INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

REDEFINING PRODUCT FAMILY DESIGN FOR ADDITIVE MANUFACTURING

Lei, Ningrong (1); Moon, Seung Ki (1); Rosen, David W. (2)
1: Nanyang Technological University, Singapore; 2: Georgia Institute of Technology, United States of America

Abstract

The paper highlights the opportunities for Additive Manufacturing (AM) based product family design to operate in a much broader design space that is free from constraints which arise in traditional product family designs from finding a compromise between commonality and performance. The proposed method starts by establishing design requirements and defining the customization space. Subsequently a utility-based objective function is employed to optimize individual products for multiple objectives. The final step identifies potential commonalities that can be exploited in order to reduce the manufacturing cost. We incorporate an AM cost model into the product family design process and to explore the effects of eliminating the commonality requirement. To show the feasibility of the method, a family of finger pumps is investigated. The results show a significant performance improvement when compared to conventional product family design methods. The results also show that, with the advantages of AM, the customization cost is consistently low. These results provide confidence that the proposed method yields affordable customization without compromising individual product performances.

Keywords: Optimisation, Product modelling, Product families, Additive manufacturing, Decision making

Contact:
Prof. Seung Ki Moon
Nanyang Technological University
School of Mechanical and Aerospace Engineering
Singapore
skmoon@ntu.edu.sg

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Many enterprises use product family design strategies to increase product customization and to reduce time-to-market while keeping the cost under control (Jiao et al., 2005). The design of platforms, within a product family, enables manufacturers to maintain the economic benefits of having common parts and processes while still being able to offer variety to customers (Thevenot and Simpson, 2006). Conventional product family optimization focuses on exploiting the commonality between individual products (Moon et al., 2010). The fundamental assumption is that common components are less cost intensive than distinctive ones (Silva and Alves, 2006). Hence, harvesting the benefits of product family design means to identify features and functions that can be shared amongst products. However, product family design compromises on which customer needs are satisfied. To rectify this shortcoming requires a move away from mass customization to individualization.

Additive Manufacturing (AM) is a manufacturing resource that produces shaped parts by gradual creation or addition of solid material. This is fundamentally different from traditional forming and material removal manufacturing techniques (Kruth et al., 1998). The main benefit of AM is the ability to manufacture parts of virtually any geometric complexity without the need for tooling. With the beneficial properties, changes to product family variant geometries, be they subtle or substantial, may be applied without the need to incur the delays and costs of producing new tooling, significantly reducing costs in the early stage of product development. Hopkinson and Dickens (2003) pointed out that AM has significant advantages for low volume production over traditional manufacturing technologies. We predict that AM can pave the way to mass individualization and thereby remedy the shortcomings of product family design.

This paper highlights the opportunities for AM based product family design to operate in a much broader design space that is free from constraints which arise in traditional product family designs from finding a compromise between commonality and performance of products. A family of positive displacement finger pumps is investigated that are candidates for meeting growing needs of home-based and portable medical devices, where small size, energy efficiency and low cost are critical requirements. The product family design problem is reformulated with broader ranges of design variables and no requirements for commonality. The problem is solved using a utility-based optimization method for each product variant, since commonality is no longer required. The product family is assumed to be manufactured using AM, with a suitable cost model and objective, so that they can be designed for individual needs or applications. This product family is motivated specifically by the need for new types of haemodialysis systems, but has broader applications to other devices.

The rest of the paper is organized as follows: Section 2 gives a review of product family design methods and advanced AM technologies. Section 3 introduces the proposed optimization method. Section 4 discusses the case study that is used to test the proposed method. Conclusions and further work are presented in Section 5.

2 LITERATURE REVIEW

For the last 50 years, product families and platform-based design strategies have received significant attention from both academia and industry. Thevenot and Simpson (2006) developed a product variety trade-off evaluation method which helps designers to resolve the trade-off between platform commonality and individual product performance within a product family. Jiao and Tseng (1999) developed a product family architecture model that handles the trade-offs between diverse customer requirements, design reusability and process capabilities. Martin and Ishii (2002) introduced a design for variety method that includes generational variety and coupling indices, to help reduce the design effort and time-to-market for products in a family. For these existing methods, platform variables are either common to all products in the family or not shared at all. This might result in over designed lower end products, and under designed high end products. To overcome this limitation, Hernandez et al. (2003) proposed the Product Platform Constructal Theory Method (PPCTM), which enables a designer to develop platforms for customizable products while handling issues of multiple levels of commonality, multiple product specifications, and the inherent trade-offs between platform extent and performance. The method was further extended by Williams et al. (2011) to enable designers to systematically manage modularity and commonality in both product and process platforms design. Hume (2013) further evolved the PPCTM by incorporating sensitivity analysis, and demonstrated the method's application to a finger pump family.

