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A Proposal of Lean Design Integration Method for Hierarchical Architecture Type Product Systems
(A Practical Example in Refrigerator Development applying Model Based Family Design Method using Product Platform)

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ABSTRACT

In developing process for competitive commercial refrigerator/ air-conditioning system products, practical whole system integration method is very important to realize a compact product with high cost performance. These products are characterized by hierarchical architecture type module product systems. This paper proposes a practical lean development method which combines 1D and 3D-CAE analysis with human decision making process. A Model-based development method using product base platform is also proposed for realizing a practical product family series development. Finally, the effectiveness of this method is demonstrated quantitatively by applying to an energy saving type household refrigerator.

1. INTRODUCTION

In recent years, the development of refrigerators and air conditioning products has responded to diversifying customer needs. It is necessary to develop multifunctional, high-performance, low-cost products with a short lead time. In the energy-saving design of air conditioning and refrigerator products, there is a system hierarchy feature that adjusts the cycle operating point when integrating the entire system while improving the performance of subsystem devices such as heat exchangers and compressors or etc. Furthermore, each device in the subsystem has many design parameters and many combinations of modules. In addition, in the development process of a real product system, a judgment process using implicit empirical knowledge that cannot be implemented in a digital method is indispensable. This paper introduces a set-based integration method using practical 1D-CAE and 3D analysis tools. We also present a lean operation procedure including a flexible specification adjustment method among multiple project members. Where, "lean" means “muscular without extravagance".

2. DESIGN FRAMEWORK FOR HIERARCHICAL SYSTEM PRODUCTS

2.1 Design issues aimed by the proposed method

Today, vapor compression heat pump systems are widely used in air conditioning and refrigerator products. In this system, main subsystems consist of evaporator, condenser, compressor, expansion device or so. During these product development project, design of individual module devices can proceed in parallel by each mechanical designer. However, the balance operating point of the heat pump system that combines each subsystem is determined by balancing of non-linear thermodynamic equilibrium interaction occurs between each subsystem. Therefore, design parameter changes of each device and the evaluation of the system operating point of the integrated cycle system are repeated many times to optimize the design variables toward the targeted design performance. For such realistic development issues, lean system optimization method that can use for complicated hierarchical architecture type product is desired in the manufacturing industry.

2.2 Proposal of development framework for integrated products with system hierarchy

Fig. 1 shows a framework (process flow) that optimizes product design by repeatedly integration between subsystem devices and the whole product system. Through the process of narrowing down a common design solution set Ω by multiple members and the final product specifications are identified by chief engineer. This is also an artistic design convergence process for synthesizing each other over and over again. We propose a lean system design framework by integrating ① and ② frequently for effective system optimization with right people in the right place at the right time. In this paper, the energy-saving design of a refrigerator will be explained as an application example. In the system integration process, design adjustment of each device is repeated until the design value reaches the targeted whole system performance.

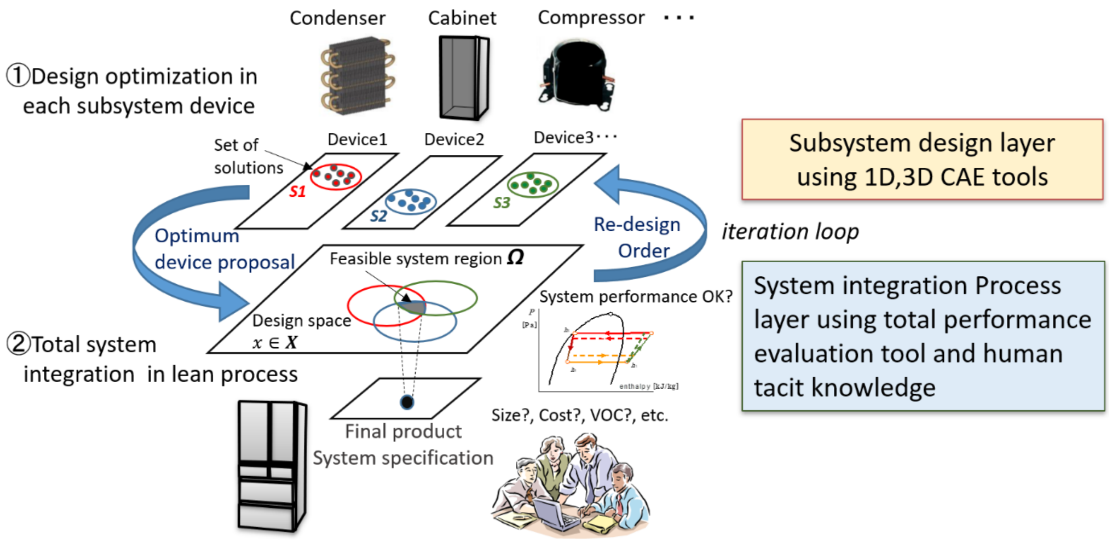


Fig.1 Proposed lean development process using set-based design method which combines digital tool with human tacit knowledge for architecture type product having hierarchical interaction between system and subsystem

① Subsystem design (example of heat exchanger module design)

To realize an efficient refrigeration cycle system, it is necessary to improve the performance of each heat exchanger that reduces the heat transfer temperature difference ΔT between air and refrigerant. However, there are many design variables to be decided such as fin shape, fin pitch, refrigerant pipe diameter, pipe groove shape and fan rotation speed or so. Each team member visualizes the trade-off relationship of each design field from the set-based calculation with the 1D-CAE tool, and then shares information between project members each other for system allocation adjustment.

