what extent the reference design can achieve the constructability criteria and set a course of redesign. Based on this evaluation, the constructability criteria, to which the reference façade design should be improved, are determined. Generally, simplification, standardisation, use of easy-to-find products, and use of enhanced details are the most prominent constructability criteria for reducing the complexity of the reference façade and supporting production with standard products.

The following step of this phase is to determine which parts of the façade will be subject to redesign. DFA function analysis is performed to determine essential and non-essential parts. In this phase of the analysis, technical or economic limitations are largely ignored to encourage breakthrough thinking by removing the mental constraints of existing solutions. Then, the parts that provide the functions that are not required in the redesign are defined by comparing the design objectives of redesign and reference design. With the data obtained from the BOM, availability of the parts that form the façade is assessed according to the availability questions. Availability of manufacturing and construction process inputs is evaluated to determine redesign constraints.

The steps of this phase, which analyse the reference façade according to the constructability, functionality, and availability criteria, are shown in Fig. 8.

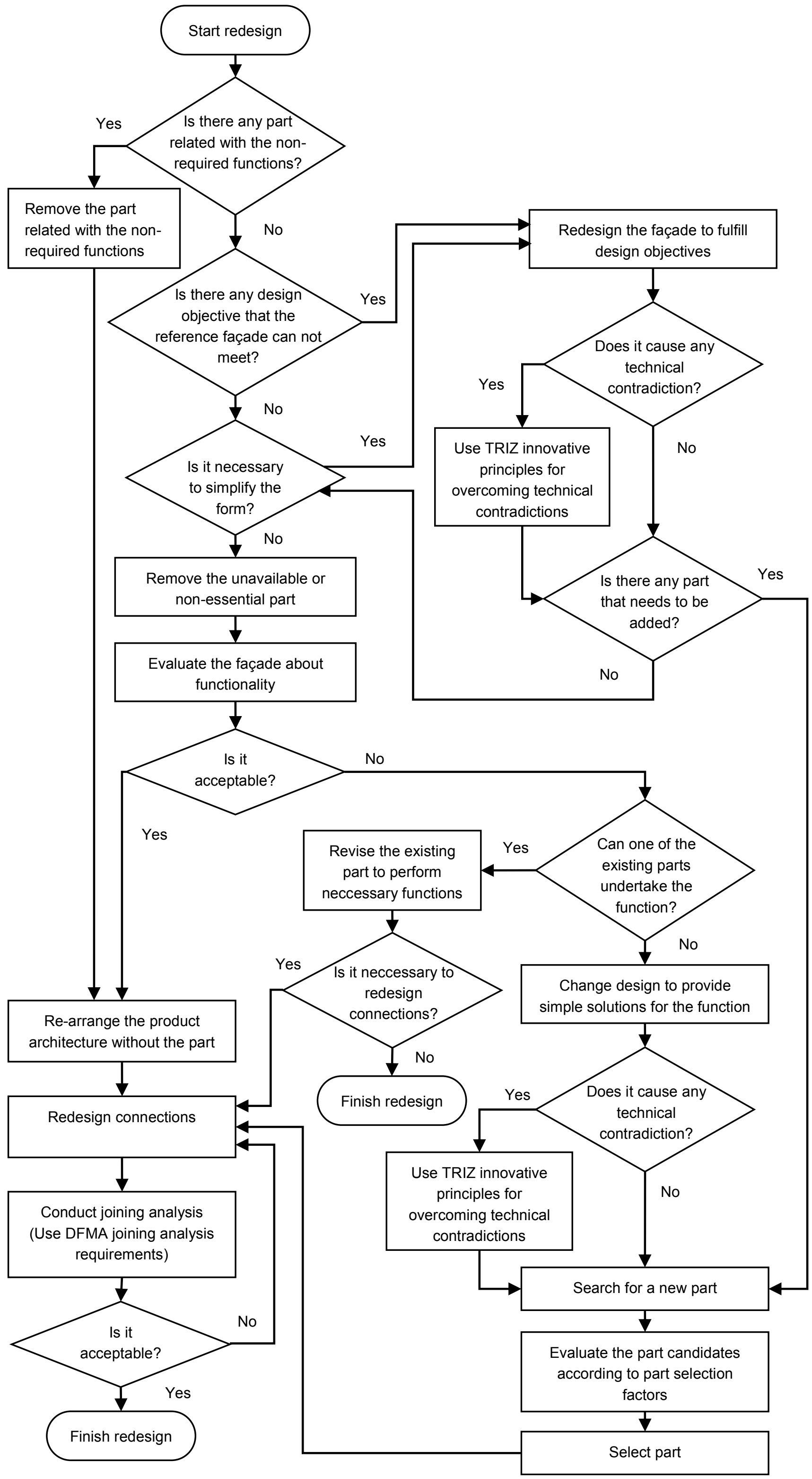


FIG. 9 Phase IV: Redesign of the reference façade, process flowchart

3.4 PHASE IV: REDESIGN OF THE REFERENCE FAÇADE

Redesign of a system is a special case of design activity, which includes not only choosing the parts, but also managing their connections, assigning functions, and reconfiguring the system. Parametric, adaptive, or original redesign solutions can be achieved according to the changes made in the reference façade. The redesign approach adopted in this research is based on the organisation of form, elimination, replacement or addition of parts, and reconfiguration, depending on the design objectives.

First, the parts that provide the functions that are not required depending on the function analysis are removed from the system. If there are functions that the reference façade does not provide, means of meeting these through use of existing parts are sought. The form is arranged to simplify the design. Contradictions encountered in the redesign are eliminated with TRIZ tools. New parts are identified as substitutes for those that cannot be supplied feasibly by current sources. Part selection factors, such as material properties, cost, and joinability, are used to evaluate candidates. Parts are checked for compatibility; their connections are designed and subjected to joining analysis according to DFMA joining analysis requirements, such as load bearing capacity, corrosion resistance, and maintainability. The flowchart showing the process steps is given in Fig. 9.

3.5 PHASE V: EVALUATION OF THE REDESIGNED FAÇADE

