A PARAMETRIC DESIGN FRAMEWORK TO SUPPORT STRUCTURAL AND FUNCTIONAL MODELING OF COMPLEX CONSUMER ELECTRONICS PRODUCTS

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ABSTRACT
Today's market demand for smaller and more powerful consumer electronic devices poses a major challenge to the rapid design of products. In addition, the ability to perform strategic coordination among different stakeholders within the enterprise increasingly becomes an important criterion for global engineering. In this study, we first introduce a typical design process involving distributed design teams. In particular, this process allows a thermal–acoustic design of cavities, i.e., air space inside the enclosure, in terms of flow rate and acoustic radiation resistance. Then, we investigate a module-based design optimization approach defining cavity as a module to efficiently support such processes. We ensure the design control of both cavity characteristics in an internationally distributed project through design data analysis using the Systems Modeling Language (SysML) and the resulting product model descriptions of the system architecture.

Keywords: Global Engineering, Consumer Electronics, SysML, Product Model, Simulation

1 INTRODUCTION
Internationally distributed design of consumer electronics (CE) is rapidly becoming a preferred method for individual product development because of the diverse market demands in different countries, diversification of supply chains from procurement to distribution, and advantages in labor cost. Various studies [1] [13] [14] of collaborative design efforts across different countries and various businesses taking place today have identified the following major factors that hinder quality, cost, and delivery of product design in the so-called distributed design environments:

- Lack of communication due to the time difference, physical distance, and company policies.
- Unevenness or disparity in skills and experience of the experts employed at design sites.
- Irregular distribution of experts (each site does not have experts in all areas).

These risk factors should be considered in the design of complex and difficult models. Recent studies show that in some cases, there are more disadvantages than advantages inherent in the division of labor. However, such disadvantages would not usually show up in the conventional scheme of a centralized design effort because all employees understand the culture and rules particular to a locale. Therefore, it is strongly desired to establish a structured design method that guarantees both the originality and quality of product design, i.e., a method that yields quality design for products with distinctive features and values.

Common problems in product design include poor convergence (required characteristics are not obtained) after prototyping in a distributed design project; iteration of work such as redesigning and poor performances in terms of thermal characteristics, acoustic noise, and Electro Magnetic Interference. In several cases, modules such as semiconductors, printed circuit boards, and other devices are the basic units for division of design effort. However, for the completed product to operate as a system, it is necessary to consider interactions among modules from an early design stage. Distribution of design makes it difficult to discuss the subject between different locales, and this is the major reason why iteration of design work is often required. In other words, in addition to the characteristics of each module and component, any issue that affects cavity and, therefore, the overall performance of a product will be a significant risk, especially in products that are thin and miniaturized. Cavity is formed by layout of many modules inside the enclosure; however, there is no specific engineer in charge of the dimensions of cavity in CE industries, and therefore, in many cases,

it is difficult to control the detailed characteristics of empty space. Thus, a new framework that reduces design iterations in an internationally distributed design paradigm is desired. [4]
On the basis of the above discussion, this paper evaluates the design methodology that enables stabilization of interactions arising from physical coupling of components on the system level for designing products for which development takes place at multiple design sites, especially for ultra-thin and miniaturized products that have high degrees of complexity and difficulty.
In terms of concurrent design among multi-disciplinary design teams, Balmelli [11] proposed the Model-driven systems development using SysML. This approach uses multiple viewpoints, such as Operational, Functional, and Physical view, to separately address different engineering concerns while maintaining an integrated representation of the underlying design. Goto and Eguchi et al. [17] also proposed multilayer modeling of structure/behavior/requirement using SysML to describe product design information. They utilized the method to realize impact analysis of the design change from the initial design.
In particular, this paper proposes a design framework that eliminates inconsistent performance of system components due to lack of communication between design sites, and also eliminates iteration of work usually required to correct such inconsistencies. For this, we propose a thorough product model that consists of structural and functional modeling of complex consumer electronics. This paper evaluates the product model description using SysML, and focuses on the combination of the multilayer product model and the corresponding simulation models. This modeling approach includes the creation and assignment of tentative system boundary condition (Initial target values; ITVs) to the each module in the functional design phase, and updating ITVs appropriately in the structural design phase under the SysML based design platform. Our investigations for a particular product show that a trade-off between independent module design and system design using structural and functional modeling leads to a potentially optimal design for the problem studied.

2 MODULE SYSTEM ARCHITECTURE FOR CE PRODUCTS

2.1 Cavity module definition

Figure 1 shows a typical CE product. A simplified sample of module structure is shown in Figure 2 for the purposes of discussion. There are four modules: M1, M2, M3, and cavity. The forth module, i.e., cavity, governs physical couplings among the common modules.