Common to all this research is the realization that a successful product platform must balance performance and commonality of individual products in the family. However, performance and commonality are two conflicting objectives, a sharing platform for all products in the family means to establish a compromise which resolves the conflict. Furthermore, product variety induced manufacturing complexity has become a significant problem (Wang et al., 2011). Offering affordable customization is the foremost difficulty that enterprises face when they follow the product family design paradigm. Most of the product family design literature focuses on methodologies that optimize processes in the traditional manufacturing technology context. However, new technology, especially new manufacturing technology, can be a game changer.

In AM processes, parts are fabricated by adding material in a layer-by-layer manner. Some common AM processes include stereolithography (SL), fused deposition modelling (FDM), selective laser sintering (SLS) and 3D printing (3DP). Reviews of numerous AM technologies were performed in previous works (Gibson et al., 2010; Hopkinson et al., 2006). With the unique capabilities for fabricating components with high complexity in shape, function, and material, AM technologies have greatly increased design freedom in product development. Over the past two decades, the research community has developed novel AM processes and applied them in aerospace (Thomas et al., 1996 Feb, Moon et al., 2014), automotive (Ding, 2004) and biomedical (Rengier et al., 2010) fields. The main benefit of AM is the ability to manufacture parts of virtually any geometric complexity without the need for tooling. The beneficial properties of AM can be used to add value by customizing selected features in product family design (Lei et al., 2013). Hague et al. (2004) predicted that AM will have a profound influence on product family processes. Hence, AM enables new design concepts and models.

3 METHODOLOGY

We introduce a utility-based product family design method with AM realization. AM provides affordable customization, eliminating design trade-offs between product performance and cost. A key assumption in product family design is that increased standardization leads to reduced cost, while increased variety requires significant cost increases. This assumption is no longer valid when AM is used to manufacture components in a product family. A formulation for a scalable product family design problem is presented in this section, along with a design method that assumes AM is used for mechanical part fabrication.

3.1 Product family design method

The proposed method incorporates AM technologies into product family design and is a variant of other methods for the design of a scalable product family (Jose and Tollenaere, 2005). The idea of a scalable product family is that the platform is adjustable by changing values of dimensions or other parameters to adjust the sizes of components in the platform. This is in contrast to modular product families or platforms where modules are swapped in order to generate variety.

As shown in Figure 1, the method starts with the designer defining the primary requirements for the product family. For the example in this paper, 10 flow rates are the requirements for a family of pumps that is to be designed. In the second step, the customization space is defined by identifying the design variables and their ranges, which include the scaling variables. Also, market demand is estimated for the product family members. The subsequent step optimizes individual products to best achieve the requirements, subject to designer preferences. The final stage identifies potential commonalities that we can exploit in order to reduce the product family development cost further.

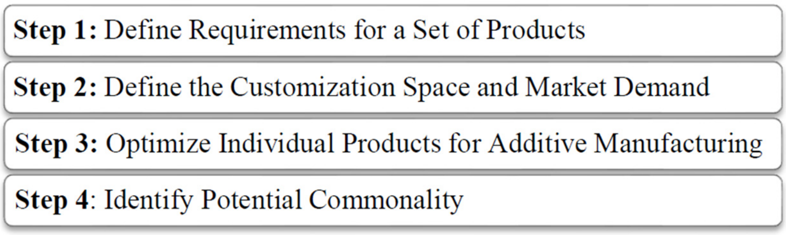

Figure 1. Four-step product family design method for additive manufacturing

3.2 Define the customization space and market demand

Based on the requirements that distinguish members of the product family, the designer identifies a set of scaling variables (i.e., dimensions or other parameters) that control the size and performance of products in the family. These become some of the design variables, x_{ij}, that are adjusted to generate the family. Goals are identified that represent objectives to be achieved, and are functions of the design variables. Hard constraints are also identified. Bounds on the variables are defined in order to identify the extent of the customization design space. An objective function of the goals is formulated; in this work, a utility-based formulation is used so that the objective is to maximize expected utility, which is equivalent to minimizing the difference between 1 (the maximum expected utility) and the expected utility of the product family.