② Overall system integrated design (example of system COP verification calculation)

For example, the chief engineer (project management team) performs a combination analysis of each device and adjusts the design allocation to investigate the difference from the target COP obtained by Eq. (1).

$$COP_{\mathrm{comp}} = \frac{Q_{\mathrm{wall}}}{W_{\mathrm{comp}}} \tag{1}$$

$$Q_{\mathrm{wall}} = \int q_{\mathrm{x}} \cdot \mathrm{d}A_{\mathrm{wall}} = \int K_{\mathrm{x}}(T_{\mathrm{a,o}} - T_{\mathrm{a,i}})\mathrm{d}A_{\mathrm{wall}} \tag{2}$$

$$K_{\mathrm{x}} = \frac{1}{\dfrac{1}{\alpha_{\mathrm{o}}} + \Sigma\dfrac{t}{\lambda} + \dfrac{1}{\alpha_{\mathrm{i}}}} \tag{3}$$

In the case of a refrigerator, the heat load that can be calculated by integrating the heat flux through the wall are estimated by Eq (2) and (3). COP also estimated from the equilibrium state on the p-h diagram by using 1D cycle calculation tool. As a result of the integrated calculation, when the calculated value exceeds the target compressor power consumption, the project leader resets the budget distribution of each subsystem and asks the subsystem members to redesign. For successful lean development, it is important to operate as Socio-Technical system including lean management skills that highly combines Experienced People, Standardized Process, and Sophisticated Tools, as shown in Fig. 2. To promote efficient system integration within a limited development time, the concrete key is a lean operation process that integrates 1D and 3D analysis tools suitable for each design phase and flexible decision making in human systems. In the next chapter, I will describe in detail using example of development application to household refrigerators.

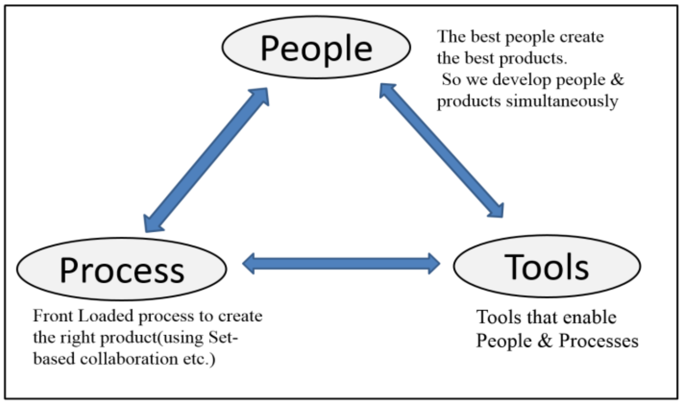


Fig.2 Socio-Technical Systems Model of Lean Product / Process Development
(Edited with reference to (Morgan and Liker,2006))

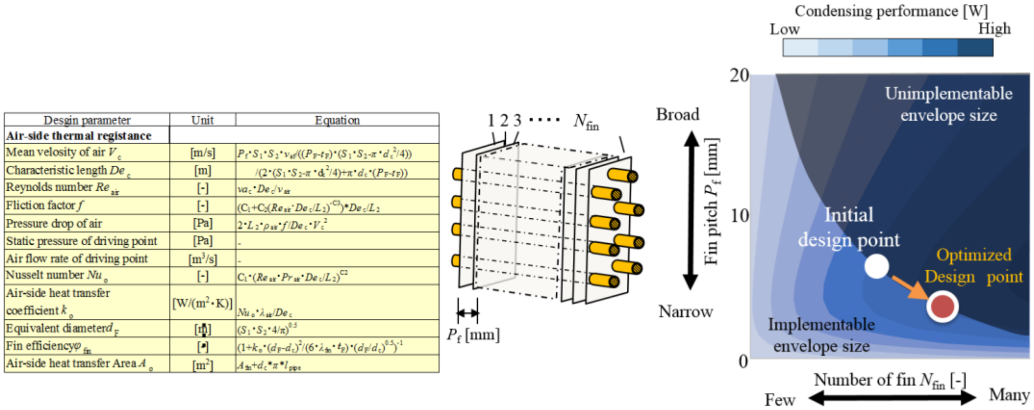
3. APPLICATION EXAMPLE OF THE PROPOSED METHOD

3.1 Application to energy-saving design of household refrigerators

3.1.1 Individual device performance design methods in subsystems

(1)Subsystem design example 1: Heat exchanger module design with Knowledge Base Development

In the design of heat exchangers, there is a problem that the total number of combinations of design parameters such as fin shape, number of fins, fin pitch, refrigerant pipe diameter, inner groove shape, air-cooled fan wind speed, etc. is enormous. We have developed an EXCLE-based 1D calculation tool for fin-tube heat exchangers, which is a coupling of fluid nodal network model. This 1D tool with less computation load than large scale CFD makes it easy to grasp the whole map of the design space by set-based calculations. For example, Fig. 3 shows "set-based knowledge map" for candidate solutions that take into account manufacturing constraints.



