Title:
Optimized Development: Defining Design Rules through Product Optimization Techniques

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Keywords:
Optimization, Configuration, Refrigerator, Embodiment design

DOI: 10.14733/cadconfP.2015.159-163

Introduction:
The importance of automation and optimization in the design and the production processes of an industrial product is increasing, especially with regards to resources consumption and product quality. Optimization strategies can play a fundamental role during product design, by allowing the designer to study a greater number of product configurations and reach an optimal result with an automated process.

Parametric optimization is currently used mainly as the last step of product development; detailed design. Once the embodiment [1] of the product has been defined, optimization algorithms can enhance its performance by finding the most favorable product configuration. By modifying detailed parameters, without changing the general embodiment, optimization can optimize trade-offs, like energy-saving vs. costs, without ever solving them. In fact, such trade-offs are frequently highlighted by the product final optimization, when it's sadly too late in the product development to tackle them.

This paper proposes a methodology based on design optimization that can help designers and engineers from the first steps of the embodiment design of the products. By parameterizing the product through the implementation of mathematical and numerical models, the procedure allows to detect trends and behaviors that can guide the designers through the first stages of product development, by defining the important product variables and highlighting the inherent performance trade-offs. This set of results can enhance the importance of the traditional optimization technique, making it an integrating part of the design process, rather than the last step of product development.

The procedure has been tested on two exemplary case studies pertaining to food product refrigeration: a refrigerated display unit and a cabinet shelf.

Main idea:
The proposed methodology aims at defining a set of product-specific design rules that will guide the designer during the early stages of product development. In order to achieve such a goal, we aim at describing the product design space through the integration of a set of design evaluation and analysis tools: parametric optimization, DoE analysis, clustering analysis, and MCDM/penalty function algorithms. Design rules are then formulated based on how the product mathematical model responds to each design variable.

The procedure comprises four main steps (Fig. 1): (a) pre-processing, the parameterization of the product and its performance criteria; (b) processing, the appraisal of the design space through both optimization and factorial algorithms; (c) post-processing, a set of analysis tools aimed at refining the results of the processing phase, and (d) results evaluation, a critical review of the previous outputs to determine a set of design guidelines. Each phase is described in the following subsections.

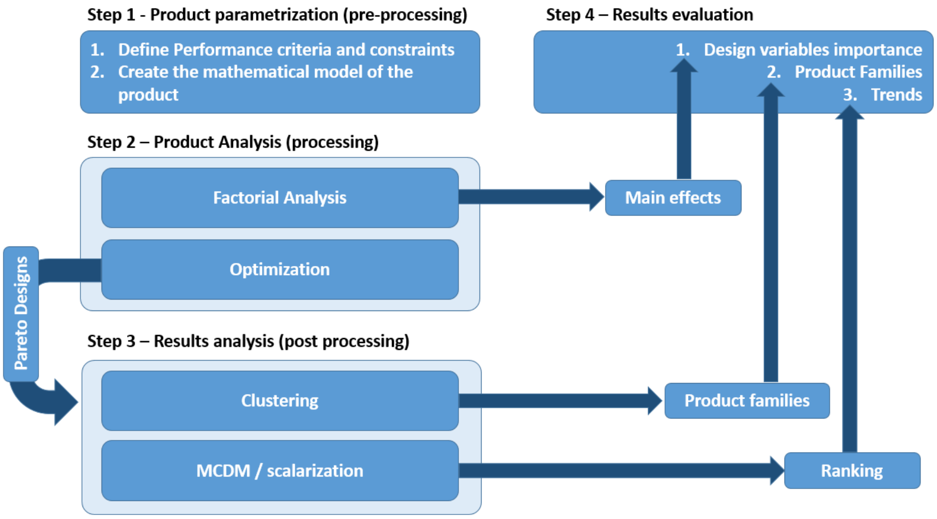

Fig. 1: Steps of the optimization methodology.

Pre-processing

Pre-processing is an essential step in any product simulation. Its goal is to mathematically describe the product performance and constraints, through a set of analytical or numerical equations [2]. It can entail a numerical model such as FEA, CFD, CAM, and any other form of CAE required determining the product characteristics. However, the model should be repeatable and consistent across the entire design space. The product performance and constraints are a function of a set of variables of finite range. For instance, the compliance of a beam is a function of its length, which may vary between a lower and a higher boundary; the compliance may be either a product performance criterion to be maximized, or a product constraint that must meet a certain value range. Defining a product performance, constraints, and design variables is a key step of the methodology [3], [4]. Only key variables should be included in the analysis, as best results are achieved with a low number of design parameters.