In this phase, the façade system obtained as a result of the redesign activities is evaluated in relation to the design objectives. A stepwise evaluation approach is performed. First, constructability evaluation and constructability index comparison are conducted. The constructability evaluation of the redesigned system is repeated with the same method used in Phase 3. The purpose is to clarify to what extent the constructability of the redesigned façade has changed in relation to specific constructability criteria. If the evaluation results do not meet the design objectives and a significant constructability improvement has not been achieved, redesign iterations are needed. If the constructability improvement is in the acceptable range and the scope of the changes requires the performance of the façade to be tested, then prototyping and performance testing processes are performed according to the test plan. The test plan gives a description of the test types to be performed and outlines when the test will be done. If the performance test results are acceptable, the detailed design is finalised, and documents related to production, assembly, transportation, and operation are fully prepared.

4 A CASE STUDY

Application of the redesign procedure is demonstrated through a case study. The actions performed in the process steps depending on the phases of the procedure are described in the following sections.

4.1 APPLICATION OF PHASE I: PLANNING

The aim of this phase is to determine the design objectives of the required façade system and, in this context, to select the most proper existing adaptive façade for redesign. For this purpose, it is recommended that the design objectives checklist be used for a comprehensive identification of the required façade. Since, in this case, the selection of the existing adaptive façade to be redesigned is not dependent on any particular project, the design objectives checklist is not needed in this phase. Instead, the existing adaptive façade selection is made on the basis of having access to design and production details of the façade that enables the redesign. In this context, the adaptive façade of the Training Academy, designed by Ackermann und Partner and located in Unterschleißheim, Germany, is selected as the reference façade for the case study (Fig. 10). It is assumed that the reference façade is to be redesigned for a project in Turkey, with consideration given to intellectual property rights. It is known that not all the design parameters of the reference façade are compatible with a project in Turkey. Even so, to simplify the redesign process, it is assumed that the environmental parameters and the design objectives remain the same for this case study. The focus of the redesign is using standard products and simplifying the system to improve the constructability of the reference façade in market conditions of Turkey.


a


b

FIG. 10 a) Front view and b) corridor view of the adaptive façade of the Training Academy in Unterschleißheim *(Schulungsgebäude in Unterschleißheim, 2018)*