Desgin parameter	Unit	Equation
Air-side thermal registance		
Mean velosity of air V_c	[m/s]	$P_f \cdot S_1 \cdot S_2 \cdot v_{af}/((P_F-t_F)\cdot(S_1 \cdot S_2-\pi \cdot d_c^2/4))$
Characteristic length De_c	[m]	$/(2\cdot(S_1 \cdot S_2-\pi \cdot d_c^2/4)+\pi \cdot d_c \cdot(P_F-t_F))$
Reynolds number Re_{air}	[-]	$va_c \cdot De_c/\nu_{air}$
Fliction factor f	[-]	$(C_1+C_2(Re_{air} \cdot De_c/L_2)^{-C3})*De_c/L_2$
Pressure drop of air	[Pa]	$2 \cdot L_2 \cdot \rho_{air} \cdot f/De_c \cdot V_c^2$
Static pressure of driving point	[Pa]	-
Air flow rate of driving point	[m³/s]	-
Nusselt number Nu_o	[-]	$C_1 \cdot (Re_{air} \cdot Pr_{air} \cdot De_c/L_2)^{C2}$
Air-side heat transfer coefficient k_o	[W/(m²·K)]	$Nu_o \cdot \lambda_{air}/De_c$
Equivalent diameterd_F	[m]	$(S_1 \cdot S_2 \cdot 4/\pi)^{0.5}$
Fin efficiencyφ_{fin}	[-]	$(1+k_o \cdot (d_F-d_c)^2/(6 \cdot \lambda_{fin} \cdot t_F) \cdot (d_F/d_c)^{0.5})^{-1}$
Air-side heat transfer Area A_o	[m²]	$A_{fin}+d_c*\pi*l_{pipe}$

Fig.3 Excel Spreadsheet based 1D thermal analysis tool for fin-tube type heat exchanger
and set-based parameter study results example.

An identified candidate narrowed down after 1D analysis is estimated by detailed 3D CFD (Fig. 4) and finally verified experimentally with the prototype (Fig. 5). Fig.6 shows our proposing set-based lean development process using 1D, 3D analysis and experimental validation. For this efficient Knowledge Based Development, it is important and rational to understand the whole map of design space even in the 1st order at first, rather than starting with an empirically expected pinpoint solution.

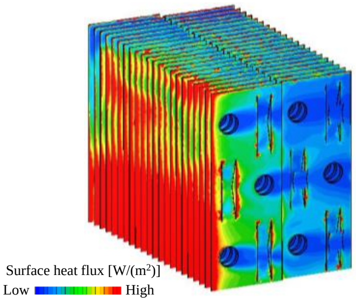


Fig.4 Thermal and fluid 3D analysis results of a fin-tube type condenser

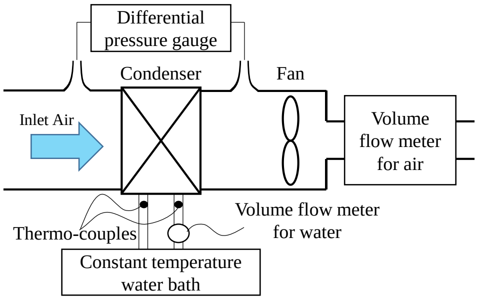


Fig.5 Experimental setup for measurement of condenser heat transfer performance

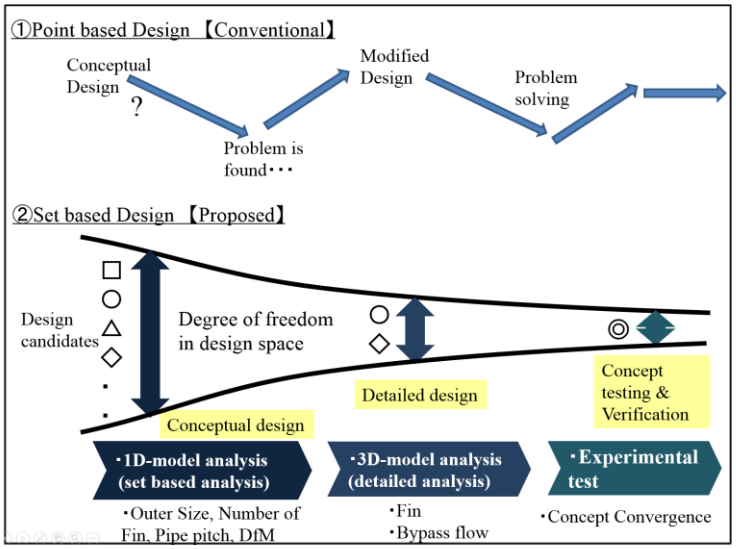


Fig.6 Proposed set-based lean development approach using 1D, 3D analysis and experimental estimation (Edited with reference to (Ward et al.,2014))