Figure 1. Typical configuration of CE products

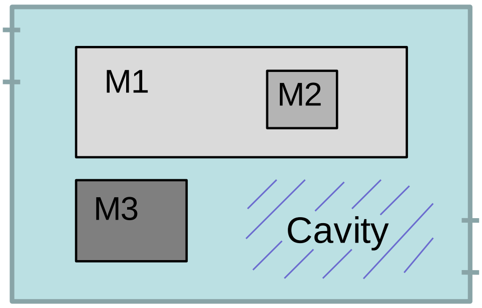


Figure 2. Sample of the CE product system

There are engineers who are in charge of the design of the commonly used parts/modules. However, cavity is formed by layout of many other modules inside the enclosure, and there is no explicit apportionment of responsibility for the dimensions and performance of cavity. Therefore, in many cases, it is difficult to control the detailed characteristics of this empty space. In addition, cavity affects multiple system characteristics such as thermal issues related to impedance (flow resistivity), noise property related to acoustic radiation efficiency, and so on. [9] [15] We proceed to investigate the module-based design optimization approach defining cavity as a module to support collaborative design process.

2.2 Interfaces among modules

In the distributed design project, each module is designed at a different site; however, they are coupled in physical implementation and have an effect on the system performance, resulting in iteration of work such as redesigning. It is necessary to consider the thermal interfaces among modules from an early design stage [8]. Figure 3 describes energy transmission among the four modules, which include a cavity module, using a SysML sequence diagram. This diagram can be transformed to the behavior coupling matrix expressing module coupling conditions. Using this kind of behavior modeling, we can identify thermal interfaces among modules, which can form a basis from which we can prepare system boundary conditions for the detailed design of each module. The authors proposed a design framework that eliminates inconsistent performance of modules due to lack of communication between design sites. Modules' system boundary conditions are assigned using above-mentioned behavior coupling matrix and work distribution matrix [13]. These tentative system boundary conditions named Initial Target Values (ITVs) shall be provided to each module design site after functional design (system architecting) phase. ITVs are tentative values for each module, and their exact values can be obtained only by physical prototyping or a system-level thermal simulation. However, from the energy based calculations using physical model simulation in the functional design phase and a knowledge database based on past products, we can determine practical ITVs for the thermal design of each module.

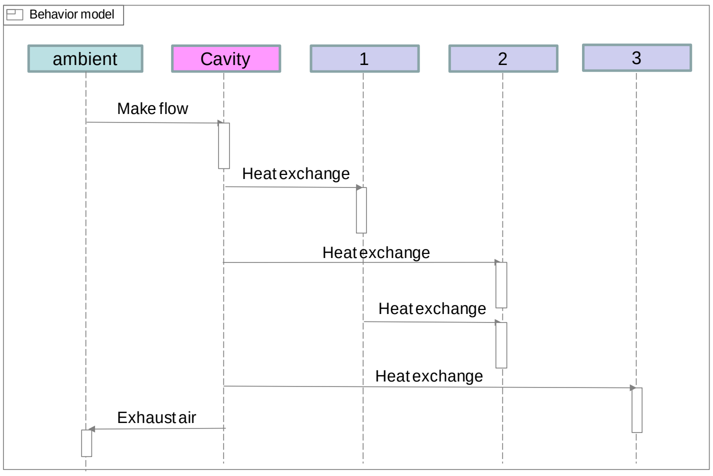


Figure 3. Behavior model for a CE product

	1	2	3	Cavity
1	0	0	0	**1**
2	**1**	0	0	**1**
3	0	0	0	**1**
Cavity	**1**	**1**	**1**	**1**

Figure 4. Behavior coupling matrix

2.3 Product model and simulation model

For the completed product to operate as a system, it is necessary to thoroughly consider the thermal interactions among modules from an early design stage even in projects with distribution of design. As stated above, ITVs as tentative interface parameters work as a bridge among independent design sites. Besides setting ITVs first, the convergence to appropriate ITVs with trade-offs between the modules and the system during the design process is also important. However, in an actual distributed design project, each design site tends to optimize its design with its own performance/business metrics irrespective of the overall system performance. Therefore, the system design needs to have a function to share the reference framework of the system performance among all sites. [3]

Figure 5 shows the contexture of the product model required to achieve the abovementioned approach for our design framework development. In the figure, on the left side is the so-called product model covering product functions (the result of logical design) and structures (commonly used bill of materials), and the right side explains the accompanying simulation models for both the function and the structure levels. Upper right is the energy-based physical simulation model at the system architecting phase, and lower right is the module level simulation for detailed design of each module.