4.2 APPLICATION OF PHASE II: DEFINITION OF THE REFERENCE FAÇADE

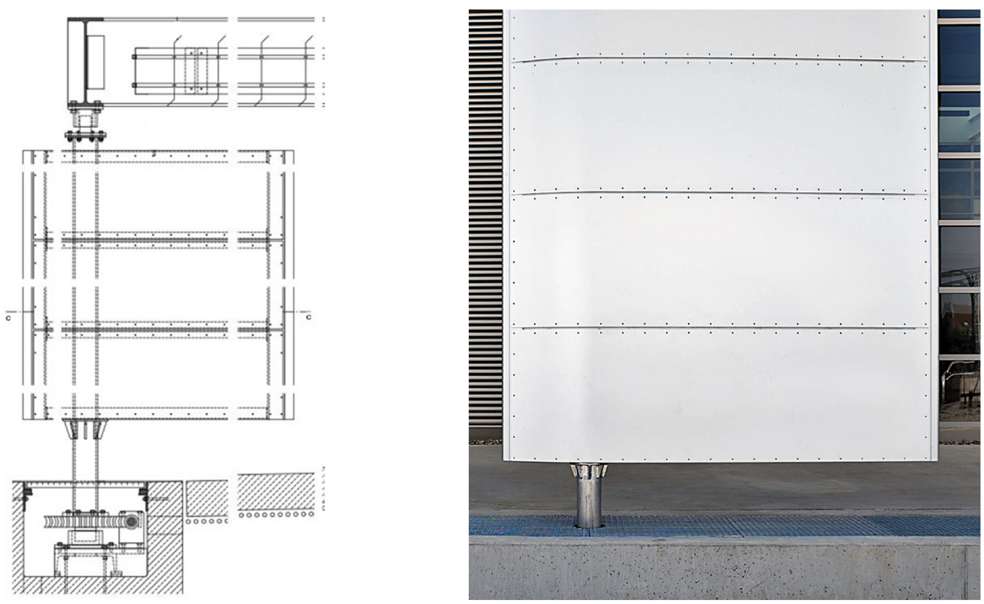
In this phase, the reference façade is defined by application of the process steps shown in Fig. 7, in terms of the data and details obtained from the literature (Schumacher, Schaeffer, & Vogt, 2010; Schittich, 2005) and the assumptions made based on them. As a first step, design objectives and constraints that are effective in the design of the reference façade are described. Here, the design objectives checklist is used to systematically present the data obtained from the literature and to provide a comprehensive description. In the checklist of 22 criteria, the reference façade is defined in the context of 9 criteria; those most relevant for redesign purposes are shown in Table 1. Following this, the characteristic features that define the change event performed by the adaptive façade are revealed based on the classification checklist. The simplified adaptive façade classification checklist, based on the characteristics of the reference façade, is given in Table 2. The details of the adaptive façade are compiled from the literature (Fig. 11 and 12).

CRITERIA	EXPLANATORY QUESTIONS	TRAINING ACADEMY
Environment	To which environmental influences is the façade subjected during the operation, manufacturing, storage, and transporta-tion?	Wind, temperature, vehicle vibration
Performance/ Functions	Which function(s) does the façade have to fulfil?	Be wide enough to allow the passage of vehicles, prevent solar gains, provide panel load support, and automatic movement according to position of sun
	By what parameters will the functional characteristics be assessed?	Dimensions, load capacity, movement capacity, solar shading
Size and Weight	What are the dimensions of the proposed façade panel?	h: 6.67m; w: 2.50m; d: 0.25m
	What is the weight of the proposed façade panel?	1000kg
	Does production, transport, or use process define limits in relation to the maximum dimensions or weight? Explain the poten-tial constraints.	Be wide enough to allow the passage of vehicles, be within the dimensions of road transfer, and must be lightweight.
Aesthetics, Appearance, and Finish	What are the aesthetic preferences? Should the façade fit in with an architectural style or concept?	Sail-like sunscreen panels
Social and Political Implications	Is there a social idea that the design should reflect?	Symbolic value: Sail-like sunscreens sym-bolize the technical mobility of the training academy and symbolize the dynamic mobility of the BMW Group.
Quantity	What is the size of the production?	43 units of sunscreen panel