(2)Subsystem design example 2: Thin design of the insulation cabinet wall

As an example of subsystem development, we will also introduce an application example in an insulating cabinet wall design. The main function of the heat pump type refrigerator is to pump up the heat load Q_{WALL} with thermal conduction through insulating wall in proportion to the temperature difference ΔT between the outside and the inside air. When considering maximizing the storage volume inside of refrigerator, it is important to make the wall thickness t_{WALL} as thin as possible. So, the optimal combination design of VIP(Vacuum Insulation Panel) and urethane foam is one of a key issue with considering maximize cost performance.

At a product concept making stage, one-dimensional wall heat conduction set-base calculation is performed with 1D based Excel model by using Eq.(2),(3). This 1D approach is easy and especially effective at the conceptual design stage. For example, the thickness of the heat insulating wall suitable for each room such as a refrigerating room, freezing room, vegetable room and icing room with different temperature zones are estimated respectively and each sensitivity curve are visualized. From the perspective of cost performance, the thermal conductivity λ of VIP is 1/10 or less of urethane foam resin, which is high thermal insulation, but since it is expensive. So the VIP thickness for each part allocation and usage are also optimized by using this design space map as shown in Fig.7.

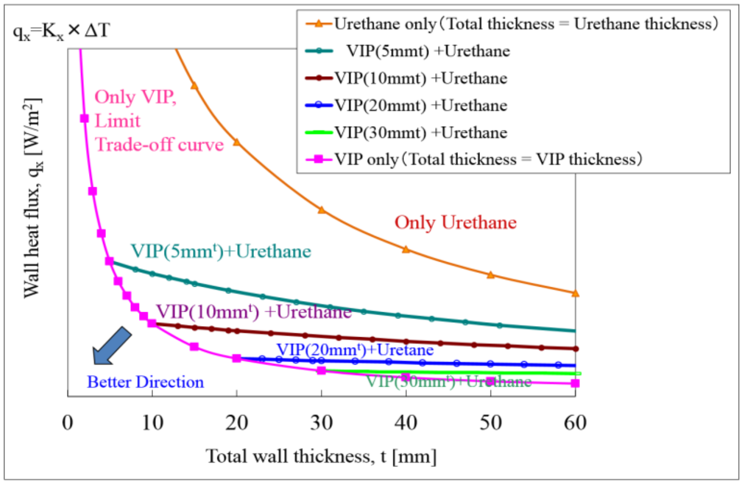
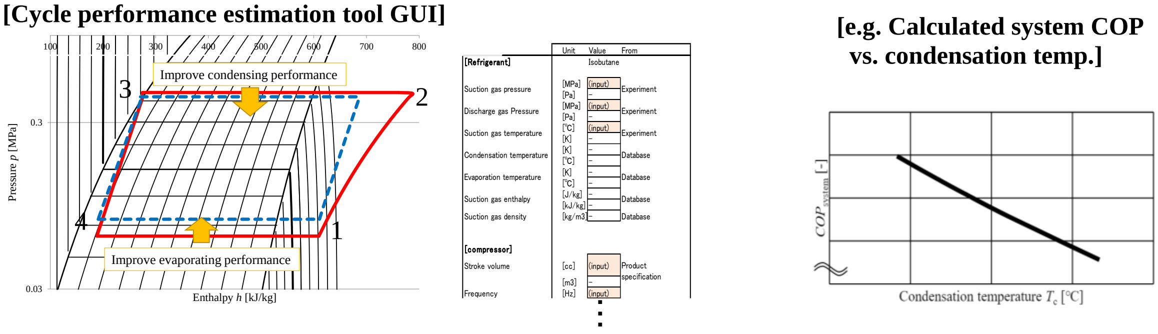


Fig.7 An example of 1D set-based parameter analysis result on Refrigerator wall thickness and heat flux

3.1.2 Verification method for integrated performance of the whole system

(1)Whole system integrated design example 1：Overall system COP verification process using 1D cycle tool

Whole system integration team uses the Excel based refrigeration cycle calculation tool as in Fig. 8 to check the sensitivity of the effect of each device performance to the target system performance on the p-h diagram and optimize the allocation for each device. Physical property value of refrigerant in this tool are numerically modeled by using databases such as REFPROP. Product system COP as the design progresses is estimated from the equilibrium state on the p-h (Molie) diagram by using 1D cycle calculation tool and visually analyzed at any time. In the energy-saving design of the system, the parameters of each device are adjusted many times until the design target is satisfied while improving the real design operation cycle (solid red line in Fig. 8) to be closer to the ideal cycle (blue dashed line in Fig. 8). While looking at the calculated results on the right side of the Fig.8, if the 1D cycle result calculated by integrating proposed devices from each subsystem team exceeds the system target COP or power consumption, the project leader reallocates the performance target value of each subsystem and requests the subsystem redesign. This process is repeated until the target value is satisfied.