Processing

The processing phase is the most automated step of the procedure. Its aim is to produce a consistent number of factorial and optimal designs, through the use of standard factorial and optimization algorithms, to populate the product design space.

Post-processing

Post-processing is a further enhancement of the previous step results, to highlight possible trends that may provide useful design guidelines. The main tools of the post-processing phase are:

- DoE main effects. Main effects quantify the relative influence of each design variable (Fig. 2). Their main function is to provide the means to focus on the important parameters, and eliminate ineffective parameters, thus reducing the number of design variables. For the proposed procedure, main effects also allow to weight the relative importance of the eventual design rules upon the importance of the involved variables. Main effects are determined on the results of the factorial DoE designs.
- Clustering analysis (Fig. 3). Clustering analysis [5] is applied to the Pareto designs of the parametric optimization results. Its main function is to determine product families of similar performance. This grants the designer a first qualitative assessment of the correlation between design variables and performance criteria.

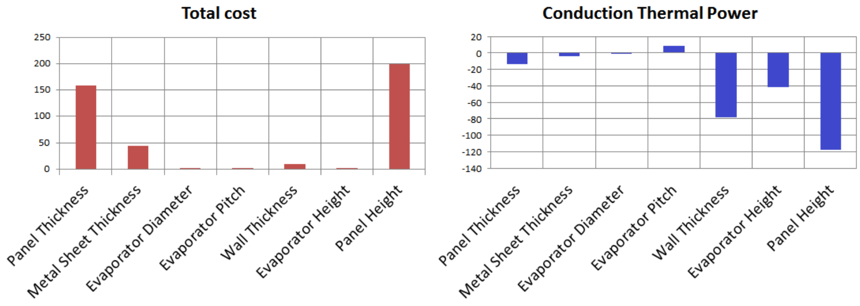

Fig. 2: Influence chart of Input vs. Output.

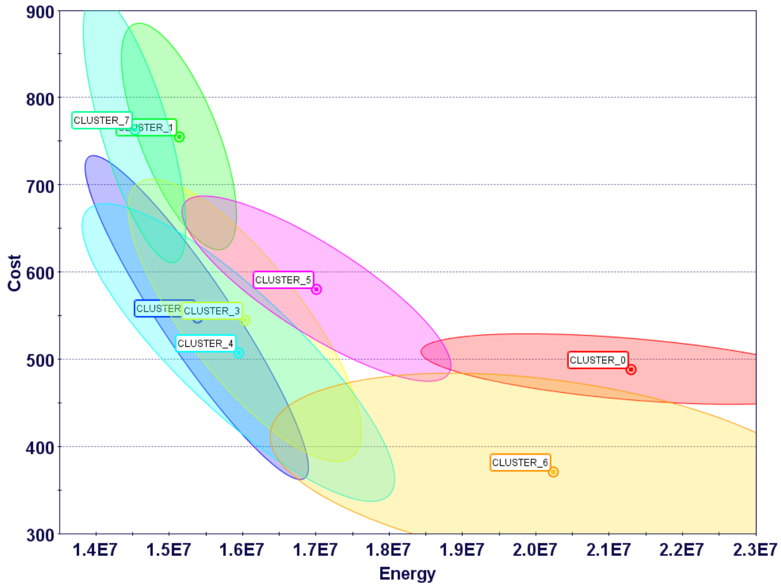

Fig. 3: Cluster analysis of the optimization results.

- MCDM/penalty function. Multi Criteria Decision Making, or a penalty function algorithm, can be applied to the Pareto designs of the parametric optimization results, in order to reduce the number of design objectives (performance criteria) to a single value. This allows a ranking of the optimal designs, from best to worst.