TABLE 1 Design objectives related with the redesign of the reference façade

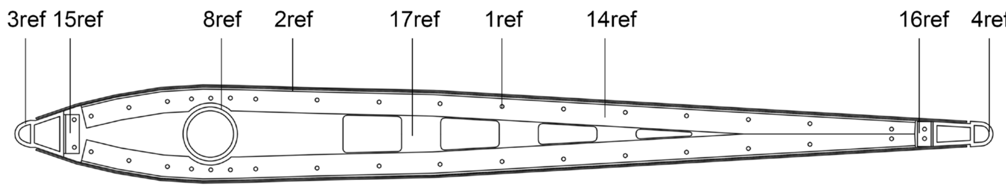
CLASSIFICATION CRITERIA	TRAINING ACADEMY ADAPTIVE FACADE CHARACTERISTICS
Elements of Adaptation	Sunscreen (Building component)
Spatial Morphology	Not integrated to the façade; outside of the façade plane
Agent of Adaptation	Individual inhabitants, exterior environment, solar radiation
Response to Adaptation Agent	Dynamic
Type of Movement	Rotation
Size of Spatial Adaptation	Metres
Limit of Motion	Inclusive (180 degrees on the vertical shaft)
Structural System for Dynamic Adaptation	Plate structure swivel around a vertical shaft
Type of Actuator	Motor-Based
Type of Control/Operation	Direct and indirect control
System Response Time	Seconds to minutes
System Degree of Adaptability	Hybrid
Level of Architectural Visibility (Rush Classification)	Visible, with location or orientation change
Effect of Adaptation	Prevent solar gains
Degree of Performance Alteration	Medium*
System Complexity	Level 2*
* These assessments are hypothetical; Level 2 describes relatively simple systems in the ordinal scale of 1-4	

TABLE 2 Presentation of the reference façade characteristics, which define the change event according to adaptive façade classification criteria.



a *b*

FIG. 11 a) Section drawing *(Schittich, 2005)* and b) partial view from the bottom of the reference façade sunscreen panel (*Schittich,2005; Schulungsgebäude in Unterschleißheim, 2018)*



1ref) Rivet | 4ref) Edge profile (B) | 15ref) T profile (B)
2ref) Aluminium sheet cladding | 8ref) Tube profile | 16ref) T profile (C)
3ref) Edge profile (A) | 14ref) T profile (A) | 17ref) Hollow rib

FIG. 12 Reference façade sunscreen panel cross section detail *(Adapted from Schittich, 2005)*
*Part numbers are linked with the BOM and 'ref' indicates the parts of the reference design.

Project Name:		Training Academy in Unterschleißheim									
Total Part Count:		1264									
				Dimensions (mm)							
Part No	Part Name	Quantity	Function	Width	Length	Height	Weight	Material	Manufacturing Process	Supplier	Unit Cost
A	Cladding Assembly										
1	Rivet	50x16	Join parts Allow damage free movement					Aluminium	Standard		
2	Aluminium sheet cladding	16	Provide sun shading	t:3	2400	83		Anodized Aluminium	Standard		
B	Edge Profile Assembly										
1	Rivet	32x2	Join parts Allow damage free movement					Aluminium	Standard		
3	Edge profile A	1	Create stiffness perpendicular to surface Prevent material deterioration	120	125	6670		Aluminium	Custom		
4	Edge profile B	1	Create stiffness perpendicular to surface Prevent material deterioration	65	155	6670		Aluminium	Custom		
C	Vertical Shaft Assembly										
5	Circular plate A	1	Allow joining of parts	Ø240 outer; Ø140 inner		10		Aluminium	Custom		
6	Circular plate B	1	Bear structural loads	Ø250 outer; Ø140 inner		10		Aluminium	Custom		
7	Triangular plate	8	Transfer load	t:9	45	100		Aluminium	Custom		
8	Tube profile	1	Bear structural loads Allow movement	Ø140 outer; Ø120 inner		7320		Aluminium	Standard		
D	Top And Bottom Rib Assembly										
1	Rivet	38x2	Join parts Allow damage free movement					Aluminium	Standard		
9	L profile A	2	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
10	L profile B	2	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
11	L profile C	2	Allow joining of parts Transfer load	40 (t:5)	100	100		Aluminium	Standard		
12	L profile D	2	Allow joining of parts Transfer load	40 (t:5)	50	100		Aluminium	Standard		
13	Solid rib	2	Bear structural loads Create stiffness perpendicular to surface	235	2215	t:5		Aluminium	Custom		
E	Mid Ribs Assembly										
1	Rivet	38x7	Join parts Allow damage free movement					Aluminium	Standard		
14	T profile A	2x7	Allow joining of parts Transfer load	60 (t:5)	2130	100		Aluminium	Custom		
15	T profile B	1x7	Allow joining of parts Transfer load	40 (t:5)	100	100		Aluminium	Standard		
16	T profile C	1x7	Allow joining of parts Transfer load	40 (t:5)	50	100		Aluminium	Standard		
17	Hollow rib	1x7	Bear structural loads Create stiffness perpendicular to surface	235	2215	t:5		Aluminium	Custom		