[Cycle performance estimation tool GUI]

[e.g. Calculated system COP vs. condensation temp.]

	Unit	Value	From
[Refrigerant]		Isobutane	
Suction gas pressure	[MPa]	(input)	Experiment
	[Pa]	–	
Discharge gas Pressure	[MPa]	(input)	Experiment
	[Pa]	–	
Suction gas temperature	[°C]	(input)	Experiment
	[K]	–	
Condensation temperature	[K]	–	Database
	[°C]	–	
Evaporation temperature	[K]	–	Database
	[°C]	–	
Suction gas enthalpy	[J/kg]	–	Database
	[kJ/kg]	–	
Suction gas density	[kg/m3]	–	Database
[compressor]			
Stroke volume	[cc]	(input)	Product specification
	[m3]	–	
Frequency	[Hz]	(input)	

⋮

Fig.8 1D Excel Spreadsheet based refrigeration cycle COP evaluation tool for system integration

(2) Whole system design example 2：Calculation of heat return through cabinet wall using 3D-Analysis

As mentioned above, the insulation structure concept of the cabinet wall was studied and roughly decided by using the 1D calculation. However, in the actual refrigerator, local heat flux from the condensing pipe installed on the side wall of the cabinet flow back three-dimensionally into the cabinet and lowers the system COP. This local heat bridge path, returned from the side condensing pipe to the inside of the wall, are difficult to measure experimentally. So, we improve the heat return by using the 3D detailed analysis model for the whole refrigerator cabinet as shown in Fig.

9. This visualization method was very effective in optimizing the refrigerant piping pattern and sheet metal flange shape to minimize the heat bridge affection. As a results, by using effective integrated utilization of 1D order estimation and 3D detailed analysis, VIP based new cabinet platform “SMART CUBE” (Fig.9) was developed and released. In the commercial products from many refrigerator manufacturers, this product has the highest level of energy saving performance while providing a large internal volume for customers and the effectiveness of this method has been proved.

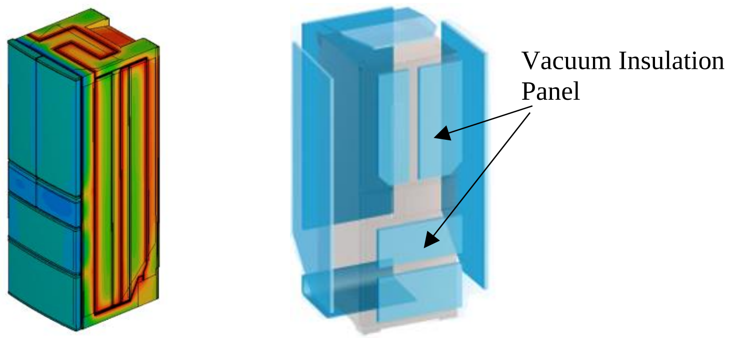


Fig.9 A result of 3D thermal interference analysis of innovative refrigerator platform “SMART CUBE”

3.1.3 System integration process of the whole product, and lean operation method

In the actual product development process, not only the tasks that can be calculated by digital analysis tool, but also many implicit knowledge-based comprehensive judgment tasks are always working. Therefore, multidisciplinary interactive decision making process by chief engineer is important with multiple subsystem engineers in regular meeting scene. Fig.10 shows the overall picture of the organizational team structure for lean co-creation processes. Each design progress was presented and system budgeting was updated through weekly regular working groups (WGs). The analysis results as trade-off curve by each subsystem team were projected on a “OOBEYA screen” and knowledge shared closely. Then, “Study of the shape of each element device (Analysis)” and “System integration (Synthesis) activity” are repeatedly discussed and gradually converged by chief engineer.