Results evaluation

Design guidelines are defined by studying the previous step results. Trends are extracted by choosing a subset of the highest-ranking designs from the MCDM/penalty function analysis. Trends take the form of a direct relationship between the ranking and each design variable: e.g. *increasing variable (a) results in a higher ranking*, or *variable (b) has an optimal value around 50% of its range*. Further trends can be determined on multiple performance criteria by studying the Pareto designs of the optimization and the clustering results. Trends take the form of a direct relationship between the product performance indicator (ranking) and each design variable: e.g., *increasing variable (a) results in a higher performance*; *variable (b) has an optimal value around 50% of its range*. This might seem trivial results, but they are not so intuitive when combining multiple objectives in a single performance indicator. Trends can also take the form of a comparison between variables: e.g., *variable (b) has the most beneficial effect on product performance.*

Trends are then combined to create guidelines for further product development. Guidelines describe the characteristics of the optimal product and highlight important trade-offs that the designer will have to optimize or resolve. This is by no means the final step of product development, but rather the starting point. With the guidelines is possible to identify direction of design in terms certain layout of insulation, for example identification of wall thickness range with a condenser that covers all the refrigerator surface, or the location of insulation panels with respect to the location of the heat exchangers. These guidelines will guide the designer during the development process, by highlighting the hotspots of the design effort, and removing any previous misconception which might have led the designer astray.

Case Studies:

The proposed methodology was tested during a research program on commercial food refrigeration cabinets: a closed refrigerated display unit and a cabinet shelf. The research project aims at studying a limited set of product configurations in order to define the most promising areas of further development. Additionally, the project aims at: studying the influence of a limited set of product specific parameters on the overall performance, defining regions of overlapping technology, and detailing a set of design rules based on the results of a product optimization.

Both studies entailed the development of a dedicated mathematical model, to simulate the thermal exchange and determine power consumption and operational cost. The cabinet performance has been assessed through four objectives: the energy consumption of the cabinet; the material cost of the cabinet; the Total Display Area (TDA) of the cabinet; the Total Display Volume (TDV) of the cabinet. Performance constraints concern food products temperatures, which may not rise over a certain value across the entire cabinet.

In order to identify trends for product development, the proposed methodology needs a ranking of all Pareto designs across the range of performance criteria. In order to achieve this, following the product optimization the four performance criteria were reduced to a single objective: operational cost. The operational cost was defined as the cost of running the cabinet for a period of three years (material cost and energy consumption), minus the economic benefit of a higher TDA and TDV. It was then possible to rank the Pareto designs and select the top 100. The best 100 designs in operational cost have been studied in detail to define a set of design rules, based on the results of the product optimization.

By studying the best results, it was possible to define a set of twelve design guidelines and rules that enable the minimization of the operational cost over a three-year running period. These design guidelines target each optimization variable, as well as the overall product. For example, two values of optimal airflow of about 0.05 kg/s, and a mid-range value of 0.11 kg/s. Regression lines don't show a clear benefit for either value, which indicates that it should be possible to build two different product configurations of similar performance. Choosing either airflow value, in fact, will result in a different set of values for the remaining optimization variables. The resulting guideline is: *Two distinct air flow values were found to be optimal. Each configuration should be studied in detail before choosing the nominal airflow rate.*

In a similar way, a set of guidelines was defined for the second case study, the refrigerated cabinet shelf, providing trends and design rules in terms of the layout of the insulating material, and the use of special insulation panels. The analysis also highlighted the relation between the height of the evaporator and the shape of the condenser; allowed to identify a correct universal thickness for the special insulating panels; and provided important clues for the shape of the condenser. These guidelines can help the designer during the embodiment phase of product design, by focusing the development effort on critical areas, and highlighting possible trade-offs and unexplored configurations.

Conclusions:

The proposed methodology, called *Optimized Development*, aims at using optimization techniques as one of the first tools of product development, applicable during the embodiment phase. By describing the design space through a finite set of optimal and factorial configurations, and by using statistical, clustering, and multi-criteria tools, the proposed procedure can describe the characteristics of a product, which has yet to be thoroughly defined. The output is a set of design

Proceedings of CAD'15, London, UK, June 22-25, 2015, 159-163

guidelines that describe the design challenges at an early stage, when there is still time to address trade-offs, and, possibly, resolve them before the final, and more classical, product optimization. The methodology should not be viewed as an alternative to the standard step of product optimization, but rather as a complementary phase, with a broader scope, aimed at studying the relationship between product performance and design variables.

The approach has been tested on two kinds of refrigerators for commercial exposition. Results show the feasibility and benefit of applying *Optimized Development* from the early stages of product development. On the other hand, the main limit of the methodology is the need of parameterizing the product, which binds the analysis to the choice of parameters.

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