FIG. 13 The BOM of one sunscreen panel of the reference façade

After this point, the processes that the reference façade has passed, in reverse order from the installation at the construction site, are examined and the system is theoretically taken apart. Manufacturing and construction processes of the sunscreen panels are investigated with the experts and the necessary inputs, such as equipment and skilled labour, are determined. Accordingly, relatively simple equipment is needed in these processes, such as an aluminium welding machine, a rivet machine, and a low-capacity crane. The BOM of one sunscreen panel is created according to the BOM template and in the order of theoretical take-apart process (Fig. 13). With the information obtained from the previous process, the assembly diagram is created by defining the joints of the parts according to DIN 8593.

4.3 APPLICATION OF PHASE III: ANALYSIS OF THE REFERENCE FAÇADE

Based on the data compiled at the previous phase, constructability, availability, and function analysis of the reference façade is performed during this phase, to determine the redesign strategy and the parts to be focused on during redesign. The process flow is carried out according to the steps shown in Fig. 8.

First, the experts to evaluate the constructability of the reference façade, using the approach explained in Section 3.3, are chosen. Since the sunscreen panels are completely made from aluminium material, constructability evaluation is carried out by aluminium profile and façade manufacturers operating in Turkey who are engaged with aluminium processing and have sufficient knowledge about manufacturing and construction processes. As a result of the evaluation, it is stated that due to the sail-like form of sunscreen panels, materials need custom shaping, which complicates the production process. Furthermore, the assembly process gets complicated due to the excessive number of assembly parts. In this context, the constructability criteria on which to focus the redesign are chosen to be simplification and standardisation, in order to manufacture the system with readily available products in common sizes and configurations, and with the minimum number of parts for assembly. Thereafter, essential and non-essential parts are identified using the DFA functional analysis tool (Table 3).

ESSENTIAL PARTS	BOM Part Number	NON-ESSENTIAL PARTS	BOM Part Number
Aluminium sheet cladding	2	Rivets	1
Tube profile (base part)	8	Edge profiles (A, B)	3, 4
Solid ribs	13	Circular plates (A, B)	5, 6
Hollow ribs	17	Triangular plates	7
		L profiles (A, B, C, D)	9, 10, 11, 12
		T profiles (A, B, C)	14,15,16

TABLE 3 Essential and non-essential parts of the reference façade according to DFA functional analysis

Since the redesign aims to have the same functional characteristics as the reference façade, there are no unrequired functions, nor parts related to them. The availability assessment of the parts is done on an ordinal scale of 1-5, in the context of the answers given to the seven availability questions. The scale defines the cases in which 5 represents the highest, and 1 represents the lowest availability. According to the assessment made with the experts, this value is set at 3 (medium availability), since each part except the aluminium tube requires geometric configuration and custom shaping, and the complexity level of these processes are considered. Required equipment in the production, assembly, and installation processes are also available in Turkey's market conditions, but their cost should be considered.

As a result of the analysis carried out in this phase, the following redesign strategies are identified: (i) removal of non-essential parts from the system, (ii) replacement of parts, which cannot be removed from the system and require special shaping, with standard products, and (iii) simplification of the panel form.

4.4 APPLICATION OF PHASE IV: REDESIGN OF THE REFERENCE FAÇADE

In the redesign phase, the process given in Fig. 9 is repeatedly used and various alternatives are developed within the strategies determined during the analysis phase. The form of the sunscreen is rationalised in such a way that it would not cause a fundamental change at its functions. The form change also removes the necessity of custom shaping of the adjoining parts: T profile A, L profile A and B, which are identified in Fig. 13.