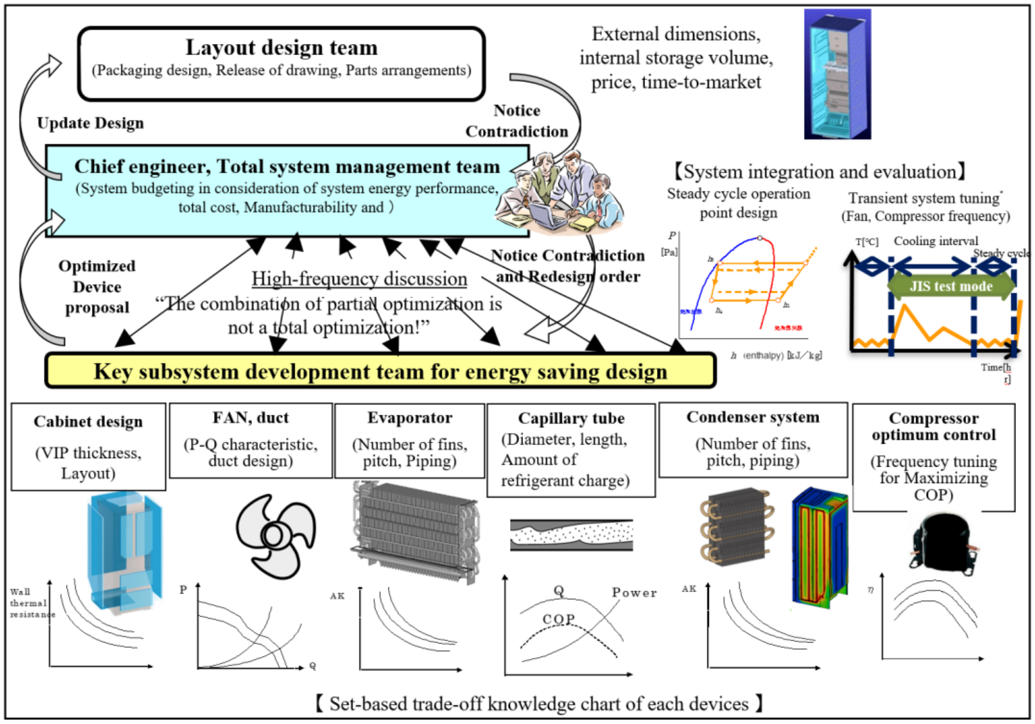


Fig.10 Proposed pragmatic lean set-based development approach using CAE and humanistic collaboration

4. DISCUSSION
PLATFORM BASED FAMILY PRODUCT DESIGN WITH COMMON ARCHITECTURE

As explained before, the heat transfer rate Q_{WALL} through the insulating cabinet walls of various volume sizes can be calculated by equations (2) and (3). For example, if the family cabinet box volume is enlarged and the outer surface area A_{WALL} increases, the heat load Q_{WALL} also increases in proportion to A_{WALL}. For family product series deployment using common P/F, the box volume is enlarged in and the outer surface area A_{WALL} increases, the fin-and-tube type inner evaporator also expands in the width direction to increase the cooling capacity. As a result of this way, an increase in the temperature inside the refrigerator and a decrease in performance can be compensated and canceled. In such design case, 1D equation with physical similarity principle shown in Eq.(4) to (7) is theoretically useful. Fig.11 shows an example of a product in which a “517 liter cabinet” is used as a basic platform and dimensions are similarly adjusted for family series product with different internal volumes. The width of the evaporator, W_{HEX}, is also increased based on the thermodynamic similarity equation in response to the increase in heat load due to the expansion of the cabinet box size. This methodology is called as a “common architecture design” in design system engineering field. Similar to this example way, 1D rule based design with similarity law also applied to the other fields, fluid dynamics and structural design, so that product series cabinets with different internal volumes satisfy the design target specification in a short design time.

$$Q_{\mathrm{HEX}} \propto Q_{\mathrm{wall}} \propto A_{\mathrm{wall}} \tag{4}$$

$$\Delta T_{\mathrm{eva}} = T_{\mathrm{in}} - T_{\mathrm{eva}} = \frac{Q_{\mathrm{HEX}}}{A_{\mathrm{f}} \cdot v_{\mathrm{f}} \cdot \rho \cdot C_{\mathrm{p}} \{1 - \exp\left(-NTU\right)\}} \tag{5}$$

$$NTU = \frac{\mathrm{K} \cdot \mathrm{A}}{F \cdot \rho \cdot C_{\mathrm{p}}} \tag{6}$$