Our proposed approach requires to set the necessary ITVs using a physical simulation model during the logical design phase that focuses on product functions. This is followed by updating the ITV values for the global optimal condition after starting each module design. The key point is that even in the independent module design phase, each design site could conduct a trade-off study between its own design and system parameters by sensitivity analysis of module design parameters and ITVs using module level simulations. We propose this collaborative design framework using a product model with accompanying simulation models.

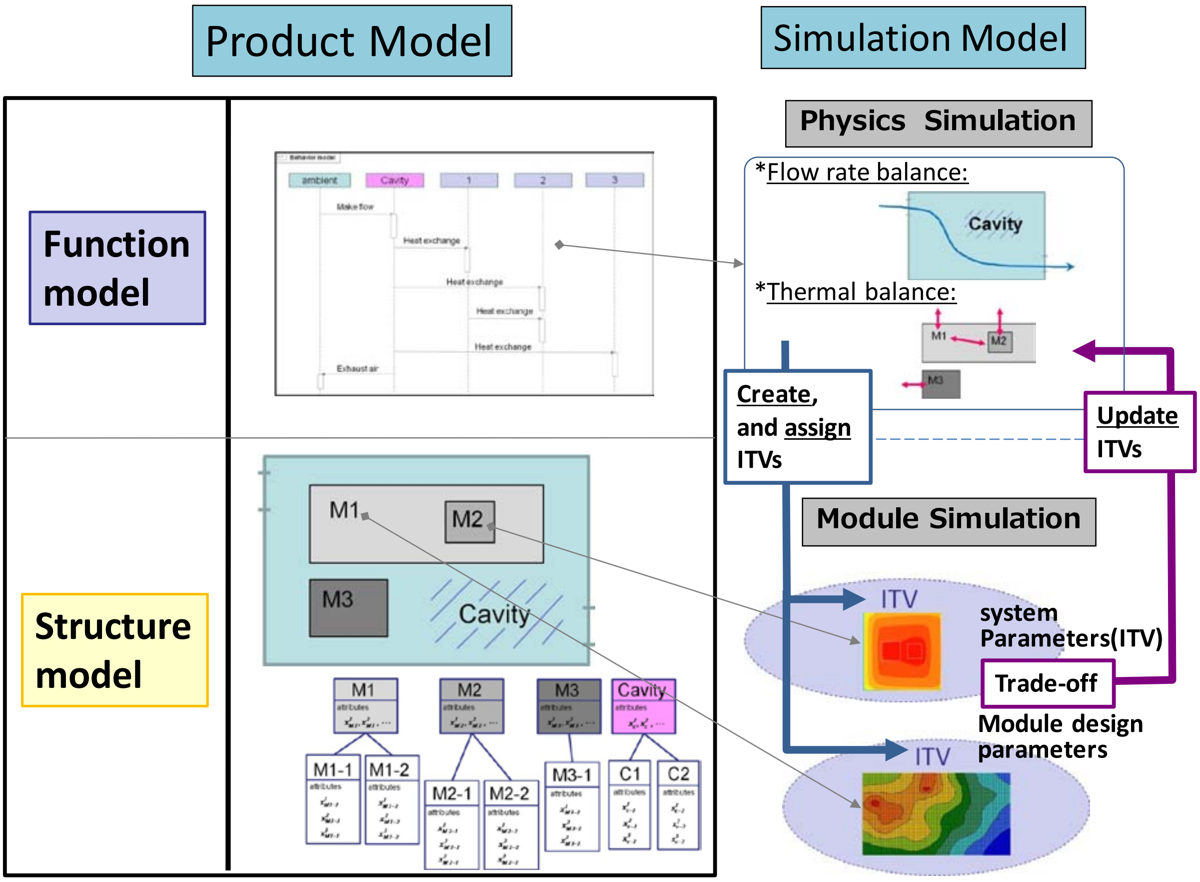
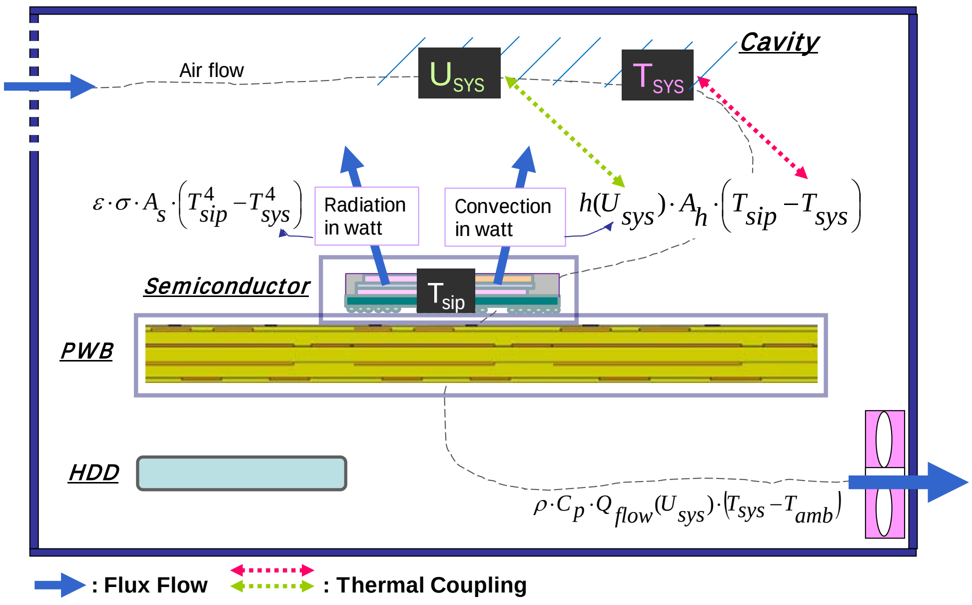