The next step after the form change is to remove unavailable or non-essential parts from the system. In this context, custom edge profiles are evaluated first. Without their functions, the system is not considered acceptable, and the functions could not be transferred to any of the existing parts. Therefore, standard products are sought to undertake the functions of these parts. Since they provide integrity of the frame and increase its strength by creating stiffness perpendicular to the surface, as well as protecting the edges of the aluminium sheet cladding from deterioration, proper products that could undertake both functions could not be found in the product catalogue survey. So, it is decided that the functions should be met by separate products. With this new point of view, another product catalogue survey is conducted, and this time suitable products are found. Since only one profile pair is considered feasible for replacement, product selection assessment is not needed. The function of preventing material deterioration is provided by a standard profile produced for use in another industry, and the function of creating stiffness perpendicular to the surface is provided by a standard U profile. Joining of these two profiles is provided by riveting. A joining analysis is performed according to the DFMA joining analysis criteria that are highlighted in the context of this detail, such as load bearing capacity, and the joining is found feasible. This constitutes the first redesign alternative and is detailed as shown in Fig. 14.

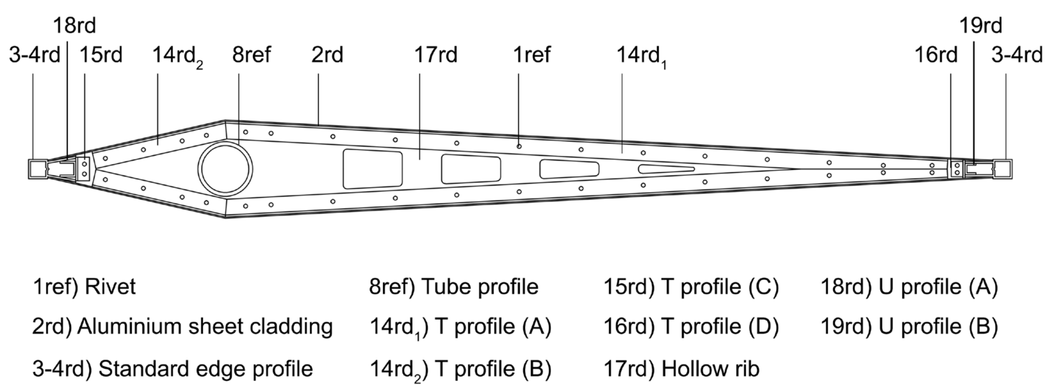


FIG. 14 Redesigned sunscreen panel cross section detail, alternative 1
*Part numbers are linked with the reference BOM, and "ref" indicates the unmodified parts of the reference façade and 'rd' indicates the replaced or modified parts of the redesign.

Furthermore, solutions are investigated to reduce the number of parts by transferring the assembly function of the T and L profiles to the ribs. Thus, all T and L-section aluminium profiles and the rivets which join them to the ribs could be eliminated from the system. In this context, three solution alternatives are developed: (i) welding aluminium plates to the rib, (ii) bending the edges of the rib to give a shape of L, and (iii) to obtain the T shape at the edges, replacing the original 5mm rib with two 2.5mm ribs which are bent in L form from their edges and riveted to each other. Consequently, the whole redesign process resulted in four redesign alternatives.

4.5 APPLICATION OF PHASE V: EVALUATION OF THE REDESIGNED FAÇADE

The four redesign alternatives that resulted from the redesign process are introduced into the evaluation process during this phase. It is assumed that there is no significant change in the adaptive performance of each alternative, since the movement mechanism, type of movement control, overall dimensions, and the aluminium sheet surface cladding of the sunscreen panels remain unchanged. With regard to the evaluations of the experts, it is revealed that modifying the ribs to undertake the assembly function is a promising idea in terms of reducing the number of parts and assembly steps; however, aluminium welding is not preferred over riveting in terms of application difficulty and cost. Furthermore, it is stated that the bending alternatives should be subject to some evaluations to determine their applicability, such as the complexity that the bending process will bring on the rib shaping and calculation of the changing load bearing capacities. As a result of these evaluations, only the first alternative, with form change and part replacement, is subjected to constructability evaluation. The capability of using products in common sizes and configurations, brought by the form change, and replacement of custom profiles with standard profiles, improved the simplification and standardisation scores of the system. On the other hand, number of parts and assembly steps of the system have increased, since the function of the custom profile is fulfilled by two standard profiles and they are joined by riveting. In this respect, the points taken from the use of a minimum number of parts criterion have been reduced. Nevertheless, the redesigned sunscreen panel has a higher constructability index than the reference design. It is also expected that the manufacturing costs are reduced by the redesign. Consequently, this redesign alternative does not require further evaluation such as performance testing. However, it is considered useful to develop alternatives to reduce the number of the parts.