3.3 Optimize individual products for additive manufacturing

A generic scaling problem formulation for product family design is shown in Figure 2, that is based on the discussion above. N members of the product family are assumed, with one or more requirements defining these family members. The set of design variables, which include the scaling variables, is denoted x_{ij}, where i indexes over the variables and j indexes over the N family members. Goals and constraints are functions of the x_{ij} and model soft, respectively hard, constraints. The bounds on the design variables indicate the extent of customization that can be achieved in the product family. Consistent with the utility-based model of designer preferences, each goal is modelled using a utility function, u_{kj}, where k indexes over the goals. Then, the objective function is formulated as a weighted sum of the goal utility functions, where the w_{kj} are the designer specified weights.
In this paper, the product family design problem is solved using exhaustive search.

Given:	Parametric scaling variables Requirements that define the individuals in the product family, N is number of individuals An appropriate mathematical model User preferences for objectives (if needed)	
Find:	The values of the design and scaling variables, x_{ij}	
Satisfy:	Goals:	u_{kj}, Defined by designer (e.g., design limits, cost, efficiency)
	Constraints:	Defined by designer (e.g. failure criteria, design limits, cost)
	Bounds:	$x_{ij,min} \leq x_{ij} \leq x_{ij,max}$
Minimize:	The objective function $Z_k = 1 - U_k = 1 - \sum w_{kj} u_{kj}$	

Figure 2. Formulation of the utility-based product family design problem

3.4 AM cost model formulation

We assume that the product family designs will be fabricated using the polymer powder bed fusion (also known as Selective Laser Sintering (SLS)) process. Though the cost estimation used in this research is based on the SLS process, it is general for most any AM techniques (Gibson et al., 2010). It can be broken down into machine purchase (*P*), machine operation (*O*), material (*M*) and labour (*L*) costs, as is expressed with the following formula:

$$C = P + O + M + L \tag{1}$$

We assume that there are n variants in the product family. To simplify the cost model, we assume that each SLS build consists of copies of a single variant. Once the cost of each build, $\mathrm{C_{B_i}}$, is found, the cost of the single part, $\mathrm{C_{P_i}}$, can be calculated as the entire cost of the build divided by the number of the parts, N_i, in each build.
The purchase price for one build is defined as:

$$P = \frac{\mathrm{PurchasePrice} \times T_B}{\mathrm{Uptime} \times 24 \times 365 \times \mathrm{Year}} \tag{2}$$

where PurchasePrice is the machine cost in dollars, T_B is the time for the build in hours, Year is the life span of the machine, and Uptime represents the machine utilization rate.

The operation cost per part, O, is defined as the cost of running the machine during the build time, which is a function of utility costs and overhead:

$$O = T_B \times C_o \tag{3}$$

The operation cost is the cost that relates to machine maintenance, utility costs, cost of factory floor space, and company overhead. C_o is the operation cost rate.
Material cost (M) is given by:

$$M = (V_B + W_B) \times \rho \times C_m \tag{4}$$

$$W_B = (1 - \sigma) \times (V_{bed} - V_B) \tag{5}$$

where V_B is the volume of the entire build, sum of the N parts with volume (V_P) include in the build; W_B is the material volume wasted per build; ρ is the material mass density; C_m is the material cost per kg, PL_x, PL_y , and PL_z are the size of the platform in x, y, and z dimensions; V_{bed} is the volume of the build platform that is express by PL_x, PL_y , and PL_z; $\sigma \in [0,1]$ is the recycle factor, depending on the manufacture. In this case, we assume $\sigma = 0.8$.
Labor cost is related to the time T_l required for technicians to set up the build, remove fabricated parts, clean the parts, and get the machine ready for the next build.

$$L = \frac{\text{TechSalary} \times T_l}{\text{Annualworkh}} \tag{6}$$

where TechSalary is the technician salary per year and Annualworkh represents the annual work hours.