$$\frac{Q_{\mathrm{HEX}}}{A_{\mathrm{f}} \cdot v_{\mathrm{f}}} = Const \tag{7}$$

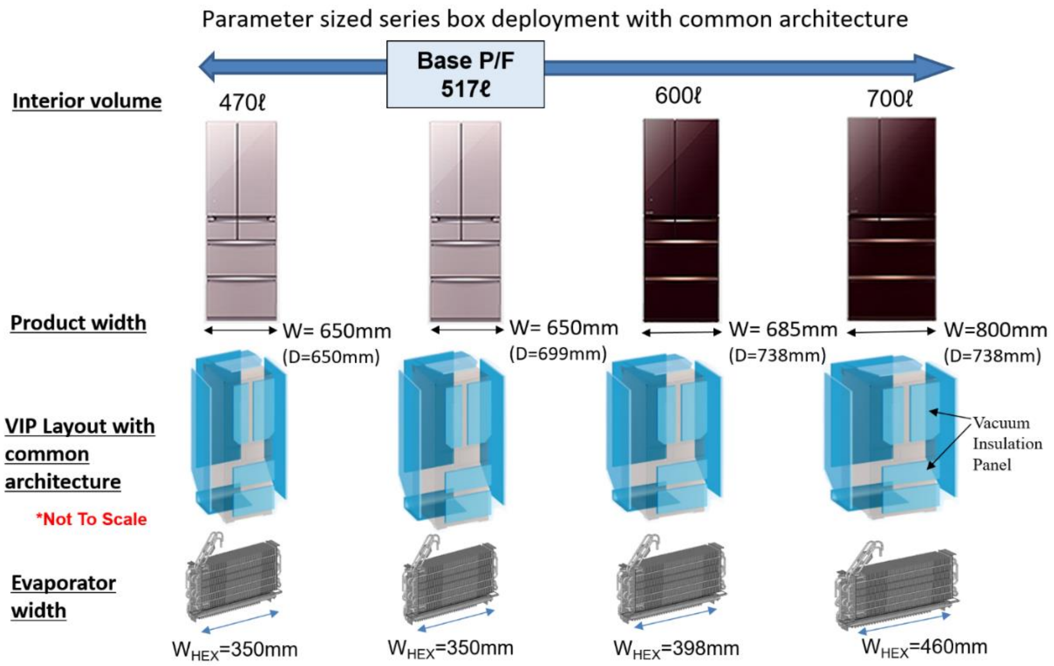


Fig.11 SMARTCUBE family common architecture design
with parameter sizing based on thermodynamic similarity rule

4.1 Optimization of total cost of product series considering reduction of manufacturing cost

From the perspective of cost planning to optimize corporate profits, balance optimization of "function costs" for individual products and "total variety costs in family series" should be considered. Where, "function costs" is composed of material cost, processing cost, assembly and inspection cost. Efforts to shorten the standard time and reduce the manufacturing cost by considering DfM (Design for Manufacturability) are also indispensable. On the other hand, "variety costs" includes commonly used mold cost, setup cost, yard cost, and worker proficiency effect. Incidentally, variety cost is also said to be "hidden and untouched cost (buried gold)". As shown in conceptual Fig. 12, if only each product cost down is conducted without considering the series total cost, because the number of molds and management cost will increase and there is a possibility that the total profit will decrease. Conversely, in the case of standard design, there is a possibility that the cost of each product (redundancy) will increase due to non-individual optimization. So, this curve has the optimum value when considering the total profit and ultimate variety design aim is, of course, to minimize total business cost. Therefore, it is also necessary to have precise cost prediction models for each product, and to optimize the cost of the whole product series. Furthermore, as the third important factor, it is important issue to reduce "Control Costs", including budget of engineer man-hours, ordering staff costs, and quality control costs etc. In the next chapter, we will demonstrate in detail and quantitatively that our proposed P/F based lean development is also effective to reduce "Control Costs".

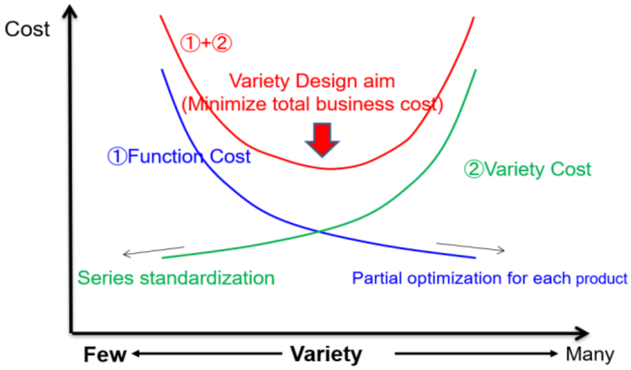


Fig. 12 Trade off Curve between Cost and Variety Design

4.2 Evaluation of development cost reduction effects by using proposed P/F based development

In this chapter, we prove that proposed platform based development method is effective in significantly reducing total development costs. Fig.13 shows a cost comparison before and after applying this platform development concept. In this figure, (i) cumulative total prototype cost and (ii) normalized mold costs by each development year are on the vertical axis, and the year of development is on the horizontal axis, and a quantitative comparison is made.

① At the case of single-year development, specifications were continuously changed while designing and prototyping, so the cumulative amount of prototyping development costs and mold improvement costs continued to increase. It took a high working load with long period to repeat design changes in order to improve the lack of energy-saving performance and reworking of prototypes occurred until the end of development. As a result, the extension of product development in the previous year resulted in a negative cycle in which the start of development in the next year was delayed.

② On the other hand, in the case of reusing standardized P/F, product information and improvement effect can be accumulated by inheriting high-quality DNA of the past product, and there is almost no specification change at the mass production trial stage. In this P / F development case, although the mold cost increased by 20% in the first year, it has a big advantage that it decreases dramatically after the second year. In the case of this product, mold costs continue to decrease year after year compared to the case of single-year development and the four-year average was suppressed to 76% and reducing mold costs by 24% on average. Since the amount of mold for refrigerator development is very large, this reduction in mold costs will result in a dramatic increase in business profit. When looking at engineer time card after utilizing the P / F, total working hour also decreased by about 25% compared to the time of development in a single year. Of course, it goes without saying that establishing a highly competitive product P / F over several years is the key to the success of this P / F strategy.