5 CONCLUSION

Despite their high environmental performance, practical application of adaptive façades is very limited. The majority of the current examples are developed by engineer-to-order design processes, as project-oriented, custom, and complex solutions. Even though its translation into a ready-for-market product is very challenging, this is still considered to be a very promising idea. As a starting point, simple, flexible, and easily accessible solutions are needed to increase the feasibility of adaptive façades. One of these solutions is to simplify the design of adaptive façades using engineered standard products with the least number of parts and layers. In this context, this paper aimed to develop a design procedure to support designing adaptive façades with standard products to improve constructability through simplification.

The research starts by generating concepts for designing adaptive façades to be manufactured using standard products. Among several concepts, 'redesigning dynamic adaptive façades' is selected for further investigation, in terms of solution goals determined for this research. A preliminary case study is conducted without a systematic method to redesign an adaptive façade to be manufactured with standard products. The steps of the redesign process are captured and analysed, and the aspects that need improvement are revealed. To systematise and improve the captured design process, façade design, product design, product redesign, systematic problem-solving, and design improvement methods are analysed and adapted to the adaptive façade redesign process. Thus, a redesign procedure is generated by the combined application of DFMA and TRIZ in the synthesis of reverse engineering and redesign processes.

Subsequent to the procedure development, its application is tested through a case study. Each phase is evaluated separately in terms of functionality and ease of application. Determining the factors, namely the design objectives, affecting the decisions of façade design of the developing architectural project in Phase I, enables a comparison with the design objectives of the existing façades. This makes it possible to recognise the possible contradictions in the first stage of redesign and to take precautions against them. It is also useful for selecting the most proper existing adaptive façade as a reference façade for redesign. Furthermore, redesign can be misleading without an extensive understanding of the reference façade. Phase II and III provide an extensive analysis of the reference façade and become vital in making the right redesign decisions. The checklists, templates, and evaluation criteria given in the procedure ease its application. In general, the process steps are well described and can be easily followed except for some cases described below. Among them, the application of Phase IV, the redesign, is relatively complicated as it requires multiple iterations to achieve a reasonable solution. Nevertheless, the several redesign alternatives that followed as an outcome of the case study have demonstrated that it is applicable and useful from this point of view. Phase V provides a framework for evaluation of the redesign. Its stepwise evaluation approach avoids unnecessary workload. The case study has resulted in a redesign which has a higher constructability index and a higher potential for feasible manufacturing in Turkey's construction market compared to the reference façade. In this context, the use of the procedure has yielded positive results.

The redesign procedure is both product and process focused, representing a structured approach to manufacturing adaptive façades with standard products. It supports the improvement of constructability through system simplification. It is proposed that it be used by the designer responsible for the adaptive façade design, with experts who have a comprehensive knowledge on required subjects, such as materials, production techniques, and local market conditions. It is sequential in theory; each phase produces input for the next. However, multiple iterations within and between the phases may be needed to achieve the best solution. Although it is assumed that such systematic methods could restrict creativity and innovation, it is a case-based approach, and use of the procedure may also provoke thought by imposing actions that the designers had not previously conceived. Furthermore, the procedure is suitable for expansion. It can accommodate additional tools for design analysis to support unforeseen design objectives. It can also be utilised for original adaptive façade design after determining the product architecture, to analyse and improve the design for manufacturing.

Besides all the promising features, the procedure has some limitations. The quality of the redesigned adaptive façade cannot be isolated from the reference façade, nor from the level of expertise of the designers using the procedure. Therefore, the right choice of experts and reference façade has a great impact on the quality of the redesign. Although redesign is a widely used method in product design, its practical application in adaptive façade design is currently limited due to the lack of detailed information about existing adaptive façades. In addition, the intellectual property rights of the reference façade must be considered in the redesign. Moreover, the absence of product databases makes it difficult to select products in a controlled way, which in turn affects the connection design and can give rise to extra design iterations.

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