3.5 Build time model

The time required to fabricate the parts is an important factor which influences the operation cost. The manufacturing time per build can be expressed as the sum of scan or deposition time (T_{xy}), recoat time (T_z), and delay time (T_d). We adapted the time functions from Ruffo et al. (2006). The total manufacturing time T_B is calculated as:

$$T_B = T_{xy} + T_z + T_d \tag{7}$$

To determine material deposition time the part layout is crucial. In this scenario, we assume that parts are of similar size and they are laid out in a rectangular grid from left to right and top to bottom based on their bounding box sizes. The bounding box V_{bb} is the minimum geometrical box that contains a part. bb_x, bb_y, and bb_z are the bounding box in x, y, and z dimensions respectively. In addition, x, y, and z dimension gaps as well as edge gaps, are defined to ensure that parts do not touch or get too close to the edges: g_x, g_y, g_z, and g_e respectively (defined in mm). The number of parts that can fit in x, y and z directions are N_x, N_y and N_z respectively. The maximum number of parts in each build can be computed as in Equation (8):

$$N = N_x \times N_y \times N_z = \left(\frac{PL_x + g_x - 2g_e}{bb_x + g_x}\right)\left(\frac{PL_y + g_y - 2g_e}{bb_y + g_y}\right)\left(\frac{PL_z + g_z - 2g_e}{bb_z + g_z}\right) \tag{8}$$

The recoating time T_z is linear to total height of the packing layers ($bb_z \times N_z$). It is expressed as follow:

$$T_z = (180 - 120 \times \delta) \times bb_z \times N_z + 400 \tag{9}$$

where $\delta \in [0,1]$ is the packing ratio, that is defined as the ratio between V_B and V_{bed}.
The deposition time T_{xy} can be approximated by Equation (10) (Ruffo et al., 2006). It is based on the time to scan the entire bounding box reduced by a density factor $\vartheta \in [0,1]$.

$$T_{xy} = \vartheta \times T_{bb_{xy}} \tag{10}$$

$$T_{bb_{xy}} = (0.042 \times (bb_x \times N_x)^{-0.1809} \times bb_x \times bb_y) \times bb_z \times N \tag{11}$$

$$\vartheta = \begin{cases} 0.3422 \times \tau^2 + 0.2468 \times \tau + 0.45 & \text{if } \tau < 0.4 \\ 0.417 \times e^{0.9283 \times \tau} & \text{if } \tau > 0.4 \end{cases} \tag{12}$$

where $T_{bb_{xy}}$ is the time to scan all the bounding box layers in the build. τ is the compact ratio, and is defined as the ratio between the volume of the part, V_P, and the volume of its bounding box, V_{bb}.
Many processes have delays built into their operations. The values of these delays are constant and they are set up by an operator. According to the 3D systems recommendation, T_d is set up as 60 min.
The methodology used in this paper is general and open to any additive manufacturing technique, although the particular case studied here regards an SLS machine.

4 CASE STUDY

4.1 Motivation

End stage renal disease (ESRD), commonly known as kidney failure, is a significant medical problem (Hsu et al. 2004). With a continuing year-to-year increase over a quarter-century, more than 738,000 patients were diagnosed with ESRD in 2012 (U.S. Renal Data System, 2012). Over 560,000 patients depend on treatments in dedicated dialysis centres for three to five hours, usually three times a week. Even with dialysis treatment, patients still suffer from accelerated cardiovascular disease and infections. Hence, technology to miniaturize and automate home dialysis is necessary to offer extended daily dialysis to most dialysis patients. Recent reports estimate that the size of the home market is 7% of the haemodialysis market and 35-52% of current patients qualify for home treatment (U.S. Renal Data System, 2012). This translates to 10,000 patients with home haemodialysis devices in 2012 and growing to over 14,000 by 2017.
To address the demand for portable home haemodialysis devices, initial investigations demonstrated that substantial improvements in pump size and efficiency were possible (Hume, 2013, Kang et al., 2011). The finger pump maintains the benefits of traditional positive displacement roller pumps (i.e., no fluid contamination) with the added benefits of higher efficiency and smaller size compared to pumps with a similar flow rate, as well as a reduction in clotting when pumping biological fluids. A CAD model of the pump design is shown in Figure 3. Two rows of fingers are utilized in the pump, where one row is used to pump blood, while the other pumps dialysate. The displacement pattern of the fingers is controlled by a camshaft that is driven by an electric motor through a gear train.