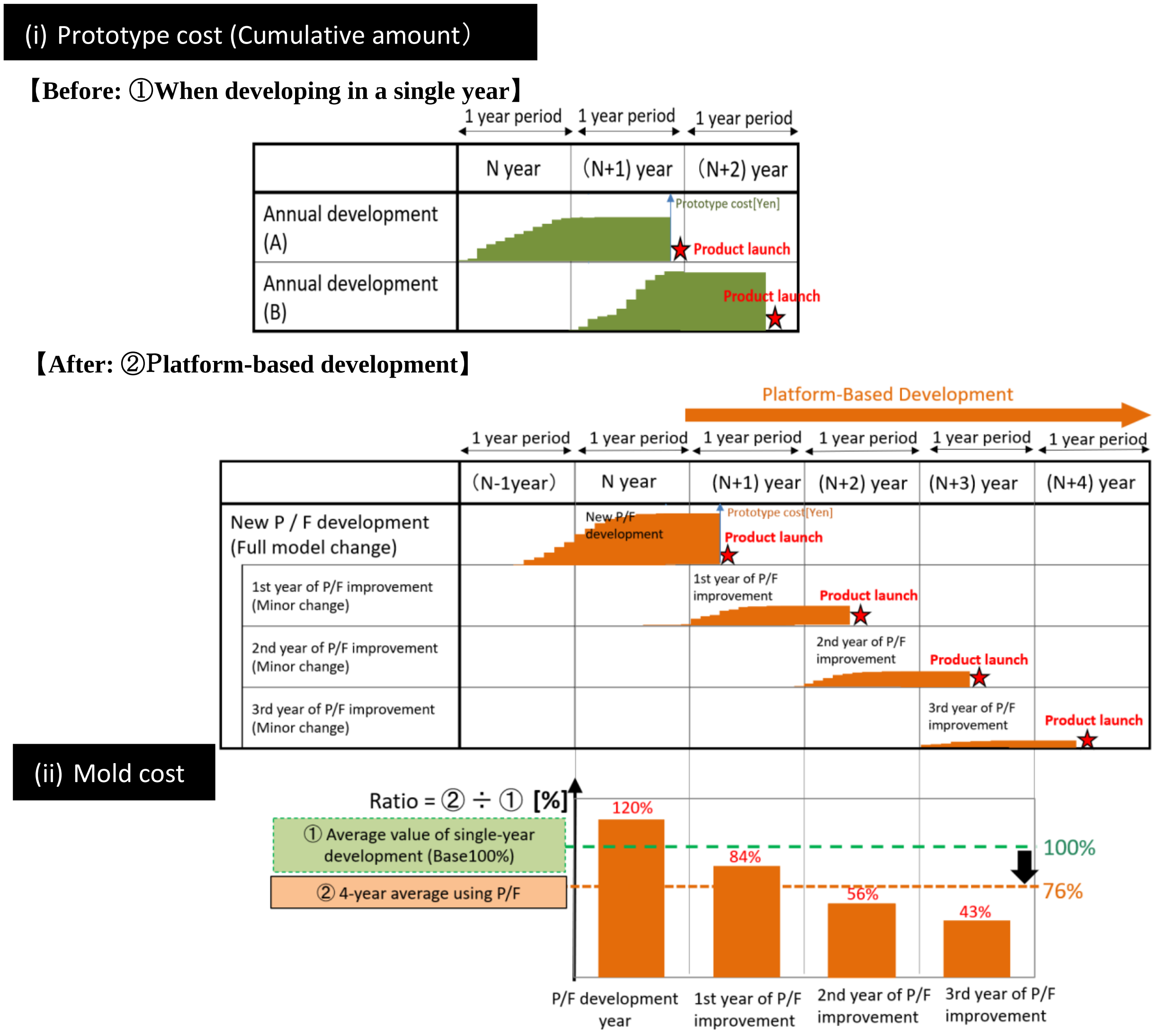


Fig.13 Development cost reduction effect with and without platform design method

As a result of our product and process innovation, ultimately, start timing of the next year's model can be allocated ahead by 0.5 years earlier than the vacant period due to the reduction of rework load and it possible to achieve smooth development transition and leveling of annual load. Consequently, it has become possible to develop over 1.5 years from the previous year. In other words, 1.5 years with partial overlap development was achieved without increasing the number of development staff. In addition, the peak load on the upstream of development, which was a principle issue of Front Loading Development, was also leveled and solved.

5. CONCLUSIONS

This paper proposed a practical lean development method which combines 1D and 3D-CAE analysis with human decision making process. Also, Model-based product family development method using product platform is also proposed using actual new concept energy saving domestic refrigerator. Finally, we proved that our proposed methods could work effectively for actual hierarchical architecture type refrigerator development and process innovation effect also demonstrated quantitatively by comparing before and after cost date.

NOMENCLATURE

COP : Coefficient Of Performance [-]
t : Insulation wall thickness [m]
K : Overall heat transfer rate of the wall [W/m^{2}K]
α : Heat transfer coefficient [W/m^{2}K]
λ : Thermal conductivity [W/mK]

Subscript

comp	compressor
eva	evaporator
cond	condenser
HEX	Heat Exchanger
i	inside of refrigerator
o	outside of refrigerator
x	local
wall	cabinet wall

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