Figure 5. Product model with accompanying simulation model

3 PRODUCT MODEL DEVELOPMENT USING SYSML

In the previous section, we described a design framework that eliminates both inconsistent performances of modules due to lack of communication between design sites and iteration of work required to correct such inconsistencies. Authors developed physical simulation models of the system performance that considers cavity as a module in the system architecture phase.

In this section, we investigate the utilization of the product model by SysML [11] [16] as a joint platform for distributed design environment to realize the abovementioned design framework in the actual CE product design project. Figure 6 shows CE product considering the thermal interactions between the semiconductor and the cavity module. SysML model descriptions clear up the interfaces among modules by the visualization using many types of diagram in the system architecture phase, and then derive external system boundary (ITVs) from the interfaces identified for the detailed design of decomposed module (physical phase). Using sensitivity analysis, this section also discusses the trade-off between module design variables and system parameters.



temperature of SiP, PWB, cavity of system, ambient : T_{sip}, T_b, T_{sys}, T_{amb}

area of SiP top surface, SiP bottom, PWB, heatsink : A_s , A_{sipb} , A_b , A_h

coefficient of heat transfer : h , heat conductivity : λ , velocity in the cavity : U_{sys} , flow rate: Q_{flow}

radiation factor: ε , Stefan-Boltzmann constant : σ

Figure 6. Thermal interface diagram for a CE product

3.1 Interface identification

Figure 7 shows a behavior model in terms of the cooling function, which keeps the module temperature safe for normal operation, for the CE product in Figure 6. It describes heat exchange/transfer with external air and thermal interchange between modules using the format of SysML sequence diagram. Figure 8 shows a functional architecture diagram of the system automatically created from the SysML sequence diagram. As shown in this figure, all modules (M1, M2, M3, and M4) having thermal interfaces with the cavity module could be assigned ITVs derived from attributes of cavity and physical model simulation as shown in Figure 5. For comparison, an architecture diagram of the system for which cavity is not defined as a module is shown in Figure 9. In this product system description, each module has multiple thermal interactions and therefore many corresponding interfaces need to be defined. It is clear from the comparison that the definition of cavity as a module is effective for interface description, assignment of ITVs, and independent module design in the distributed design project.

Detailed observation of the diagram reveals that the cooling function consists of two kinds of phenomenon: drawing air outside the enclosure and creating air flow in the cavity, and exchanging thermal flux among modules and cavity. Therefore, we could identify the two major equations: flow rate balance and thermal balance, for the energy-based physical simulation model at the system architecting phase. Flow rate balance includes cavity's system impedance, pressure drop between the inlet and outlet, and flow rate. Thermal balance consists of temperature, heat dissipations, and thermal conductance, which is a function of flow rate. Then, we can quantify ITVs using this physical simulation model.

Conventional design project of CE products usually use bill of materials based on structural 3D CAD data as a common reference for design information in the distributed project. We propose the product model that consists of function and structure. In particular, the functional part of the product model includes behavior models, which could properly express the interfaces among functional modules, and could also be utilized to derive the physical simulation model. This SysML-based multilayered product model associated with the simulation model is an important part of our developed collaborative design framework.