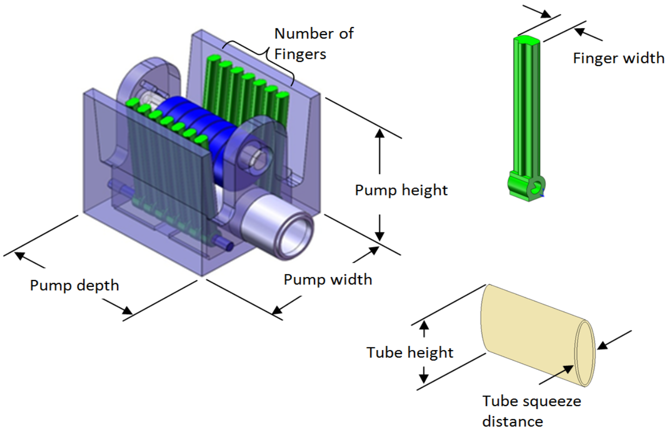

Figure 3. Finger pump design and design parameters (Courtesy, Kang, J (2011))

Apart from haemodialysis, this technology, and its benefits, can be utilized in many other applications where roller pumps are currently used; however, each application will require a different flow rate and hence additional design work is necessary. The finger pump consists of five design variables, which are the scaling variables: t_w, t_h, f_w, n_f, v. The pump width, depth, and height dimensions are variables that depend on these five design variables. Our method integrates AM cost analysis into the product family optimization process. The research results are compared to those from Hume. For the pump, the assembly consisting of the housing, fingers, and camshaft will be fabricated using SLS process with Duraform or other nylon material. The following sections describe the details of the proposed method.

4.2 Define the requirements, customization space and market demand

As described in Section 3.2, the space of customization is defined by three components: specifying the variety to be offered, determining the range of variety to be offered, and analysing the market. For simplicity, variety will be offered for only one design specification, namely pump flow rate. This represents a one dimensional customization space. With such a design space, a manufacturer can offer a continuous range of flow rates from 100 ml/min to 600 ml/min. Demand modelling is selected to be a uniform distribution of 10,000 products across the space.

4.3 Formulate the objective functions

The design goal is to maximize the overall performance and minimize the manufacturing cost within the product family. The performance is characterized by two objective functions: pump efficiency maximization and pump volume minimization.

4.3.1 Efficiency, volume and cost functions

The average efficiency of the family is calculated as the average of the ratio of fluid power to pump brake power, as shown in Equation (13). Similarly, the average volume of the product family is calculated as the average of the volumes for each product variant, as shown in Equation (14).

$$\bar{\eta} = \frac{1}{n}\sum_{i=1}^{n}\frac{\text{fluid power}}{\text{brake power}} \tag{13}$$

$$\overline{vol} = \frac{1}{n} \times \text{Depth} \times \text{Width} \times \text{Height} \tag{14}$$

where n is the total number of variants. Fluid power refers to the power required to transport the fluid at a specified flow rate with a given pressure. Brake power refers to the power input required to operate the pump. The pump dimensions are calculated based on the product specifications using the formulas found in Kang (2011).

The average cost of the family is calculated as:

$$\bar{C} = \frac{1}{n}\sum_{i=1}^{n} C_{P_i} \tag{15}$$

The SLS machine used was a 3D Systems$^{\text{TM}}$ sPro 230 HS model, and the material was Duraform PA (3D Systems$^{\text{TM}}$). Figure 4 shows the cost activities and details.

Machine costs
$P = 850{,}000\ \$$
$V_{bed} = 550 \times 550 \times 750\ \text{mm}^3$
$C_O = 22\ \$/\text{hr}$
$\text{Year} = 7\ \text{years}$
$\text{Uptime} = 0.8$

Material costs
$\rho = 10^{-3}\text{g/mm}^3$
$C_m = 70\ \$/\text{kg}$
Production labour costs
$\text{TechSalary} = 51400\ \$$
$T_l = 3\ \text{hours}$
$\text{Annualworkh} = 2080\ \text{hours}$

Figure 4. Cost activities and details

The bounding box of the finger pump is expressed as V_{bb} = Depth × Width × Height. From the Computer-Aided Design (CAD) information, of the individual design volumes and their bounding box volumes, the approximation value 0.334 was extracted for the compact ratio τ.