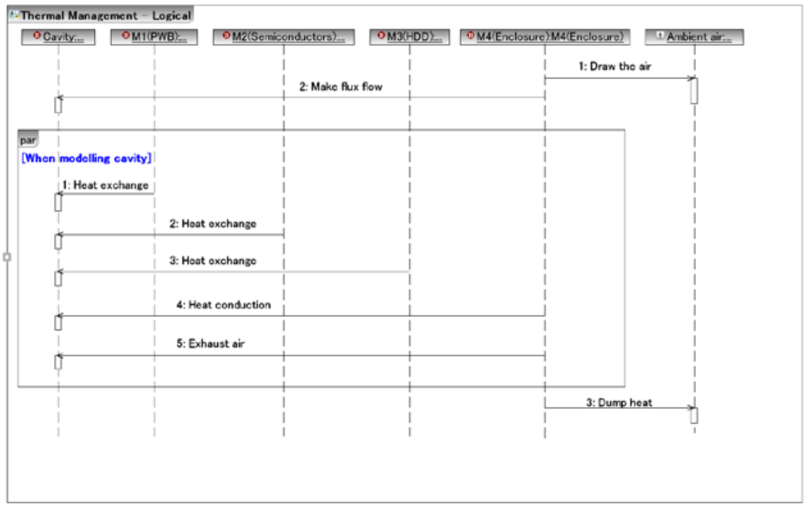


Figure 7. SysML Sequence diagram

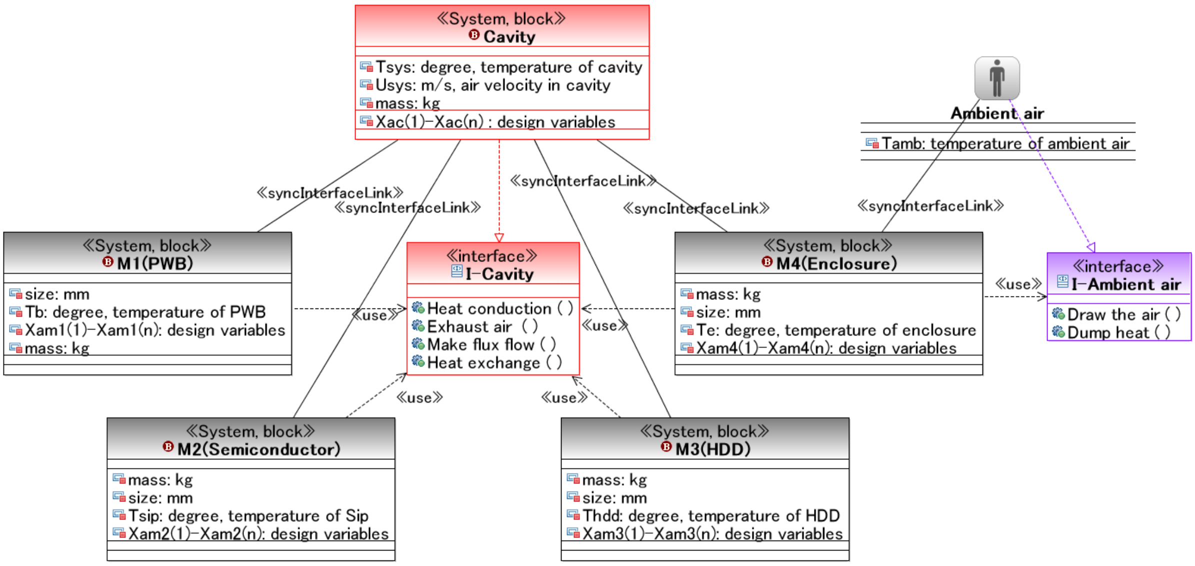


Figure 8. Function architecture (with cavity module definition)

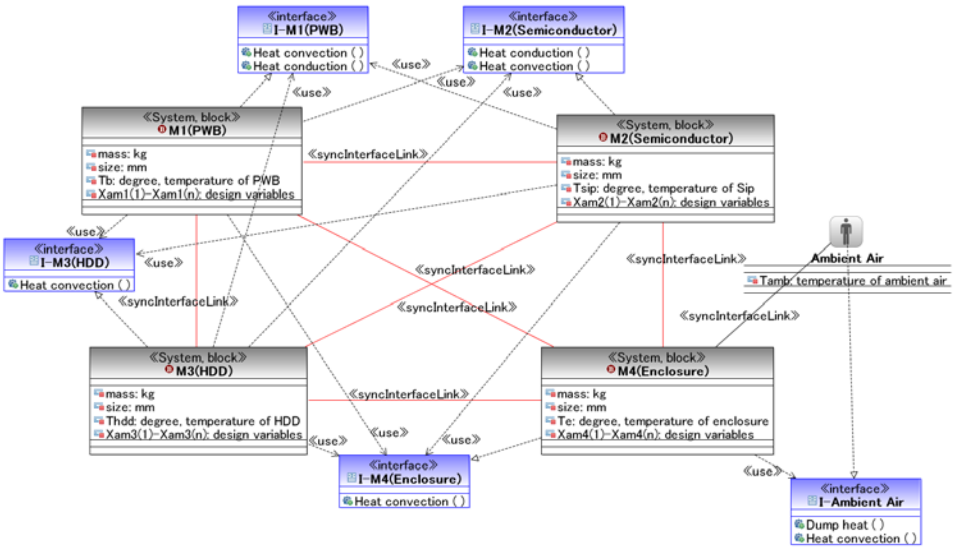


Figure 9. Function architecture (without cavity module definition)

3.2 System decomposition using ITV

This section describes the system decomposition from the architecture design (logical level) to the module detailed design (physical level). The use of ITVs derived from the physical simulation model could be a good initial boundary condition for each module design, which would be independently conducted at distributed design sites. In the SysML-based product model description, we can easily construct a structure diagram from the functional part of the product described in the previous section for the detailed design process (Figure 10). The modeling process for assigning ITVs to a semiconductor module shown in Figure 6 is as follows:

- Identify interfaces using the sequence diagram, and perform physical model simulation
- Calculate ITVs using cavity module specifications (system impedance, etc.) and physical model simulation
- Decompose the functional module to the physical module with corresponding ITVs (U_{sys}, T_{sys}, T_b)
- Start detailed module design at locales, and store the design information as design variables in the structure definition of the product model (Figure 11)

Macro model simulation in an early design stage is not as new as a distributed design methodology [2]. However, we think that our approach, which consists of defining functions using SysML description in the architecting phase and deriving physical model simulation from behavior modeling (such as sequence diagram), is unique and practical. In addition, we start with system decomposition to the detailed module design definition with system boundary conditions (ITVs), which could be defined using physical model simulation, especially for the distributed design framework. This scheme could lead the system to the global optimum in the desired performance in the distributed design work.

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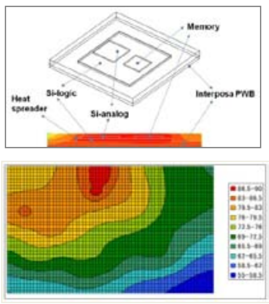
		Modules			Behavior models
		PWB	Semicon	Cavity	
System Architecting process (*Logical*)	Design Variables X_a	Heat dissipation of PWB, Thermal conductivity	Heat dissipation of SiP, Thermal conductivity	System Impedance (*S.I.*)	Physical model Simulation *Thermal balance: "Thermal conductance" × "Temperature" = "Heat dissipation" *Flow rate balance: "Pressure drop" = S.I. × "Flow rate^2"
Decomposition	Performance Requirements: P_R	Average Temperature of PWB: T_b	Average Temperature of SiP: T_{sip}	U_{sys} (ITV) T_{sys} (ITV)	
Detailed Design process (*Physical*)	Design Variables ***DV***	Detailed dimensions, Thermal Conductivities DV_{m1}	Detailed dimensions, Thermal Conductivities DV_{m2}	Fan spec., Grille at openings, Geometry of cavity	Detailed module simulation 
	ITV (external design variables)	ITV_{m1} $\begin{cases} U_{sys} \\ T_{sys} \end{cases}$	ITV_{m2} $\begin{cases} U_{sys} \\ T_{sys} \\ T_b \end{cases}$		
	Performance Requirements for QA: P_{RQ}	Temperature of PWB : $T_{b\,i}$	Temperature of Si, memory, etc. : $T_{sip\,i}$		