4.3.2 Utility functions

First, the designer's preferences are assessed to determine the utility values as shown in Table 1.

Table 1. Finger pump utility function assessment

Utility Value	Design Situation	Volume	Efficiency	Cost
1	The decision-maker's ideal attribute level	50	0.55	30
0.75	Desirable attribute level	100	0.35	60
0.50	50-50 chance of an unacceptable or an ideal attribute levels	150	0.25	150
0.25	Undesirable attribute level	200	0.15	200
0	Unacceptable attribute level	250	0.05	250

These utility values are fitted with polynomial curves in order to establish the independent utility equations, for pump efficiency, volume, and cost shown below.

$$u_\eta = -2.025\eta^2 + 3.258\eta - 0.172 \tag{16}$$

$$u_{vol} = -1.419 \times 10^{-5} vol^2 - 8.781 \times 10^{-4} vol + 1.084 \tag{17}$$

$$u_C = -2.343 \times 10^{-6} C^2 - 3.589 \times 10^{-3} C + 1.056 \tag{18}$$

Next, we combine the individual utility functions into a multi-attribute utility function. This is accomplished through a weighted sum of the three utility functions:

$$U = k_\eta u_\eta + k_{vol} u_{vol} + k_C u_C \tag{19}$$

where k_η, k_{Vol}, and k_C are scaling constants for efficiency, volume, and cost. For this design problem, the designer gives the preferences of $k_\eta = 1/3$, $k_{Vol} = 1/3$, and $k_C = 1/3$ respectively.

Finally, the objective function is formulated to minimize the deviation from the target utility (i.e. 1), which is equivalent to maximizing overall performance. It is simply $Z = 1 - U$.

4.4 Formulate the decision support problem

The customization space of the pump flow rate has been discretized into 50 ml/min increments as smaller increments can be readily achieved through voltage adjustments to change the motor speed.

For each design variant in the discretized segments, the optimization problem formulation is shown in Figure 5.

Given:	Desired flow rate r_f = (100; 150; 200; 250; 300; 350; 400; 450; 500; 550; 600)
Find:	Design Variables $\boldsymbol{x} = (t_w\ t_h\ f_w\ n_f\ v)$
Satisfy:	Bounds $0.5 \le t_w \le 2.5$ cm $0.5 \le t_h \le 2.5$ cm $0.3 \le f_w \le 1.0$ cm $5 \le n_f \le 12$ $2 \le v \le 12$ Volts
Minimize:	The objective function $Z = 1 - U$, where U is given by Equation (19)

Figure 5. Problem formulation for individual finger pump design

4.5 Solve the optimization problem to define the product family

This formulation was solved using the Matlab optimization function. The eleven individually optimized pumps designs along with their performance (efficiency and volume), and AM cost are shown in Table 2.

Table 2. Customized finger pump variants with AM-based design and comparison of baseline results

	Utility-based Product Family Optimization with AM								Sensitivity-based PPCTM Pumps		Performance Improvement (%)	
Flow Rate	n_f (No.)	t_w (cm)	t_h (cm)	f_w (cm)	v (Volts)	C_P ($)	ŋ (%)	vol (cm^3)	ŋ (%)	vol (cm^3)	ŋ (%)	vol (cm^3)
100	6	1.81	2.22	0.37	2.57	35.08	20.20	76.62	19.1	125.9	4.50	-37.47
150	6	1.61	2.01	0.53	3.15	40.71	20.18	87.68	18.0	125.9	12.67	-32.93
200	6	1.82	2.23	0.48	3.61	40.59	20.41	91.99	19.8	142.5	12.98	-31.92
250	6	1.68	2.07	0.60	4.07	46.16	20.10	100.55	18.1	142.5	11.99	-30.19
300	6	1.71	2.08	0.63	4.47	47.65	19.98	105.83	19.8	154.8	0.81	-33.13
350	6	1.73	2.11	0.66	4.83	49.02	19.96	110.74	19.0	154.8	14.95	-27.67
400	6	1.86	2.24	0.70	4.60	55.55	25.18	125.40	20.0	163.1	7.80	-29.49
450	6	1.91	2.29	0.74	4.65	62.68	27.79	135.35	18.3	163.1	34.64	-23.34
500	6	1.97	2.35	0.72	4.95	63.25	27.17	137.11	19.9	173.4	17.89	-27.08
550	6	2.07	2.46	0.72	4.94	65.79	30.03	145.81	18.6	173.4	27.47	-24.64
600	6	2.01	2.46	0.74	5.35	65.77	27.94	145.91	17.3	173.4	18.27	-26.62
								Average improvement:			25.02	-26.12

4.6 Discussion

In Table 2, four out of five design variables took distinct values for each flow rate segment. However, the number of the pump fingers was constant across the entire design space. Pump size increased for the increasing flow rate requirement, as expected. Interestingly, the cost also increased, but then seems to level off for the largest 3-4 pumps. Also, the cost is fairly low even with low production volumes. This validates our assertion that, with AM beneficial properties, the subtle changes to product family variant geometries do not necessary result in higher manufacturing cost. Additionally, we investigated different utility weights for each objective functions and repeated the optimization process. Even with widely different weights, the resulting pump designs, volumes, efficiencies, and costs showed insignificant changes. Thus, it seems that a truly affordable customization is possible.

We benchmarked the optimization results with the sensitivity-based PPCTM method for the same case study (Hume, 2013), as shown in Table 2. The proposed method shows significant improvement of the product performances. The average efficiency increased 25.02%, along with an average volume reduction of 26.12%. This improvement is reasonable because all the pumps are optimal designed for each flow rate range. The performance lose is due to commonality in sensitivity-based PPCTM design.

The final step of the proposed design method is to identify potential commonalities in order to take advantage of mass production opportunities. As mentioned, the number of fingers is constant across the pump family. However, their width varies from 0.37 cm to 0.74 cm; hence, the finger design cannot be standardized for the entire family. Since the finger widths for flow rates from 400 to 600 ml/min are similar, it is possible that the same finger design could be used for those five pump models which may enable the fingers to be injection moulded if production volumes permit. The variations in tube size and finger width cause the pump housings to be of different sizes, so further commonization is not possible.

5 CONCLUSION

The current paper described a novel product family design approach for additive manufacturing (AM). By introducing AM to product family design, we eliminate all constraints which arise in traditional product family designs from finding a compromise between commonality and performance of products. After determining both product family design space and objectives, we formulate the product family optimization problems. The optimization step yields individual optimized products. To reduce the product family development cost further, we explore the potential commonalities within the family of products.

The novelty of the proposed method is highlighted with the haemodialysis pump design case study. The proposed method achieved significant performance improvement when compared to the design methods that are constrained to tradition manufacturing processes and to seek commonality. Thus, we can conclude that the proposed method redefined the product family design with unique characteristics of AM. It provides truly affordable individualized designs without compromising the performance and cost.

In conclusion, this paper provides a new product family design method that makes it possible to consider mass individualization instead of mass customization. The integration of AM into product family design has the promise of removing a great deal of the current design for manufacturing efforts. However, further research work is necessary, for example, the use of AM for the production of functional products and assemblies. We believe that more widespread adoption of AM would reduce the machine and material costs due to economies of scale. This would significantly reduce part costs and make AM a more viable production route.

REFERENCES

Ding, Y., Lan H., Hong J., and Wu, D. (2004) An integrated manufacturing system for rapid tooling based on rapid prototyping. Robotics and Computer-Integrated Manufacturing, Vol. 20, No. 4, pp. 281–288.

Gibson, I., Rosen, D. W. and Stucker, B. (2010) Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. Boston, MA : Springer Science + Business Media, LLC, 2010.

Hague, R., Mansour, S. and Saleh, N. (2004) Material and design considerations for rapid manufacturing. International Journal of Production Research, Vol. 42, No. 22, pp. 4691–4708.

Hernandez, G., Allen, J. K., and Mistree, F. (2003) Platform Design for Customizable Products as a Problem of Access in a Geometric Space. Engineering Optimization, Vol. 35, No. 3, pp. 229-254.

Hopkinson, N. and Dickens, P. (2003) Analysis of rapid manufacturing – using layer manufacturing processes for production. Proc. Inst. Mech Engrs, Part C: J. Mechanical Engineering Science. Vol. 217, pp. 31-39.

Hopkinson, N., Hague, R. and Dickens, P., (2006) Rapid Manufacturing: An Industrial Evolution for the Digital Age. John Wiley, Chichester England.