Figure 10. System decomposition using ITV

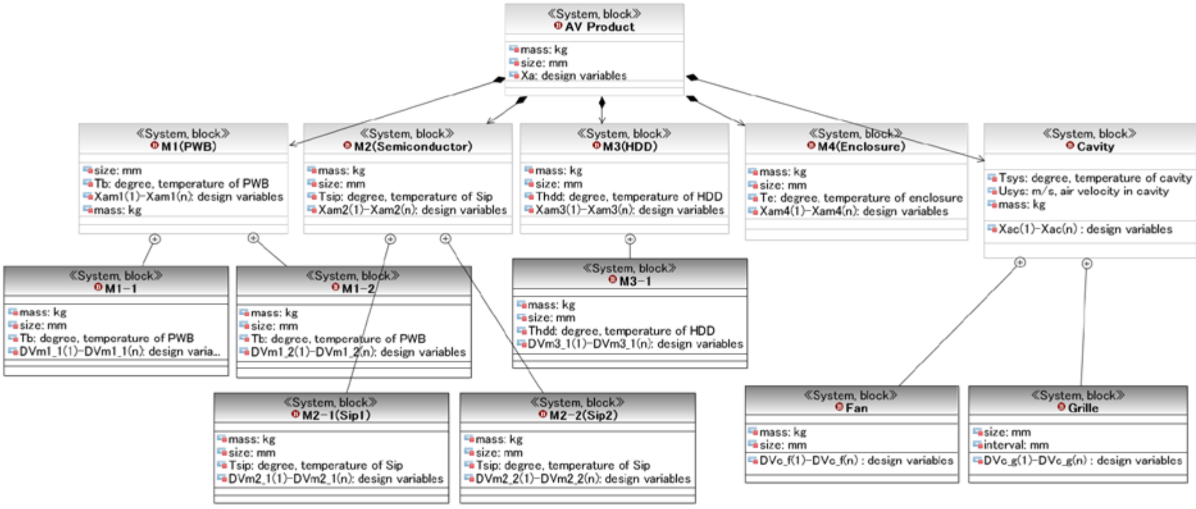


Figure 11. Structure diagram

3.3 Module/System trade-off design with sensitivity analysis

As described in the previous section, SysML model descriptions clear up the interfaces among modules in the system architecture phase. Then, the results derive the external system boundary (ITVs) using physical model simulation. In the detailed module design phase, ITVs should be updated from the initial tentative values to the final values to lead the system to a potentially optimal condition by performing trade-off study between the independent module design and the system design. This section discusses the methodology using sensitivity analysis.

Figure 12 shows the design sensitivity map for trade-off study. There are two sensitivities of performance requirements P_{RQ} which can be calculated with module simulation tools: one is sensitivity to the module design variables DV_i (internal sensitivity), and the other is sensitivity to the ITV_i (external sensitivity). If the former sensitivity is high, change in the design of the module considering cost issues would be appropriate. If the latter is high, the result indicates that there is a possibility of changing the tentative system boundary ITV_i, that is, the system design parameter or other module designs. The map in Figure 12 is effective to the trade-off study with limited design information at a certain design site.

$$\text{Internal sensitivity} = \frac{\partial P_{RQj}}{\partial DV_i} \cdot \Delta DV_i \quad (1)$$

$$\text{External sensitivity} = \frac{\partial P_{RQj}}{\partial ITV_i} \cdot \Delta ITV_i \quad (2)$$

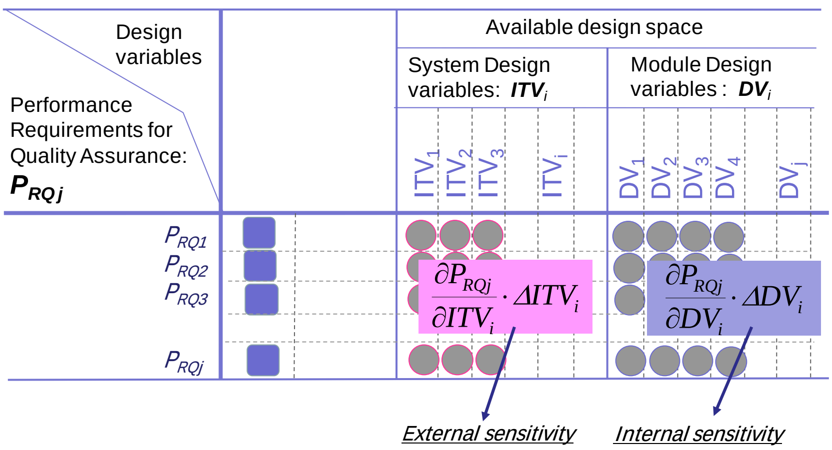


Figure 12. Available design space

3.4 Design information shearing with SyML Parametric Diagram

In this section, a linkage between design variables (both logical and physical) is modeled using SysML constraint expressions to represent system constraints. In the internationally distributed design project, each design process, such as system architecting, module detailed design, and module/system trade-off, is conducted across the country/company boundaries. The design information exchange could be done in an ad-hoc manner, and it is usually difficult to synchronize the design stages as planned. Thus, constant constraint management for the related design variables would be beneficial.

The value of ITV set as a tentative interface parameter should converge to the appropriate value for entire system through trade-offs between the modules and the system during the design process. In this design example, the process from ITV calculation to sensitivity analysis for trade-off involves important data exchange across the distributed sites. Then, SysML model sets the constraints to the design variables during that process using a parametric diagram (Figure 13). This linkage enables all the distributed design sites to collaborate when needed, and to be able to refer to the system performance through the physical model simulation resulting in a global optimal design solution.