Hsu, C-Y., Vittinghoff, E., Lin, F. and Shlipak, MG. The incidence of end-stage renal disease is increasing faster than the prevalence of chronic renal insufficiency. Ann Internal Med 2004;141: 95-101.

Hume, A. C., 2013, Platform Variable Identification Using Sensitivity Analysis for Product Platform Design, Thesis, GW Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA.

Jiao, J., Simpson, T. W. and Siddique, Z. (2005) Product family design and platform-based product development: a state-of –the art review. Journal of Intelligent Manufacturing, Vol.18, No. 5, pp. 5-29.

Jiao, J. and Tseng, M. (1999) A methodology of developing product family architecture for mass customization. Journal of Intelligent Manufacturing, Vol. 10, No. 1, pp. 3–20.

Jose, A and Tollenaere, M. (2005) Modular and platform methods for product family design: literature analysis. Journal of Intelligent Manufacturing, Vol. 16, No. 3, pp. 371-390.

Kang, J., Scholz, T., Ku, D.N., Rosen, D.W. (2011) Pump Design for a Portable Renal Replacement System, ASME J. of Medical Devices, Vol. 5, paper 031008, .

Kruth, J. P., Leu, M. C. and Nakagawa, T. (1998) Progress in additive manufacturing and rapid prototyping. CIRP Annals – Manufacturing Technology, Vol. 47, No. 2, pp. 525–540.

Lei, N., Moon, S. K., and Bi, G. (2013) Additive manufacturing and topology optimization to support product family design. in High Value Manufacturing (P. Bartolo et al., eds.), pp. 405–410, Taylor & Francis Group, London.

Martin, M. and Ishii, K. (2002) Design for variety: developing standardized and modularized product platform architectures. Research in Engineering Design, Vol. 13, pp. 213–235.

Moon, S. K., Simpson, T. W. and Kumara S. R. T. (2010) A methodology for knowledge discovery to support product family design. Annals of Operations Research, Vol. 174, No. 1, pp. 201–218.

Moon, S. K., Tan Y. E., Hwang, J., and Yoon, Y.-J. (2014) Application of 3d printing technology for designing light-weight unmanned aerial vehicle wing structures. International Journal of Precision Engineering and Manufacturing-Green Technology, Vol. 1, No. 3, pp. 223–228.

Rengier, F., Mehndiratta, A., von Tengg-Kobligk, H., Zechmann, C., Unterhinninghofen, R., Kauczor, H.-U. and Giesel, F. (2010) 3d printing based on imaging data: review of medical applications. International Journal of Computer Assisted Radiology and Surgery, Vol. 5, No. 4, pp. 335–341.

Ruffo, M, Tuck, C and Hague, R. (2006) Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes. Journal of Engineering Manufacture, Vol. 220, Part B, pp. 1417-1427.

Silva S. C. and Alves, A. C. (2006) Detailed design of product oriented manufacturing systems. Balancing Knowledge and Technology in Manufacturing and Services, pp. 359–366.

Thevenot, H. J., and Simpson, T. W. (2006) Commonality indices for product family design: a detailed comparison. Journal of Engineering Design, Vol. 17, No. 2, pp. 99–119.

Thomas, C. L., Gaffney, T. M., Kaza, S., & Lee, C. H. (1996, Feb). Rapid prototyping of large scale aerospace structures. in Aerospace Applications Conference Proceedings., 1996 IEEE, Vol. 4, pp. 219–230.

3D Systems website: www.3dsystems.com [accessed Nov 29 2014].

U.S. Renal Data System. USRDS 2012 annual data report: Atlas of end-stage renal disease in the United States. Bethesda, Md: National Institutes of Health, National Institute of Diabetes and Digestive and Kidney Diseases, 2012.
Wang, H., Zhu X., Wang H., Hu S. J., Lin, Z. and Chen, G. (2011) Multi-objective optimization of product variety and manufacturing complexity in mixed-model assembly systems. Journal of Manufacturing Systems, Vol. 30, No. 1, pp. 16–27.
Williams, C., Cochran, J. and Rosen, D. W. (2011) Additive manufacturing of metallic cellular materials via three-dimensional printing. The International Journal of Advanced Manufacturing Technology, Vol. 53, pp. 231–239.

ACKNOWLEDGEMENTS

This research was supported by an AcRF Tier 1 grant (RG94/13) from Ministry of Education, Singapore