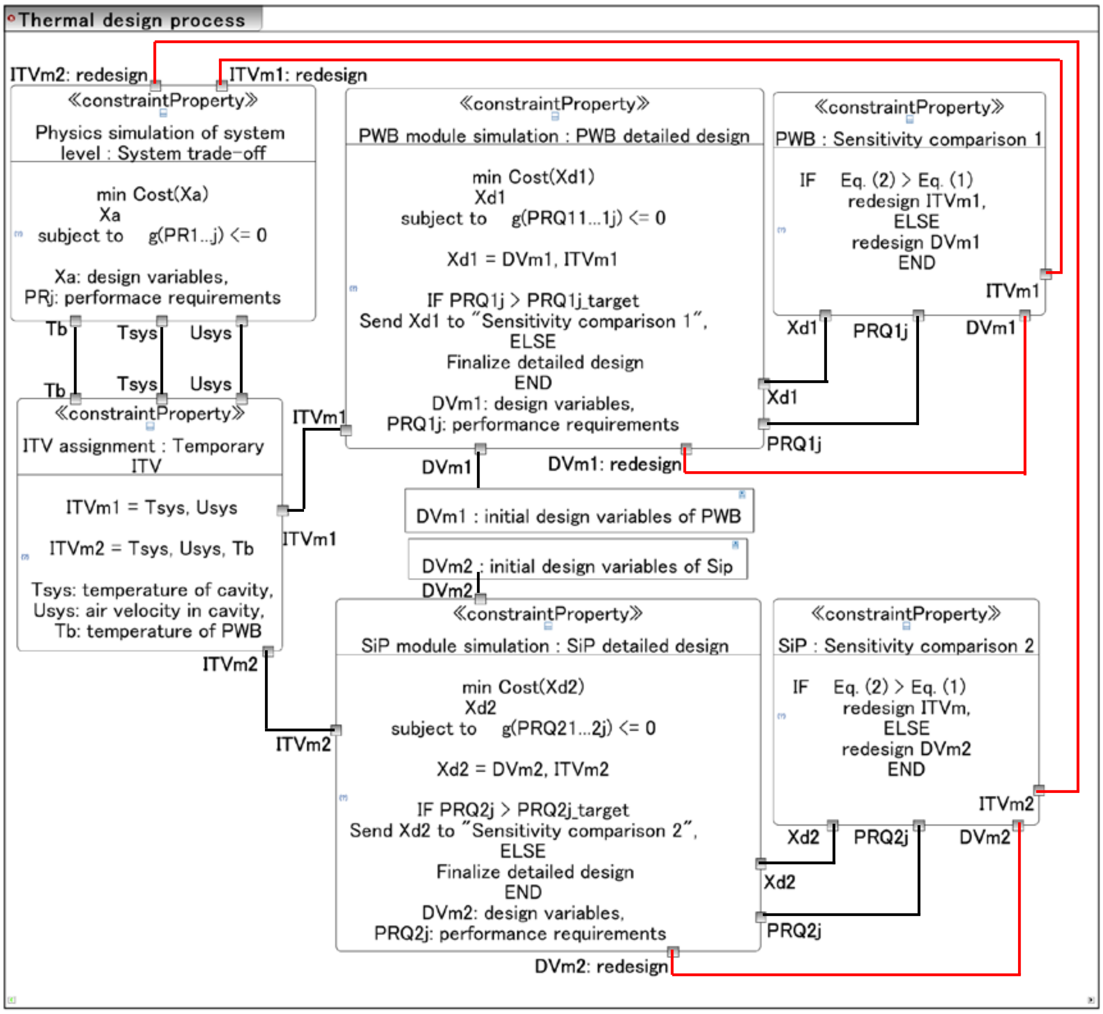


Figure 13. Parametric diagram

4 CONCLUDING REMARKS

This paper described a design framework that eliminates inconsistent performance of modules due to lack of communication between design sites, and also eliminates iteration of work required to correct such inconsistencies using ITVs during the independent module design. ITVs are calculated using behavior modeling and a physical model simulation in the system architecture phase. This framework is a module-based design methodology that considers cavity as a module in the logical design process.

Authors investigated the utilization of the product model by SysML as a joint platform for distributed design environment to realize the abovementioned design framework in the actual CE product design project. The definition of cavity as a module is effective for the interface description, assignment of ITV, and the independent module design in the distributed design project.
Authors proposed structural and functional modeling that enables all the distributed design sites to share the design information. The design process described by the SysML diagrams adopted sensitivity analysis for the trade-offs between modules and system. Using this proposed design framework, it will be possible to prevent performance defects at later design stages due to physical coupling between modules, and thus, reduce the iteration of work.

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